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Head mounted display effect on vestibular rehabilitation exercises performance

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Abstract

Objectives: Vestibular rehabilitation clinical guidelines document the additional benefit offered by the Mixed Reality environments in the reduction of symptoms and the improvement of balance in peripheral vestibular hypofunction. The HOLOBalance platform offers vestibular rehabilitation exercises, in an Augmented Reality (AR) environment, projecting them using a low- cost Head Mounted Display. The effect of the AR equipment on the performance in three of the commonest vestibular rehabilitation exercises is investigated in this pilot study. **Methods**: Twenty-five healthy adults (12/25 women) participated, executing the predetermined exercises with or without the use of the AR equipment. **Results**: Statistically significant difference was obtained only in the frequency of head movements in the yaw plane during the execution of a vestibular adaptation exercise by healthy adults (0.97 Hz; 95% CI=(0.56, 1.39), p<0.001). In terms of difficulty in exercise execution, the use of the equipment led to statistically significant differences at the vestibular-oculomotor adaptation exercise in the pitch plane (OR=3.64, 95% CI (-0.22, 7.50), p=0.049), and in the standing exercise (OR=28.28. 95% CI (23.6, 32.96), p=0.0001). **Conclusion**: The use of AR equipment in vestibular rehabilitation protocols should be adapted to the clinicians' needs.

Keywords: Augmented Reality, Exercise, Head Mounted Display, Rehabilitation, Vestibular

Introduction

Peripheral vestibular disorders are common among adults, since their prevalence is as high as 8.4%, with older population and women predominating[1]. Vestibular compensation is a natural process of the Central Nervous System starting immediately after a peripheral vestibular damage, by activating intrinsic plasticity mechanisms at a molecular and cellular level on the sensory organs and the vestibular nucleus as well as on a variety of neural networks responsible for vestibular processing[2-3], leading to the functional recovery of the vestibular system after a period of time[4]. Vestibular rehabilitation (VR) has been evaluated as the optimal treatment for people with uncompensated symptoms of dizziness and imbalance due to peripheral vestibular disorders[5-7]. Its main objectives include promotion of vestibular compensation and re-weighting of sensory inputs (reliable sensory inputs gain "weight" during postural control, suppressing the possible sensory mismatch[8-9]), leading to reduced symptom intensity and duration as well as the risk of falls[5-7]. Systematic reviews[5-6] provide moderate to strong evidence supporting the effectiveness of this

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intervention and recent clinical guidelines[7] provide clinicians with high degree of evidence-based recommendations for home-based treatment. Effectiveness of vestibular rehabilitation seems to be affected by age, physical inactivity, visual deficits, medication as well as psychological factors[10-11]. This reflects to the necessary modifications of the intervention protocol based on patients' profile without deviating from its basic principles[12].

Supervision of VR programs may have an additional positive effect compared to that of the exercises towards clinical improvement, however the relevant evidence remains weak[13]. Hence, without the appropriate guidance and feedback by a specialized physiotherapist, patients often do not follow the instructions correctly, which results in inadequate improvement and symptom prolongation[14]. Indeed, time exclusivity, positive feedback, motivation, test-retest in standardized measures, proper clinical reasoning, and opportunity for real-time correction of exercise performance are beneficial for performance and adherence[15]. Supervision promotes compliance and clinical improvement. Conversely, lack of supervision increases the dropout rate from the program[7,15].

Rehabilitation in mixed reality environments with the use of high-end technology is a novel therapeutic option with promising results. Immersive reality vestibular rehabilitation has been used in people suffering from vestibular disorders with reported benefits on perceived handicap and minimum side effects[16-17]. The use of augmented reality and holograms in a beyond the-state-of-the-art, multi-modal platform has recently become available, offering a holistic solution with respect to motivation, monitoring and supervision for people with vestibular disorders and/or in the risk of falling[18]. Recently, the HOLOBalance platform has been equipped with a real-time motion capture system for assessing the balance exercises, included in its flowchart, providing accuracy for assessing frequency of head rotations and head's range of motion (RoMotion) in yaw and pitch plane, posture assessment and gait analysis[19].

