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Evaluation of the effectiveness of a Virtual Reality-based exercise program for Unilateral Peripheral Vestibular Deficit

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Evaluation of the effectiveness of a Virtual Reality-based exercise program for Unilateral Peripheral Vestibular Deficit

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Abstract.
BACKGROUND: Recently, two types of movement sensors have been introduced into Virtual Reality (VR) therapy: motion trackers and force-plate platforms. Combining these two methods could produce better rehabilitation outcomes. Such devices, encompassing motion trackers and force platforms, are referred to as "hybrid" VR units.
OBJECTIVE: To assess the effectiveness of a low-cost hybrid VR based vestibular rehabilitation program
METHODS: A prospective, non-randomized, controlled group study comparing training using a hybrid VR unit (Group 1 $n=25$) vs. static posturography with visual feedback (Group 2 $n=25$) in patients with peripheral vestibular dysfunction was conducted. The subjects underwent 10 training sessions over 10 days (30 minute sessions). All were examined on a posturography platform at the start and 1 month after rehabilitation and completed the Vertigo Symptom Scale – Short Form (VSS-SF) questionnaire.
RESULTS: Both groups demonstrated improvement in posturographic parameters, which were statistically significant, but when comparing results between both groups there were no differences. The patients reported improvement in their subjective perception of symptoms on the VSS-SF scale, which were statistically significant in both groups, but greater in the VR group.
CONCLUSIONS: Both methods reduce postural sway, however subjective reduction of symptoms was greater in the VR group.

Keywords: Vertigo, vestibular rehabilitation, Virtual Reality

1. Introduction

Peripheral vestibular loss is the most common cause of severe vertigo and nausea. These symptoms are often accompanied by the sudden onset of spontaneous nystagmus beating towards the healthy side and disequilibrium. Patients experience fear and anxiety during or in between the attacks, which results in absence from work and a cost to society [19]. Pharmacological treatment is recommended only in the acute stage for a short time, and a further decrease of vertigo is achieved with targeted rehabilitation therapy.

Vestibular Rehabilitation Therapy (VRT) began with Cawthorne-Cooksey exercises given to patients with labyrinth deficiency after head trauma [2, 3]. The main principle of VRT is to promote a natural vestibular recovery process, generally attributed to the vestibular compensation phenomenon, which is achieved by adaptation, habituation and substitution mechanisms, as defined in the works of Herdman

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[9] and Deveze et al. [4]. Correction of unbalanced vestibular, proprioceptive and visual inputs is obtained by auditory and visual feedback or optokinetic training combined with physical exercise involving upper body, head and eye movement. VRT is a non-invasive, safe and effective treatment in patients with acute or chronic peripheral vestibular loss. Patients with peripheral lesions but poor spontaneous vestibular compensation respond well to this form of therapy [7]. Conventional VRT exercises must be performed several times, amounting to 20–40 minutes of exercise per day [8], which some patients find repetitive and monotonous. Furthermore, it is difficult for patients to receive feedback while training at home. Recent advances in technology have made it possible to exercise at home with the use of virtual reality.

Virtual Reality (VR) is a widely applied technique for generating a virtual environment using various forms of display – spherical, flat screen or head-mounted. The user can interact with objects in VR using his body movement [1]. VR has recently gained in popularity in medicine with the rapid development of mobile and visual technologies. It has been successfully applied in various medical specialties, for example: psychiatry, in treating anxiety [5], schizophrenia [18] and cognitive impairments; post-stroke hemiplegia [13]; or in pediatrics, in the rehabilitation of cerebral palsy [14].

Recently, VR was introduced to vestibular rehabilitation with various devices and protocols in which VR techniques had a similar effect to conventional vestibular therapy [1, 6]. Some of the implemented techniques utilize expensive equipment, which limits and delays treatment. Only a few studies have explored the application of commercially available, low-cost VR systems in VRT [15, 16]. These studies have focused either on force-plate technologies (Nintendo Balance Board) or motion sensor dependent devices, such as the Microsoft XBOX 360 Kinect, which our Department has studied in vestibular rehabilitation [11]. The motivational and enjoyment aspect of virtual reality-based programs may result in better compliance with exercises than conventional therapy [9]. With low costs, this method remains more affordable for rehabilitation centers than certified static posturography, and it is possible to introduce it as home therapy for maintaining vestibular compensation.

The hybrid VR devices defined by Herdman et al. [9] are built from accessories derived from commercially available technologies and combine motion sensors, force plate technology and a display for providing visual feedback and generating the VR environment. This system detects movement from the upper part of the body and measures the center of pressure displacement. By evoking a wider range of movements from the patient hybrid VR systems might have a better effect on postural control and vertigo. There is no research in the available literature regarding hybrid VR technology in vestibular rehabilitation; therefore, the aim of this study was to evaluate the effectiveness of a low-cost hybrid VR based vestibular rehabilitation program in a unilateral peripheral vestibular impairment.

2. Material and methods

A prospective, non-randomized, controlled group study comparing training using a hybrid VR vs. static posturography with visual feedback in patients with peripheral vestibular dysfunction was conducted. The study was approved of the Local Ethics Committee at the Medical University of Lodz (no. RNN/88/17/KE). All subjects provided written informed consent. All clinical investigation was conducted according to the principles expressed in the Declaration of Helsinki.

Patients who were diagnosed with vertigo and balance instability at the Balance Disorders Unit, Otolaryngology Department, Medical University of Lodz and fulfilled the study requirements were subject to a prospective analysis. The inclusion criteria were: (1) persistent vertigo and disequilibrium with unsatisfactory spontaneous compensation at least two months post-onset; (2) unilateral peripheral vestibular impairment confirmed by videonystagmography (VNG) (Ulmer SYNAPSIS 2008) as canal paresis with directional preponderance. The VNG examination assessed spontaneous ocular movements with eyes open and closed, positional tests, ocular-motor tests – smooth pursuit, optokinetic and saccadic tests, kinetic stimulation with torsion swing test – and caloric test by the Fitzgerald-Hallpike method. Patients after orthopedic surgery, with a history of epilepsy, bilateral peripheral vestibular loss or central vestibular disorder were excluded.

Fifty patients were assigned to the study groups using an alternating sequence, wherein every second individual enrolled (e.g., 1, 3, 5, etc.) was assigned to the intervention group (the Virtual Reality-based exercise program – Group 1) and the alternate patients (e.g., 2, 4, 6, etc.) were assigned to the control group

(Static posturography with visual feedback training – Group 2)

Group 1 included 25 patients, 14 women and 11 men, aged 26 to 64 years (average age 46.48 ± 10.6). Patients received ten training sessions lasting 30 minutes for two weeks using a hybrid VR unit consisting of a force plate, an upper body movement motion sensor and a central unit with a flat screen display (Neuroforma 2016, manufactured by Titanis Sp. z o.o. Warsaw, Poland).

Standing 1.5–2 meters from the display on the force plate, patients performed a set of exercises coordinating upper body movement and maintaining the center of pressure (COP) in a predetermined range or shifting the COP towards indicated positions. The software utilized includes 8 exercises for balance with 28 difficulty levels, gradually progressing from a predetermined setting according to the patient's performance. Furthermore, the range of motion on the force plate could be altered individually, depending on the affected side, thus, requiring the patient to lean more to the right in right-sided vestibular dysfunctions.

To ensure correct performance, the training was supervised by a physiotherapist. For protection purposes, the ground surface was soft, and a railing of 1.5 by 1.5 meters was put in place around the patient.

The exercise protocol consisted of two tasks. The first task was "Meteorites", a VR game set in space where a marker on the display projected the patient's COP. By moving the marker, the patient could target randomly generated, moving meteorites and satellites. The goal of the exercise was to eliminate the meteorites, thus gaining points and progressing to the next level. If a satellite was hit, the patient lost a point. Successive difficulty levels increased the speed of the objects and, simultaneously, the number of meteorites on screen.

The goal of the second task was to place hats on hangers with matching colors. The movement and selection of the hat were controlled by elevating the upper extremities and dragging the selected item across the screen to the desired location. During the exercise, the patient's COP was projected on the display in a circle, and upon reaching the periphery, the color of the circle changed from green to red. If the COP exceeded the boundaries, the hat returned to its original position. Advancing further narrowed the COP limit and extended the upper extremity range by increasing the distance between the hats and the hangers.

Group 2 included 25 people, 13 women and 12 men, aged 29 to 68 years (average age 45.20 ± 11.07). Patients received a total of ten sessions of static posturography training with visual feedback over a two-week period under the supervision of a physiotherapist. The patient stood on a firm surface with heels 5 cm apart and toes apart at a 45-degree angle. A display providing visual feedback was in front of the patient. The screen projected the patient's COP on a statokinesiogram. The task was to steer the COP representation towards a randomly generated point on the screen. Points were generated at 20-second intervals, and if the patient did not manage to reach the point, a new point was generated elsewhere. This cycle was repeated 86 times, and a total score was calculated at the end of exercise. The duration of each session was, on average, 25 minutes.

Throughout the course of the rehabilitation, both groups were instructed by physiotherapists on how to perform Cawthorne-Cooksey exercises at home and were asked to exercise three times daily.

Each group was examined before rehabilitation and one month after rehabilitation. The examination involved posturographic assessment on a static platform (Euroclinic SSS ED 8000) including a quiet stance with eyes open and eyes closed for 30 seconds. The feet were positioned with heels 5 cm apart and toes at a 45-degree angle. Each test was repeated three times, and the average score was recorded. The total length and surface of the COP in both tests were selected for further analysis. The total COP length was defined as the length of a line joining the recorded points of the COP trajectory in a 30-second period; a higher value implied greater instability. The COP surface was measured as the surface area of an ellipse containing 90% of the recorded COP trajectory points in a 30-second period. All COP calculations were computed automatically by the platform's software.

Patients also filled in the Vertigo Syndrome Scale – Short Form (VSS-SF) clinical questionnaire as proposed by Yardley et al., which has been previously used in VRT clinical trials [1, 21]. The VSS-SF is a self-assessment where patients respond to fifteen questions addressing the frequency and severity of vertigo symptoms by ranking them from 0–4 points. 0 points: "never", 1 point: "a few times (1–3 times a year)", 2 points: "several times (4–12 times a year)", 3 points: "quite often (on average, more than once a month)" and 4 points: "very often (on average more than once a week)". The questions group symptoms into two subsets: anxiety and balance. Severe vertigo is interpreted as 12 or more points.

Table 1
Comparison of COP parameter change in quiet stance with eyes open before intervention and 1 month after rehabilitation

Training method	Parameter	Before rehabilitation (Median)	1 month after rehabilitation (Median)	*P*-value[a]
Group 1 (VR) $n = 25$	COP total length [mm]	224.1 (IQR: 192.1–310.7)	211.1 (IQR: 171.2–282.3)	$P = 0.006$
	COP total surface [mm^2]	351.6 (IQR: 273.4–581.3)	351.56 (IQR: 273.4–492.1)	$P = 0.1$
Group 2 (Control) $n = 25$	COP total length [mm]	465.2 (IQR: 360.1–559.2)	409.9 (IQR: 260.6–518.4)	$P = 0.04$
	COP total surface [mm^2]	546.9 (IQR: 468.8–703.1)	532.0 (IQR: 351.6––645.3)	$P = 0.24$

Table 2
Comparison of COP parameter change in quiet stance with eyes closed before intervention and 1 month after rehabilitation

Training method	Parameter	Before rehabilitation (Median)	1 month after rehabilitation (Median)	*P*-value[a]
Group 1 (VR) $n = 25$	COP total length [mm]	387.9 (IQR: 307.1–454.0)	300.4 (IQR: 238.3–441.4)	$P = 0.001$
	COP total surface [mm^2]	703.1 (IQR: 390.6–1024.0)	532.1 (IQR: 340.1–742.2)	$P = 0.006$
Group 2 (Control) $n = 25$	COP total length [mm]	793.4 (IQR: 633.3–966.4)	657.3 (IQR: 556.2–793.7)	$P = 0.003$
	COP total surface [mm^2]	1054.7 (IQR: 760.9–1523.4)	859.4 (IQR: 721.4–1054.7)	$P = 0.003$

Table 3
Comparison of VSS-SF scores within groups before therapy and 1 month after rehabilitation

Group	Subscale	Before rehabilitation (Median, IQR)	1 month after rehabilitation	*P*-value[a]
Group 1 (VR) $n = 25$	Balance	14 IQR(13–18)	9 IQR(7–11)	$P = 0.001$
	Anxiety	13 IQR(11–15)	9 IQR(7–11)	$P = 0.001$
Group 2 (Control) $n = 25$	Balance	18 IQR(15–20)	13 IQR(11–15)	$P = 0.001$
	Anxiety	16 IQR(13–17)	13 IQR(11–14)	$P = 0.001$

The investigator performing the posturography assessments was not involved in implementing any aspect of the intervention, was blinded to group allocation and knew patients only by their unique study identifier. The participants were not blinded as the nature of both interventions does not allow for a double-blinded trial.