The Head Mounted Display (HMD) is the mandatory equipment for successful immersion in simulated environments and is commonly used in mixed reality applications[20] for medical training and education[21-22], as well as in interventions including those for balance disorders[23-24]. Recent technological advantages introduced to the medical market a series of low-cost and reliable HMD solutions allowing easier and more accurate application in rehabilitation with the implementation of a head device and a mobile phone. However, the effect of using such a low-cost HMD on the performance of vestibular rehabilitation exercises remains unclear, even though there have been studies reporting successful transfer of improved motor skills to real life or other type environments after HMD facilitated virtual reality based training[25-26].

This pilot study aims to investigate the effect of a low-cost HMD on the performance of therapeutic exercises specifically designed for the improvement of perceived handicap and disequilibrium in the context of Vestibular Rehabilitation.

Materials and Methods

Population

This is a pilot study of healthy adults (n=25; 12 women) aged from 18–50 years old, recruited in the tertiary neuro-otologic clinic of 1st Department of Otorhinolaryngology, Head and Neck Surgery, at Hippocration Hospital, Athens, Greece. Age threshold was set to avoid any age-related degeneration of the peripheral vestibular system. Sample size was in line with similar clinical trials[27].

Inclusion criteria for the study were a) absence of history of a peripheral, central or mixed vestibular disorder, b) absence of perceived symptoms related to vestibular pathology spectrum, c) normal Dizziness Handicap Inventory[28] questionnaire score (DHI<6), d) normal values for the Vestibular Ocular Reflex (VOR) gain in video-Head Impulse (v-HIT) tested in the horizontal plane, (EyeSeeCam v.1.3, gain between 0.8 and 1.2), e) no history of a severe musculoskeletal injury and f) absence of history of any systematic rheumatic disease or any cardiovascular disease. Lack of the ability to understand the Greek language for the proper and full completion of the study's outcome measures were considered exclusion criteria.

Procedure

Before the baseline assessment the participants were informed, via an informative leaflet and by the researchers, about the study and they all signed a consent form. Then, a short clinical interview was conducted and demographic information (gender, age, educational level, body mass index) physical activity levels, history of any visual disorders and any musculoskeletal symptoms were recorded. Subjects completed the DHI and had the VOR tested in yaw plane with the EyeSeeCam v.1.3. The total DHI questionnaire score and horizontal VOR gain on left and right were also recorded. After a fifteen minute's break the subject was transferred to a dedicated room where the augmented reality platform was set up. Three different exercises were performed, two on a sitting position related to VOR adaptation 's principle and one on standing related to sensory substitution's principle. In the sitting position participants had to focus on a target on eye level, moving their head horizontally (VOR adaptation exercise in the yaw plane) or vertically (VOR adaptation exercise in the pitch plane), respectively, and in the standing position participants had to stand with their eyes closed and feet close together on a foam (standing exercise). These exercises are the most used on a prescribed vestibular rehabilitation protocol and were fully described, configured, and included in the exercise flowchart implemented on the HOLOBalance platform[18-19]. HOLOBalance platform was created to integrate evidence-based multisensory rehabilitation exercises into an augmented reality (AR) environment. Among the plethora of functional balance

	Mean	Median	Std. Deviation	Minimum	Maximum
Age (years)	34.36	34	5.80	24	46
BMI	24.64	22	5.99	17	39
Education (years)	17.8	18	2.92	12	24
DHI	1.52	0.0	2.25	0.0	6
VOR_R	0.99	1	0.10	0.80	1.17
VOR_L	0.99	1	0.09	0.80	1.20

Table 1. Characteristics of the study's population. (BMI: Body Mass Index, DHI: Dizziness Handicap Inventory, VOR_R: Vestibular Ocular Reflex_ Right horizontal semicircular canal, VOR_L: Vestibular Ocular Reflex_Left horizontal semicircular canal).

	VOR adaptation exercise performed in yaw plane		VOR adaptation exercise performed in pitch plane	
	RoMotion	Frequency	RoMotion	Frequency
Before	47.65 (41.83, 53.47)	2.56 (2.26, 2.86)	42.21. (36.38, 48.03)	1.66 (1.35, 1.97)
After	51.63 (45.81, 57.45)	1.59 (1.28, 1.90)	37.72 (31.90, 43.54)	1.55 (1.24, 1.86)
Difference (p value)	3.98 (-4.22, 12.18) (p=0.19)	**0.97 (0.56, 1.39) p<0.001**	-4.49 (-12.69, 3.71) (p=0.14)	-0.11 (-0.53, 0.31) P=0.47