Continuous variables were summarized using median and interquartile range (IQR) for non-normally distributed variables. The Shapiro-Wilk test was used to assess the normal distribution of continuous variables. Comparisons within groups regarding the COP parameter and VSS-SF scale change were performed using the Wilcoxon test as the variables were non-normally distributed. To analyze the effectiveness of VR rehabilitation versus the control group, the total change of COP parameters and VSS-SF score was calculated for each individual. The median values were compared. A comparison between the groups was conducted using the Mann-Whitney test for non-normally distributed variables. The level of significance used for all analyses was 2-tailed and set at $P < 0.05$. Statistical analysis was performed using STATISTICA software (Version 13.1, Dell).

3. Results

All patients completed a full course of therapy and there were no reports of side effects.

Comparing outcomes within the groups, both the length and square surface of the COP decreased in time; however, in the quiet stance with eyes open, there was no significant change in the COP surface median (Table 1).

In a quiet stance with eyes closed, the COP parameters improved in both groups and the differences were statistically significant (Table 2).

Both study groups showed a lower score in the VSS-SF questionnaire regarding balance and anxiety subscales; the difference was greater in the balance subscale, which is more related to the physical perception of vertigo (Table 3).

The comparison of the posturographic test results between groups in eyes-open and eyes-closed conditions showed no statistically significant differences (Table 4).

The total improvement in patient-reported outcomes compared by group showed statistically significant differences in favor of VR training

Table 4
Between the groups comparison of COP parameter differences

Testing conditions	Parameter	Group 1 (VR) $n = 25$ (Median, IQR)	Group 2 (Control) $n = 25$ (Median, IQR)	P-value[a]
Quiet stance eyes open	COP length [mm]	36.6 (IQR: 6.0–53.8)	41.2 (IQR: –15.3–122.8)	$P = 0.45$
	COP surface [mm^2]	39.0 (IQR: –39.1–100.2)	39.1 (IQR: –117.2–273.4)	$P = 0.81$
Quiet stance eyes closed	COP length [mm]	48.6 (IQR: 28.6–136.1)	89.1 (IQR: 27.9–176.7)	$P = 0.34$
	COP surface [mm^2]	145.2 (IQR: 26.9–312.5)	156.3 (IQR: 18.6–536.1)	$P = 0.68$

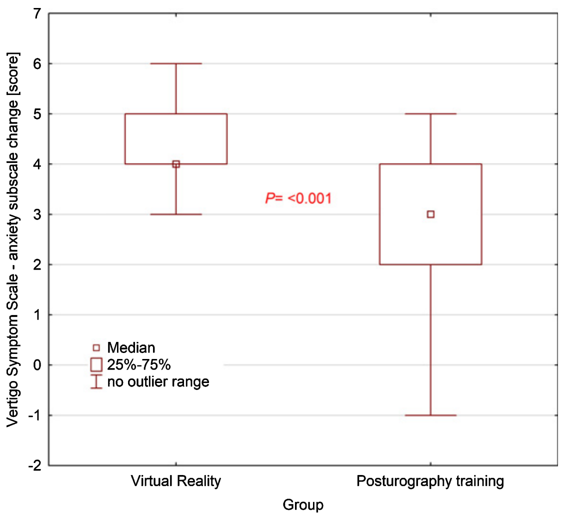

Fig. 1. Box-and-whisker plot comparing VSS-SF anxiety subscale change between groups, the p-value was calculated using the U-Mann-Whitney test.

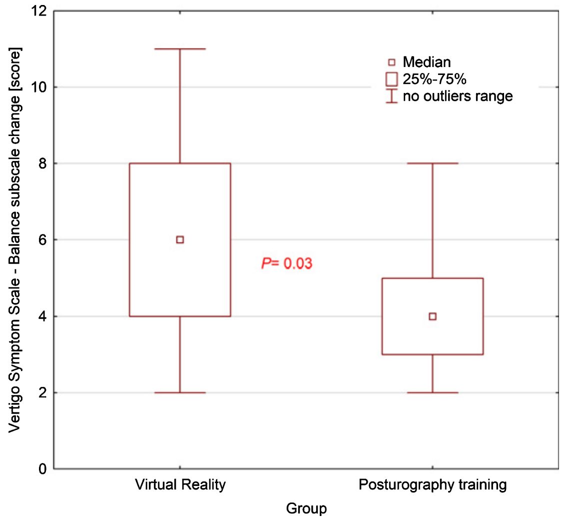

Fig. 2. Box-and-whisker plot comparing VSS-SF balance subscale change between groups, the p-value was calculated using the U-Mann-Whitney test.

(Figs. 1–3), which was most significant in the VSS-SF subscale regarding the balance scores (Fig. 2).

4. Discussion

The main goal of our study was to assess whether vestibular rehabilitation utilizing hybrid VR techniques is an effective method of rehabilitation. The current results are similar to the preliminary study conducted in our Department in 2014 [11]. In the present study, the VR method was developed further by adding a force plate to the motion sensor and applying specialized software instead of commercially available VR games. Another change to the previous protocol was that all posturographic tests were performed three times upon each visit, and an average was calculated to improve the accuracy of the small study samples. Most notably, this is the first study to our knowledge to investigate a hybrid VR technique, expanding on prior VR studies.

Prior work has established VR as an effective method of vestibular rehabilitation in a population suffering from peripheral vestibular dysfunction; however, studies in this field remain limited. For example, Meldrum et al. [17] compared the effec-

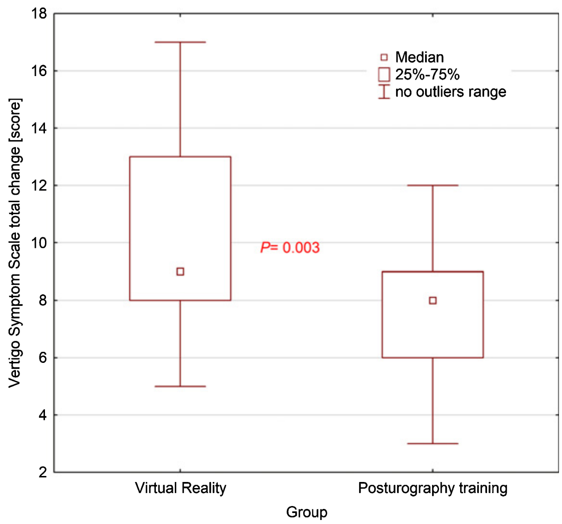

Fig. 3. Box-and-whisker plot comparing VSS-SF total change in score between groups, the p-value was calculated using the U-Mann-Whitney test.

tiveness of conventional versus virtual reality-based (Nintendo Wii Fit Plus) vestibular rehabilitation using force-plate sensors in treating patients with unilateral peripheral vestibular loss, supporting the effectiveness of force-plate VR in these patients.

In our current study, the cumulative exposure protocol was 300 minutes per patient. Bergeron et al. [1], in their meta-analysis of VR techniques of VRT in patients suffering from vertigo of peripheral origin, emphasized that VR treatment should last at least 150 minutes of cumulated virtual environment exposure to achieve positive outcomes, and that neither the duration of a particular session nor the total number of sessions is an outcome predictive factor [1].

One study on peripheral vestibular deficiency conducted by Topuz et al. [20] concluded that significant improvement in vestibular rehabilitation in patients with poor spontaneous compensation is possible six months from the onset of symptoms. In the presented study, none of the randomized patients had achieved spontaneous recovery by two months. The two-month criterion was introduced to exclude patients with acute symptoms and to provide sufficient time for spontaneous compensation.

A systemic review by Bergeron et al. [1] expressed concern that the use of virtual reality might be limited by motion- or cybersickness because of excessive sensory stimulation. None of the patients who completed training complained of cybersickness or an exacerbation of symptoms during rehabilitation.

In objective measurements, patients show improvement in both groups, with strong statistical significance in eyes-closed conditions. Comparing the total reduction of COP length and surface between the two methods, both groups improved but neither intervention was superior. VR conditions are known to increase postural sway similar to when visual input is absent [10]. Cawthorn and Cooksey, in their original studies, recommended that VRT exercises should be performed with eyes open and closed. According to their findings, performing with eyes closed decreased the patient's reliance on visual information and probably increased the vestibular and somatosensory input to the compensation mechanisms. It is possible that, because in VR conditions the visual input is modified and different than the patient's surrounding, a similar compensatory shift occurs. Such a phenomenon might contribute to a greater improvement measured in eyes-closed conditions. Further studies with greater VR immersion using head-mounted displays are required to confirm this statement.

Posturography, while allowing quantification of postural sway or instability, is not a direct measure of vertigo sensation [12]. Self-assessment questionnaires are a part of the methodology where it is impossible to directly quantify vertigo. In our study, total improvement in both VSS-SF subscales was significantly greater for the VR group ($p < 0.05$). Thus, the overall sensation of dizziness intensity decreased more with virtual reality rehabilitation.

This study was not completely randomized, which might have resulted in potential bias and baseline differences between the groups in COP measurements. Due to the high variability of the initial COP length and surface at the baseline evaluation, a precise sample size calculation is difficult to estimate even in the presence of preliminary studies. In this study, posturography group training was related to the measurement method, which might contribute to this group achieving better results in control evaluation.

This study was underpowered; thus, certain observations might not -meet the level of statistical significance. Dynamic posturography might be a more functional method of assessing balance and could be used as an objective improvement measure for future studies.

5. Conclusion

Virtual reality-based vestibular rehabilitation with the application of hybrid VR units is an enjoyable and well-tolerated method of training. Hybrid VR is not superior in postural sway reduction in comparison with the established form of vestibular rehabilitation, which is static posturography with visual feedback training. However, virtual reality training seems to have a better effect on the subjective reduction of symptoms.

For future research, the authors would recommend a three-arm randomized control trial comparing the results of vestibular rehabilitation using a motion tracking VR system, a force-plate VR system and a hybrid VR unit including more outcome measurements.

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2

Use of Virtual Reality to Assess Dynamic Posturography and Sensory Organization: Instrument Validation Study

Original Paper

Use of Virtual Reality to Assess Dynamic Posturography and Sensory Organization: Instrument Validation Study

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Abstract

Background: The Equitest system (Neurocom) is a computerized dynamic posturography device used by health care providers and clinical researchers to safely test an individual's postural control. While the Equitest system has evaluative and rehabilitative value, it may be limited owing to its cost, lack of portability, and reliance on only sagittal plane movements. Virtual reality (VR) provides an opportunity to reduce these limitations by providing more mobile and cost-effective tools while also observing a wider array of postural characteristics.

Objective: This study aimed to test the plausibility of using VR as a feasible alternative to the Equitest system for conducting a sensory organization test.

Methods: A convenience sample of 20 college-aged healthy individuals participated in the study. Participants completed the sensory organization test using the Equitest system as well as using a VR environment while standing atop a force plate (Bertec Inc). The Equitest system measures the equilibrium index. During VR trials, the estimated equilibrium index, 95% ellipse area, path length, and anterior-posterior detrended fluctuation analysis scaling exponent alpha were calculated from center of pressure data. Pearson correlation coefficients were used to assess the relationship between the equilibrium index and center of pressure–derived balance measures. Intraclass correlations for absolute agreement and consistency were calculated to compare the equilibrium index and estimated equilibrium index.

Results: Intraclass correlations demonstrated moderate consistency and absolute agreement (0.5 < intraclass correlation coefficient < 0.75) between the equilibrium index and estimated equilibrium index from the Equitest and VR sensory organization test (SOT), respectively, in four of six tested conditions. Additionally, weak to moderate correlations between force plate measurements and the equilibrium index were noted in several of the conditions.

Conclusions: This research demonstrated the plausibility of using VR as an alternative method to conduct the SOT. Ongoing development and testing of virtual environments are necessary before employing the technology as a replacement to current clinical tests.