Table 2. Marginal mean values with 95% confidence intervals and their differences for RoM and frequency of head movements for VOR adaptation exercise performed in yaw plane and pitch plane respectively. (RoMotion: Range of Motion; VOR: Vestibular Ocular Reflex; *Before*: Inertia Measurement Unit sensor with a velcro on the head; *After*: Inertia Measurement Unit sensor on the Head Mounted Display with a switched-off mobile phone on).

training exercises, their gamified variations, and motor-cognitive exercises the three exercises mentioned above are also included. Details upon the clinical protocol investigating the feasibility and acceptability of the system have already been published[18]. Prior to the experiment a demonstration of all the exercises (*pre-test phase*) was held and the participants were asked to perform them, and an agreement was made between clinicians and participants upon execution to avoid any errors due to limited understanding. A steady armless chair was used for the sitting exercises and a foam pad (Airex Balance Pad, 16" x 20" x 2.5") for the standing exercise. The monitoring system of the platform consisted by two Inertia Measurement Units (IMU) sensors (MBinetLab MMR-METAMOTIONR), placed on the head and the pelvis of the participants respectively. The IMU on the head recorded frequency, in Hertz (Hz), and RoMotion, in degrees, of head's movement either on yaw or pitch plane. The IMU on the pelvis recorded anteroposterior (frontal plane) and mediolateral (sagittal plane) sway of Centre of Pressure (CoP) displacement, measured on degrees. Data were stored in an edge computer anonymously and extracted via the HOLOBalance interface. The order of the executed exercises remained the same in all cases, but every participant performed the exercises in two different randomly selected conditions. Randomization was exported by a computed generated sequence. Two different experimental conditions were tested, before and after wearing the low-cost equipment used to create an AR environment. *Before* is referring to the implementation of an IMU with a velcro on the head of the participant with no extra weight of the HMD and the mobile phone, and *After* to the implementation of the head's IMU via the HMD (Docooler AR Headset Box Glasses 3D Holographic Hologram Display Holographic Projector for Smart Phones) with the adjustment of a mobile phone (Google Pixel 3) used for creation of AR environments which was switched-off, which means that no AR environment was projected. Duration of each exercise was one minute. Between each one of the exercises, one minute rest time was predefined. Between pre-test phase and the actual experiment and between experimental conditions the participants had a fifteen minute's break. Oral pre-recorder instructions of the exercises were provided by an avatar projected in a 2x2x2 meter box, placed behind the participants so they were able to clearly hear the instructions but not see the avatar. At the end of each exercise in both conditions, participants were asked to rate in a Likert scale (1-7) "*how difficult it was to perform the exercise*".

	Anteroposterior and mediolateral sway in the standing exercise on foam (marginal means with 95% CI)	
	AP sway	ML sway
Before	0.07 (-0.50, 0.63)	0.06 (-0.41, 0.53)
After	-0.20 (-0.76, 0.36)	0.27 (-0.19, 0.74)
Difference p value	0.26 (-0.48, 1.00) p = 0.50	0.21 (-0.45, 0.87) p = 0.52

Table 3. Marginal mean values with 95% Confidence Intervals and their differences for anteroposterior and mediolateral and sway in the standing exercise on foam (ML: mediolateral; AP: anteroposterior; Before: Inertia Measurement Unit sensor with a velcro on the head; After: Inertia Measurement Unit sensor on the Head Mounted Display with a switched-off mobile phone on; CI: Confidence Intervals).