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KEYWORDS

postural control; virtual reality; sensory organization test; intraclass correlations

Introduction

The Equitest system (Neurocom) is a computerized dynamic posturography device used by health care providers and clinical researchers to safely test an individual's postural control. Implementing the sensory organization test (SOT) using the Equitest system requires individuals to process and integrate cues from the visual, vestibular, and proprioceptive systems. This test provides clinicians and researchers with an equilibrium score for each tested condition, a sensory analysis score, a strategy analysis, and a center of gravity (COG) alignment. While the Equitest system has evaluative and rehabilitative value, it may be limited owing to its cost and lack of portability. Moreover, the performance variables provided by the Equitest system are limited, representing gross outcome measures derived only from sagittal plane movement dynamics [1]. Recent advances in technology provide opportunities to reduce these limitations by providing more mobile and cost-effective tools while also observing a wider array of postural characteristics. The purpose of this research was to evaluate the validity of using virtual reality (VR) and a force plate as an alternative to the Equitest system.

The SOT has been the dominant clinical test to assess sensory integration in the context of postural control for neurologic disorders and deficits. With the wide use of clinical dynamic posturography over the last 30 years, the Equitest system has become widely accepted as the gold standard to assess postural stability and balance in several populations (eg, children, aging adults, and military personnel) and clinical groups (eg, those with concussion, vertigo, Parkinson disease, and Alzheimer disease). By systematically disrupting the visual and somatosensory information available to an individual, it is possible to distinguish someone's reliance on the following three major sensory systems during balance tasks: the visual, somatosensory, and vestibular systems. Conveniently, the Equitest system provides an equilibrium score (indicating how little participants swayed) during each test, as well as a sensory analysis score (indicating how much they relied on each system) and strategy analysis (indicating the hip versus ankle strategy) for the battery of conditions.

While the Equitest system provides a quick evaluative tool for clinicians and researchers, it is not without limitations. First, these outcome measures are derived solely from sagittal plane movements and may not reflect a complete assessment of an individual's postural control. Second, the costs associated with the Equitest system may limit its availability in underserved communities or during times immediately following an injury (such as a sports concussion). As an alternative to the Equitest system, it may be possible to combine more recent technologies, that is, portable force plates and VR, to ameliorate these drawbacks. When these technologies are combined, they greatly reduce the cost for a clinician to own testing equipment, as well as offer the opportunity to have a portable solution that could be taken into the field. Moreover, portable force plates present the possibility to record and assess a wider range of data, such as medial-lateral dynamics, and customize the outcomes to specific clinical goals. Likewise, VR headsets have continued to improve in quality and decrease in cost, and continued developments may lead to the ability to accurately track movements in VR without additional hardware components such as force plates.

In keeping up with technological advancements, it is important to determine how new technologies can measure up to the "gold standards" they will eventually replace. Currently, VR is approaching this standard and is consistently shown to be a valuable tool to conduct postural and motor control research. Previous research has found no difference between static balance in a physical environment versus a virtual environment [2]. Additionally, several scholars have supported the efficacy of VR for use in balance assessments in a range of clinical populations, such as those with concussion, stroke, Parkinson disease, and high age [3-7]. Continuing in this trend, a large body of research has shown positive results in using VR to enhance training and rehabilitation for balance-related dysfunction [8-11]. Overall, VR has been demonstrated to accurately assess balance in addition to providing a customizable means to enhance clinical outcomes.

The purpose of this research was to compare the Equitest system to a VR balance assessment designed to mimic the SOT in a young healthy population. It was hypothesized that the equilibrium score would demonstrate high limits of agreement between the two testing conditions, supporting VR as a viable option to decrease cost and increase the accessibility of postural assessment techniques. By illustrating the viability of VR to emulate current clinical practices, future progress can focus on improving and optimizing the implementation of VR in clinical standards of care and applications to more populations of interest.

Methods

Participants

A convenience sample of 20 college-aged individuals (Table 1) was recruited to participate in this study. All participants were healthy individuals with no prior history of neurological or physical injury or dysfunction. Upon arrival, participants provided informed consent. All procedures were approved by the institutional review board, and no adverse events were encountered.

Table 1. Participant demographics.

Characteristic	Male (n=7), mean (SE)	Female (n=13), mean (SE)
Age (years)	20.8 (0.4)	20.9 (0.37)
Height (m)	1.79 (0.03)	1.66 (0.02)
Weight (kg)	77.4 (5.58)	62.8 (3.33)

Experimental Design

After providing informed consent, participants completed a SOT in two blocks, using the Equitest system and using VR. Blocks of tests were counterbalanced, and conditions within blocks were randomized.

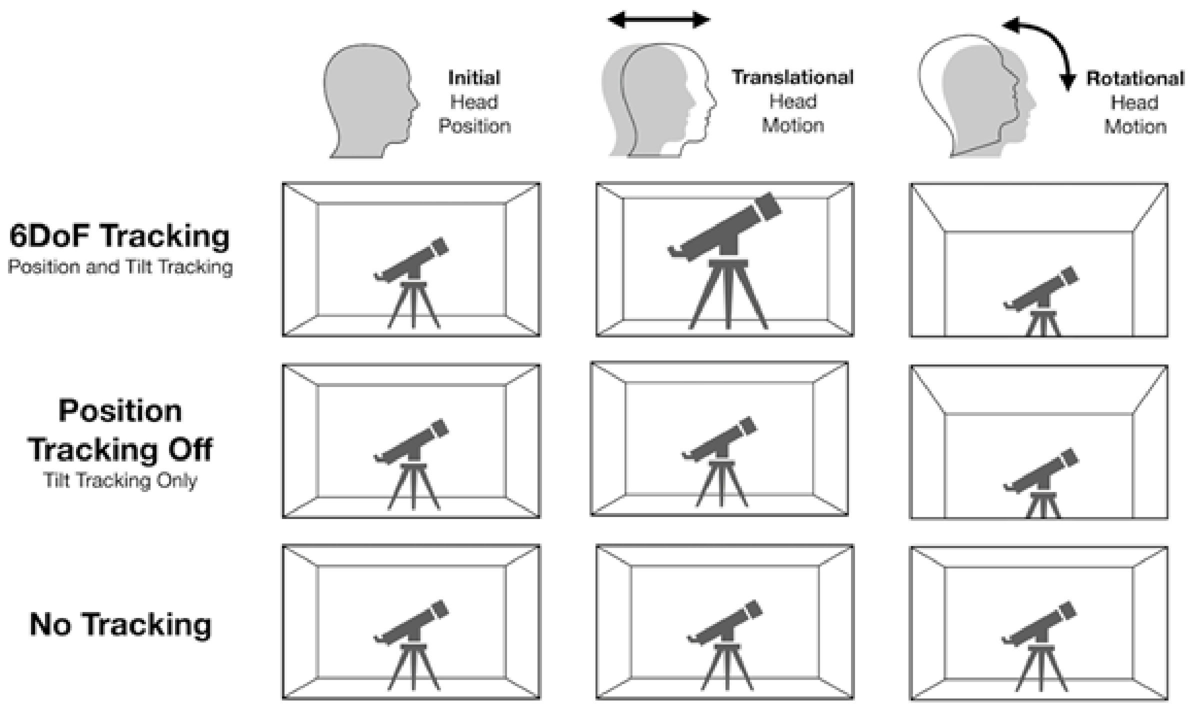
During the Equitest SOT, participants wore a harness that supported their weight in case they lost balance. Researchers helped participants into the harness so it fit comfortably and safely. The conditions during the clinical test included (1) eyes open on a stable surface, (2) eyes closed on a stable surface, (3) eyes open with a sway-referenced surround, (4) eyes open on a sway-referenced surface, (5) eyes closed on a sway-referenced surface, and (6) eyes open with both a sway-referenced surround and surface.

In the VR SOT, participants removed any glasses and wore a head-mounted display (HTC Vive, HTC). Participants adjusted the headset to ensure clarity in the virtual environment using a black screen with a textbox. To compare our VR SOT to existing SOT research performed with real machines, we created a virtual scale model of the patterns used inside of the Equitest balance system. We placed this model in the center of a white virtual testing room (10 m × 9 m in size). These models and the testing software were created using Unity 3D (v. 2018.2.10f1; Unity Technologies). Our software allowed us to test users with the following three different types of VR tracking: no tracking, head rotation tracking only, and six degrees of freedom (6DoF) tracking (Figure 1). The "no tracking" option creates an experience where the objects viewed move with the user's head as if they are attached. The second option, which is common in first-generation VR headsets, such as the Oculus DK1 and Google Daydream, is somewhat natural until users lean in a direction that moves their torso. The last of these most closely mimics reality.

Balance was tested in the following conditions in the VR environment: in a completely dark environment, eyes open in an environment that mimics the clinical test (6DoF tracking), eyes open in an environment that mimics the surround of the clinical test and moves and rotates with the participant's head (no tracking), and eyes open in an environment that mimics the surround of the clinical test and moves forward and backward with the participant's head but does not react to head rotation (head tracking only). Each condition was completed on a stable surface and on a foam surface.

For each balance condition, in both the clinical test and the VR test, participants completed two trials of 20 seconds. The order of the trials was counterbalanced between the clinical test and VR blocks, and the order of the conditions was randomized within the clinical test and VR blocks. In total, participants completed 28 trials (six clinical testing conditions × two trials each, four VR testing conditions × two surface conditions × two trials each) of 20 seconds of stationary balance. All participants provided written consent prior to beginning the experimental protocol.

Figure 1. Effect of the head tracking condition in virtual reality on a user's view with translation or rotation of the head. 6DoF: six degrees of freedom.



Data Reduction

The Equitest system calculated the equilibrium index (EI) during each SOT condition [12], and it represents the extent to which a participant sways forward or backward within a theoretical limit of 12.5° of displacement. If the participant has no sway, a score of 100 would be received, and if the participant exhibits 12.5° or greater sway (combined forward and backward), a score of 0 would be received. During the VR conditions, participants completed the test on top of a portable force plate (Bertec Inc) that collected center of pressure (COP) data at 50 Hz. Custom MATLAB (Mathworks Inc) scripts were used to detrend and filter the data (20-ms moving average filter) and subsequently calculate the estimated equilibrium index (eEI), 95% ellipse area, path length, and anterior-posterior (AP) detrended fluctuation analysis scaling exponent alpha (DFA α) from the COP data. The 95% ellipse area, path length, and AP DFA α calculations are described elsewhere and represent typical spatiotemporal characteristics of balance [13,14]. The eEI metric was derived based on the EI used by the Equitest system. To simplify this process, the forward and backward sway angles were calculated as the inverse sine function of the anterior and posterior COP displacement, respectively, divided by an estimated COG height (56% of the participant height). The first trial of each condition served as a familiarization period, and only the final trial of each condition was used for analysis. Data that were outside of three times the SD from the mean of its experimental condition were removed from the analysis. In this manner, one trial each from SOT 3 and SOT 4 was removed, along with their VR condition pair.

Statistical Analysis

To assess the relationship between EI and eEI, intraclass correlations of consistency and absolute agreement were calculated for similar conditions (Table 2). Intraclass correlation coefficient (ICC) values were interpreted as poor (<0.5), moderate (0.5-0.75), good (0.5-0.9), and excellent (>0.9) reliability [15]. Additionally, Pearson correlation coefficients were calculated to quantify the extent to which force plate measurements were associated with the EI calculated by the Equitest system within similar conditions. Correlation coefficients were interpreted as negligible (<0.3), weak (0.3-0.5), moderate (0.5-0.7), strong (0.7-0.9), or very strong (>0.9) relationships between pairs of variables [16].

Table 2. Summary of all testing conditions, their abbreviations, and the quality of visual, somatosensory, and vestibular information available in the condition.

Condition abbreviation	Equitest	Virtual reality	Information quality[a]
SOT[b] 1	Eyes opened on a stable surface	Stable virtual surround on a stable surface	Vis[c]–Som[d]–Ves[e]
SOT 2	Eyes closed on a stable surface	Blacked out environment on a stable surface	Som–Ves
SOT 3	Eyes opened with a sway-referenced surround	Head-referenced virtual surround on a stable surface	*Vis*–Som–Ves
SOT 4	Eyes opened on a sway-referenced surface	Stable virtual surround on a foam surface	Vis–*Som*–Ves
SOT 5	Eyes closed on a sway-referenced surface	Blacked out environment on a foam surface	*Som*–Ves
SOT 6	Eyes opened with a sway-referenced surround and on a sway-referenced surface	Head-referenced virtual surround on a foam surface	*Vis*–*Som*–Ves

[a]In the column, normal text indicates accurate and italic text indicates inaccurate.