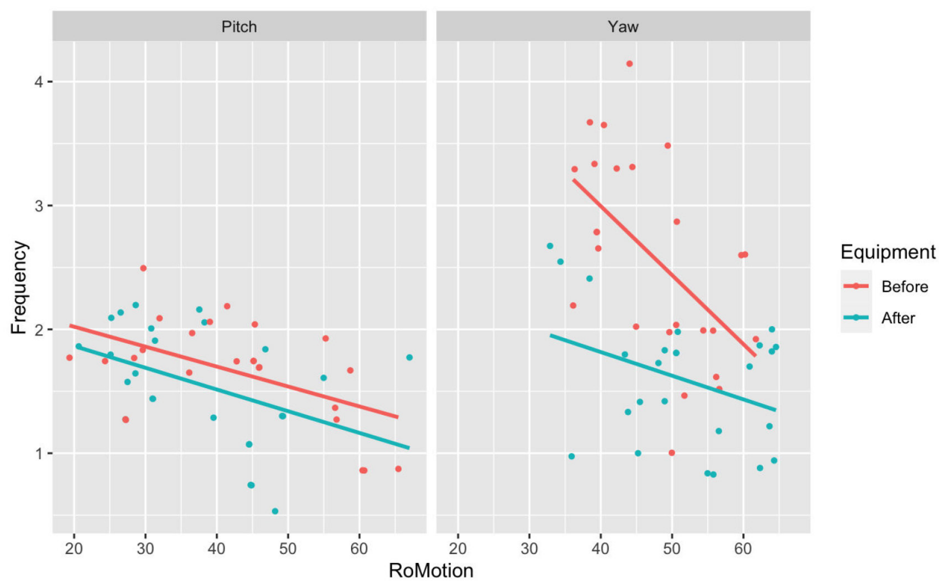

Figure 1. A scatterplot and linear gitted regression lines for RoMotion and frequency of head movements is presented for VOR adaptation exercise performed in the pitch and yaw planes. (Before: Inertia Measurement Unit sensor with a velcro on the head; After: Inertia Measurement Unit sensor on the Head Mounted Display with a switched-off mobile phone on; RoMotion: Range of Motion, VOR: Vestibular Ocular Reflex).

Statistical analysis

A three-level linear mixed effect model was used to reflect the multilevel structure of the data (repeated measurements of levels of Exercises, before and after wearing the equipment, within the same subject). Age, Sex, Body Mass Index and the interaction between wearing the Equipment and different Exercises were modelled as fixed factors. Random effects were modelled by a random intercept of Frequency within Subject to account for individual differences in the outcome measure for each subject, before wearing the equipment, and a random intercept for Exercise, to account for differences in the outcome measures in each exercise, before wearing the equipment. A random slope of the effect of wearing the Equipment within Subjects was also fitted to account for differences in the magnitude of the effect of its effect for each individual. Odds ratios for the effect of the equipment on the difficulty performing exercises between conditions were also calculated.

Linear mixed models were fitted by the restricted maximum likelihood method and t-tests using Satterthwaite's method[29-30]. Model selection was based on backward stepwise regression. Deviations from homoscedasticity or normality was verified by visual inspection of residual plots. Analysis of variance (ANOVA) tables (using the Kenward–Rogers method for estimating degrees of freedom), marginal means and significance testing of their differences were calculated via the lmerTest package[31].

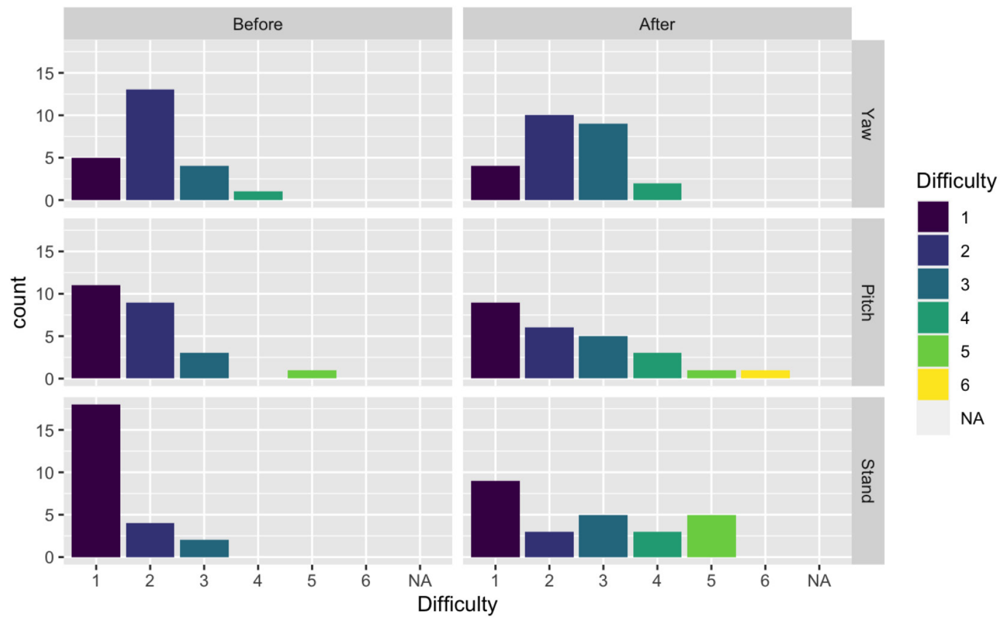

Figure 2. Histograms reporting the perceived difficulty of performing the exercises in a Likert scale between conditions (before and after wearing the equipment) for the VOR adaptation exercise in the yaw and pitch plane and in standing position. (NA: Not answered; no reported answer for the 7th point of the Likert scale, VOR: Vestibular Ocular Reflex).

Results

Model selection

The basic structural equation of the final model [Outcome measures]$_{tij}$= β_0+β_1 [Equipment]$_{tij}$+β_2 [Exercise]$_{tij}$+β_3 [Equipment]$_{tij}$ x [Exercise]$_{tij}$++u_{0ilj}+ε_{tij}
where, u_{0i} is the random intercept for Exercise nested into Subjects (capturing individual differences of the outcome measures of each exercise for each subject) within subjects, before wearing the equipment), ε_{tij} is the residual (unexplained) error.

Age, Sex and BMI were selected as fixed effects in some models, but their coefficient estimates were not significant. Random effects did not significantly contribute in the performance of the model for the standing exercise, and a standard fixed effect model was used. Baseline assessment's data are presented in Table 1. All values correspond to normal range for adults.

Head movement variables in VOR adaptation exercises

There was a statistically significant decrease of 0.97 Hz in VOR frequency in the yaw plane *After* compared to *Before* ([(0.56, 1.39) (t(48)=6.42, 95% CI=(0.56, 1.39), p<0.001) (Table 2). No statistically significant differences were observed in the range of motion in the yaw plane, and in neither of the head movement variables in the pitch plane (Table 2).

Standing exercise

No statistically differences were observed for the two experimental conditions in any of the say parameters in the standing substitution exercise (Table 3).

Difficulty in exercise execution

With respect to difficulty in execution, there was a significantly increase in the difficulty of performing the exercises *After* compared to *Before* in both the VOR adaptation exercise in the pitch plane (OR=3.64, 95% CI (-0.22, 7.50), p=0.049), and in the standing exercise (OR = 28.28. 95% CI (23.6, 32.96), p=0.0001). No statistical difference was observed in performing the VOR adaptation exercise in the yaw plane (OR=1.90, 95% CI (-1.66, 5.46), p=0.266) (Figure 2).

Discussion

We conducted a pilot study to evaluate the effectiveness of a low-cost HMD equipment used in an augmented reality environment upon the performance of three of the commonest therapeutic vestibular exercises which are integrated in the flowchart of the HoloBalance platform[18-19] and are commonly prescribed in balance rehabilitation protocols[32-34]. Statistically significant differences in the frequency of the head movement were found for the VOR adaptation exercise performed in the yaw plane *After we respect to Before* (Figure 1). However, no statistically significant differences were found regarding RoMotion between the two conditions. With the use of the low-cost HMD, the frequency of movement is decreased by 0.97 Hz ($p<0.001$) on average. For the rest of the exercises, no statistically significant differences were observed neither for frequency of head movement and RoMotion nor for sway.

Reduction of rotation frequency during therapeutic movements in the yaw plane, may be consequence of the cumulative weight of the HMD (actual weight: 399 gr) and the mobile phone (actual weight: 184 gr), as well as of the ergonomic construction of the HMD, possibly causing a forward shift of axis of motion, which is normally placed mainly on the central portion of the dens at 1^{st} – 2^{nd} cervical vertebrae level for rotation[35]. Furthermore, the perceived difficulty in performance was reported to be 3.6 times higher in the adaptation exercise in pitch plane and 28 times higher for the standing exercise in *After* compared to *Before*. This perceived difficulty may reflect the additional required activation of muscle synergies of back and neck extensors muscles, to counteract gravity and the extra placed weight of the HMD. This is a factor that clinicians should consider as a potential new external barrier that may influence adherence into a physical rehabilitation intervention.