[b]SOT: sensory organization test.

[c]Vis: visual.

[d]Som: somatosensory.

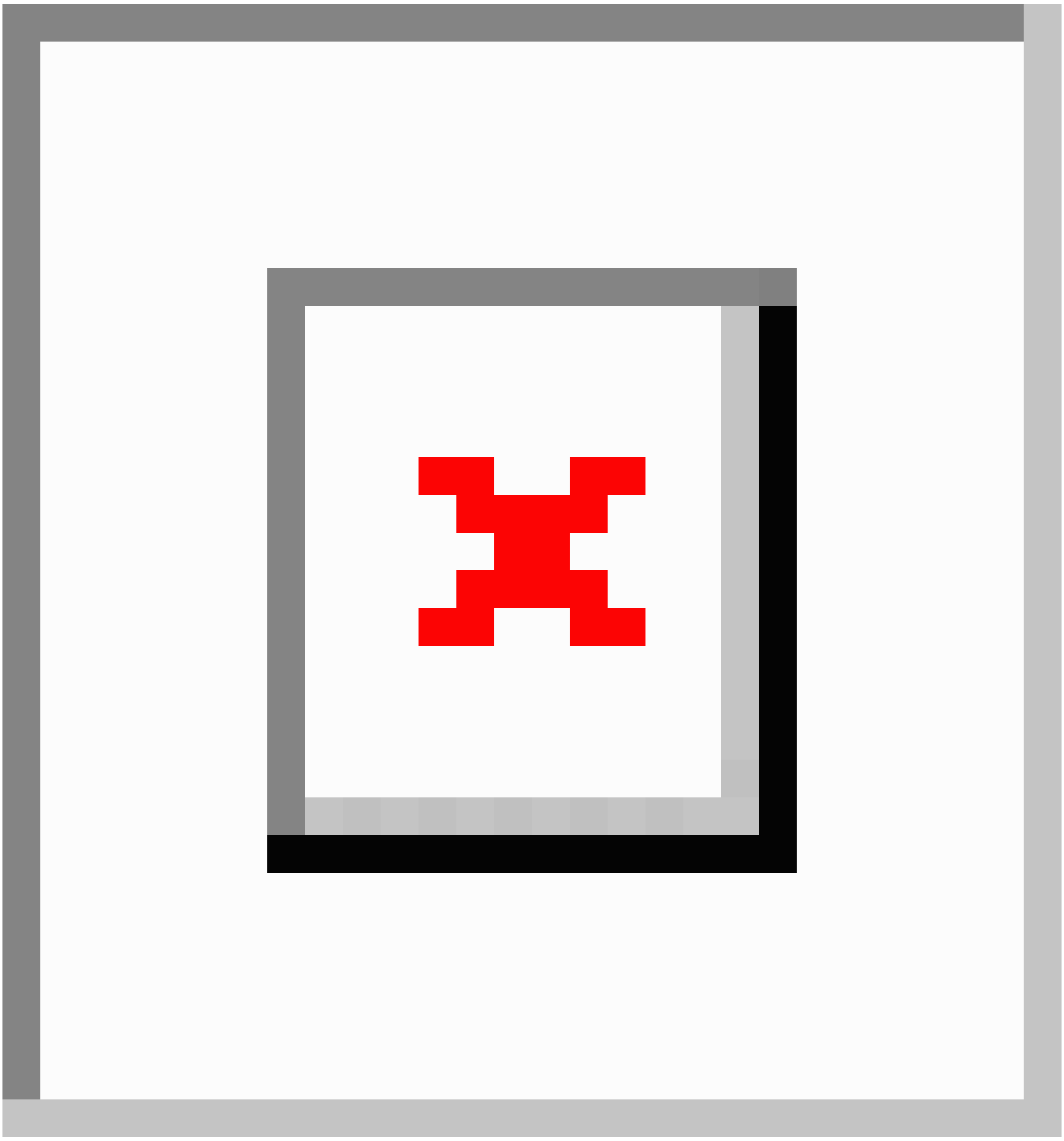
[e]Ves: vestibular.

Results

Data Presentation and Assessment of the Raw Data

Boxplots of the data showing the median (thick line), IQR (box edges), and 95% CI (whiskers) for each condition were created (Figure 2). Visual inspection of the data indicated symmetry in most conditions and increased variability in the more challenging conditions (conditions 4-6).

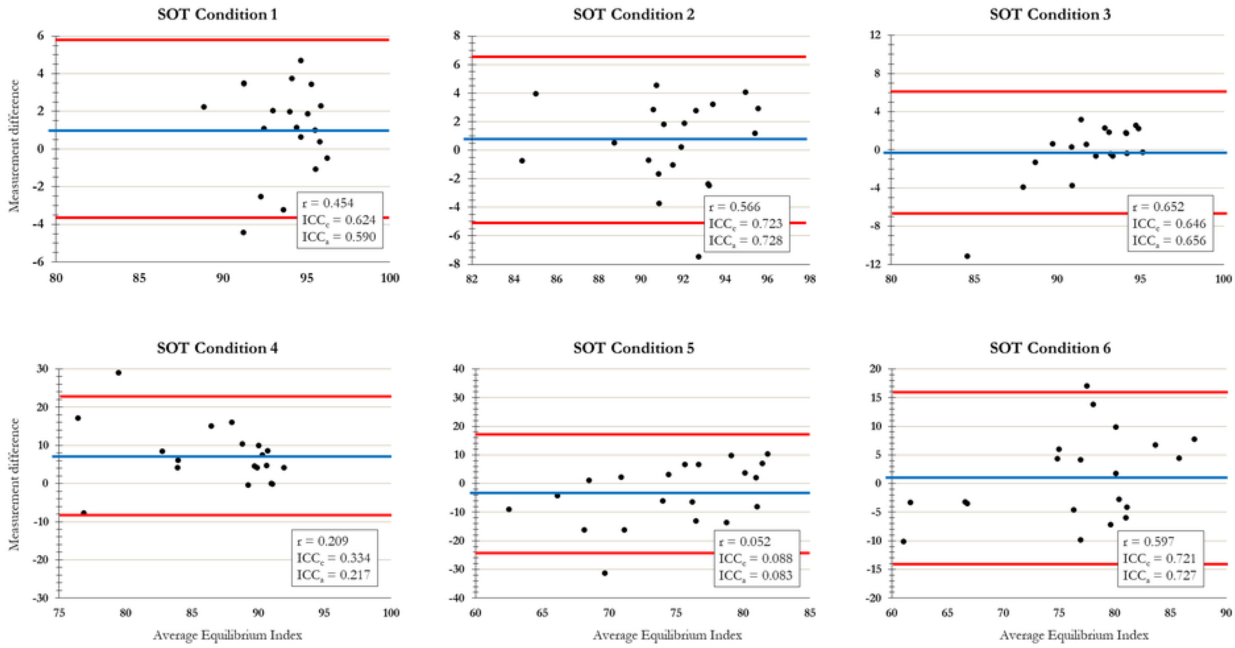
Figure 2. Boxplots of all data collected in comparable SOT (light) and VR (dark) conditions. The median value (thick line), IQR (box edges), and 95% CI (whiskers) are indicated. SOT: sensory organization test; VR: virtual reality.



Reliability of the eEI

Intraclass correlations between EI and eEI in similar conditions were evaluated and are presented alongside Bland-Altman plots in Figure 3 [17]. SOT conditions 1, 2, 3, and 6 demonstrated moderate consistency and absolute agreement with their similar VR condition counterparts. Meanwhile, SOT conditions 4 and 5 showed poor consistency and absolute agreement with similar VR conditions. The Bland-Altman plots provide a visual representation of agreement between two measurements by plotting the absolute agreement or mean difference between measurements on the vertical axis against the average of the two measurements on the horizontal axis.

Figure 3. Bland-Altman plots comparing the equilibrium index and estimated equilibrium index from the Equitest and VR SOT, respectively. The Pearson correlation coefficient (r), intraclass correlation coefficient for absolute agreement (ICCa), and intraclass correlation coefficient for consistency (ICCc) are provided. SOT: sensory organization test; VR: virtual reality.



Correlation of the EI With Force Plate Measurements

Pearson correlation coefficients were calculated between the Equitest EI and balance measures derived from COP data (Table 3). Weak to moderate significant correlations were identified between EI and eEI in SOT conditions 1 (*r*=0.454, *P*=.045), 2 (*r*=0.566, *P*=.009), 3 (*r*=0.652, *P*=.002), and 6 (*r*=0.597, *P*=.005). Additionally, weak to moderate significant correlations were identified between EI and 95% ellipse area in conditions 1 (*r*=−0.453, *P*=.045), 2 (*r*=−0.506, *P*=.02), and 6 (*r*=−0.500, *P*=.03) and AP DFA α in condition 1 (*r*=−0.511, *P*=.02). No other relevant correlations were identified between the Equitest EI and balance measurements derived from the COP data.

Table 3. Pearson correlation coefficients between force plate measurements (columns) and the equilibrium index during each sensory organization test condition.

Condition	eEI[a]	95% ellipse area	Path length	AP DFA α[b]
SOT[c] 1				
r	0.454	−0.453	−0.130	−0.511
P	.045	.045	.59	.02
SOT 2				
r	0.566	−0.506	−0.400	−0.041
P	.009	.02	.08	.86
SOT 3				
r	0.652	−0.329	−0.068	−0.234
P	.002	.17	.78	.33
SOT 4				
r	0.209	−0.143	−0.332	−0.007
P	.39	.56	.16	.98
SOT 5				
r	0.052	−0.242	−0.241	0.027
P	.83	.30	.31	.91
SOT 6				
r	0.597	−0.500	−0.334	−0.174
P	.005	.03	.15	.46

[a]eEI: estimated equilibrium index.

[b]AP DFA α: anterior-posterior detrended fluctuation analysis scaling exponent alpha.

[c]SOT: sensory organization test.

Discussion

This research has demonstrated the plausibility of using VR as an alternative to the Equitest when conducting a SOT. Although not a perfect replacement, eEI demonstrated reasonable correlations and ICCs with the clinical standard in several of the SOT conditions. Continued improvements to the VR testing environment need to be made to have more confidence in its use as a potential replacement. For example, the VR device may do a good job at mimicking the visual conditions of the SOT, but the foam mat might not equivocally disrupt somatosensory information compared with the SOT. This is supported by seeing higher correlations between EI and eEI in the intact than inaccurate somatosensory conditions (conditions 1, 2, and 3 versus conditions 4 and 5). Additionally, this study identified a number of correlations between the Equitest system and typical balance measurements derived from COP data on a force plate. Aside from eEI, 95% ellipse area and AP DFA α had some correlations with the clinical test. It is not surprising that these correlations were somewhat sparse as they distinctly measure different characteristics of balance. The SOT measures only AP sway magnitude, while COP data can be used to calculate sway magnitude in the frontal and sagittal planes combined or to measure aspects of how variability is structured in an individual plane. For example, 95% ellipse area quantifies the gross postural control behavior during quiet stance [18] and AP DFA α quantifies the structure of variability within an individual's AP sway trajectory (ie, how random or deterministic the data is) [19], whereas EI evaluates how close an individual gets to a theoretical limit of stability [20]. The measures evaluated in this study were selected to represent a small array of postural control measurements, and future research should evaluate the clinical utility of individual metrics.

The recent surge in consumer-ready VR headsets has the potential to greatly reduce the cost of conducting balance assessments while also providing additional accessibility to sites outside of the clinic, for example, on the sideline during an athletic event. Likewise, using force plates opens access to raw, processed, and derived outcome measures that take advantage of the full scope of postural dynamics and present the opportunity to have more accurate information at the clinician's disposal. In the future, it may even be possible to accurately assess balance (and gait) using only the self-contained tracking of VR headsets. This research serves as a point from which we can merge motor control assessments with the accelerating advancements in consumer technologies.

Conflicts of Interest

None declared.

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Abbreviations

6DoF: six degrees of freedom
AP: anterior-posterior
COG: center of gravity

COP: center of pressure
DFA α: detrended fluctuation analysis scaling exponent alpha
eEI: estimated equilibrium index
EI: equilibrium index
ICC: intraclass correlation coefficient
SOT: sensory organization test
VR: virtual reality

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