The VOR adaptation exercise performed in the yaw plane is one of the most studied exercises in vestibular rehabilitation[36]. It aims to trigger a visuo-vestibular mismatch for the retina slip signal error, promoting a re-weighting of stimulus in the central vestibular neural circuits. The adaptation mechanism, which is activated, is frequency specific[36]. Thus, magnifying improvement in clinical outcomes, a high-velocity head movement is essential[37]. Recently updated rehabilitation clinical guidelines provide moderate evidence for the prescription of such gaze stabilization exercises[38]. The VOR is thought to be the most important vestibular reflex which operates over the head velocities of up to 8 Hz, required for normal everyday activities[39]. VOR adaptation is important for symptomatic recovery after vestibular failure, and vestibular handicap reduction is inversely proportional to the reorganization of the compensatory saccades that the VOR adaptation exercise provides[40]. In our study, a mean difference of 0.97 Hz ($p<0.001$) for head rotation in the yaw plane was observed. This result could probably reflect on some clinical consequences that experts should take into consideration with respect to exercise frequency, dosage and progression. Clinicians should be aware that in head movements in the yaw plane, frequency will probably be reduced compared to the recommended. Clinical decision making upon dosage and progression in VOR adaptation exercise in yaw plane should also take into consideration perceived symptoms and frustration level on top of metrics, at least until a fully ergonomic HMD is adapted or constructed accordingly and validated for this scope. The HMD used in the present study, was chosen over other products, during the procurement process, because of its low cost, the offered field of view and the ability to provide adequately realistic visual experience and interaction with the rest technical components on the mixed reality environment.

The use of special equipment, required for the creation of an augmented reality environment, seems to make it difficult 3.6 times to perform the exercise in the pitch plane and 28 times in the standing position. This difficulty can have a short-term impact on the performance of daily exercise session, which lasts about 20 minutes based on clinical guidelines[38]. We hypothesize that the evoked muscle fatigue will cause some level of discomfort towards the use of the equipment and an incorrect execution of exercises. Nevertheless, oscillations during standing substitution exercise are far from approaching the limits of stability. Thus, although the additional weight of the equipment makes the execution of two of the three exercises examined, it does not seem to affect the performance of the exercise individually, nor to create conditions near limits of stability. However, we hypothesize that it will create difficulties in implementing a full therapeutic exercise protocol in an augmented reality environment with the use of existing low-cost equipment and so clinicians should take this into account when prescribing vestibular rehabilitation exercises, adopting longer breaks between exercises or modifying the dosage (fewer exercises/more times daily). Findings in no way imply that the general safety instructions given during the performance of balance exercises should not be considered and thoroughly monitored. Future electromyography on activated muscles recordings will confirm or reject the above hypotheses.

It is not expected that the equipment alone, as patients acquiring motor skills into an augmented environment, will significantly influence effectiveness. Evidence of the performance in highly immersive environments is at least promising[20-21], hence examples for rehabilitation in mixed reality environments are extremely limited[41]. Improvement of technological solutions soon will provide the necessary equipment for transferring motor learning principles[42] into augmented reality and enhancing personalized intervention. However, the overall outcome should be weighted as additional motivation and commitment provided by augmented reality platforms should be considered as variables which has led to an increase of completion rate exceeding 50% in the HoloBalance proof of concept study (unpublished data). Nevertheless, it must be emphasized that the existence of metrics, concerning the execution of vestibular rehabilitation exercises, objectifies any clinical decision and is expected to improve the clinical intervention of Vestibular Rehabilitation per se, either with or without use of technology.

Limitations

Our pilot study was necessary for resolving safety and performance issues prior to implementation of the HOLOBalance platform to people with balance disorders, as accurately described in the feasibility protocol[18].

Investigating the effect of this specific equipment on the performance of the exercises in pathological populations will provide answers to the clinical questions presented above (exercise frequency, dosage and progression, adherence). It is obvious that changing the equipment any exercise performance will be modified, in an unpredictable way. Thus, we recommend that such pilot studies precede the actual clinical studies so that researchers understand the possible effect of the equipment used in mixed reality environments upon exercise parameters.

Conclusion

This study compared the performance of healthy adults in Vestibular Rehabilitation exercises with and without the use of equipment necessary for the projection of an augmented reality-based avatar guiding and correcting the performance of the exercises. Statistically significant difference was obtained in the frequency of head movements but not in the range of motion in the yaw plane during performance of a vestibular adaptation exercise by healthy adults. No statistically significant differences were found for variables in the vestibular adaptation exercise in pitch plane as well as in one of the most demanding of the standing exercises, usually prescribed by physiotherapists. It is imperative that the optimal equipment is designed and tested in healthy adults, before any integration into augmented reality environments.

Ethics approval

Approval was obtained by the Ethics Committee of the Hippocration Athens Hospital was obtained (39444/16-3-2021). Participants were informed about the study through leaflet and verbal communication by the researchers.

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