EFFECTS OF VIRTUAL REALITY EXERGAME ON PSYCHOPHYSIOLOGICAL AND POSTURAL DISORDERS IN ELDERLY PATIENTS

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Balance impairment at advanced age is a serious medical problem that often has significant implications and affects the quality of the patient's life. Among the underlying causes are overall slowness of motor response and vestibular syndrome. Virtual reality exergames, including reaction and balance training, hold promise for managing balance dysfunction. The aim of this study was to investigate the effects of a combination rehabilitation program containing elements of virtual reality exergame on the postural and psychophysiological parameters of elderly patients with small vascular disease The study was conducted in 24 patients with small vascular disease (median age: 66 years). All patients underwent a virtual reality rehabilitation program. Psychophysiological, postural and clinical evaluations were performed at baseline and after the program was completed. Balance function measured on the Berg scale improved significantly and was 53 [52; 55] after the training program vs 50 [45; 54] at baseline ($p < 0.05$). The strategy of balance control also changed: the Romberg ratio was 266 [199.5; 478.5] before rehabilitation and 221 [149.25; 404] after the program was completed ($p < 0.05$). The most pronounced changes in the measured psychophysiological parameters occurred in the simple audiomotor reaction, which improved from 210 [174.25; 245.5] at baseline to 180.5 [170.5; 208] after rehabilitation ($p < 0.05$). Thus, the combination balance and reaction virtual reality training is an effective rehabilitation method for advanced-age patients with balance impairment.

Keywords: neurorehabilitation, virtual reality, balance impairment, reaction time

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ВЛИЯНИЕ ТРЕНИРОВОК В ВИРТУАЛЬНОЙ РЕАЛЬНОСТИ НА ПСИХОФИЗИОЛОГИЧЕСКИЕ И ПОСТУРАЛЬНЫЕ НАРУШЕНИЯ У ПОЖИЛЫХ

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Нарушение равновесия в пожилом возрасте является острой проблемой в современной медицине и часто приводит к серьезным последствиям, снижающим качество жизни. К основным причинам такого нарушения относят замедление скорости реакции и вестибуло-атактический синдром. Для коррекции нарушений равновесия у данной категории больных наибольший интерес представляет технология виртуальной реальности, в частности с комбинированной тренировкой скорости реакции и равновесия. Целью исследования было изучить влияние комбинированных тренировок в виртуальной среде на постуральные и психофизиологические показатели у пожилых пациентов с хронической ишемией головного мозга (ХИГМ). В исследование было включено 24 пациента с диагнозом ХИГМ (медиана возраста составила 66 лет). Все пациенты проходили тренировку в виртуальной реальности. До и после тренировки пациентам проводили психофизиологическое и стабилометрическое тестирование, а также клиническую оценку. Выявлено, что у пациентов значимо улучшается функция равновесия по шкале баланса Берг до 50 [45; 54], после 53 [52; 55] ($p < 0{,}05$), а также изменяется стратегия поддержания равновесия по результатам стабилометрии, что подтверждено уменьшением коэффициента Ромберга после реабилитации: до 266 [199,5; 478,5], после 221 [149,25; 404] ($p < 0{,}05$). Среди психофизиологических показателей наиболее значимые изменения наблюдали в улучшении простой слухо-моторной реакции: до 210 [174,25; 245,5], после 180,5 [170,5; 208] ($p < 0{,}05$). Таким образом, комбинированная тренировка скорости реакции и равновесия в виртуальной среде является эффективным методом реабилитации пациентов пожилого возраста с нарушением функции равновесия.

Ключевые слова: нейрореабилитация, виртуальная реальность, постуральные нарушения, время реакции

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Motor and balance dysfunction is the primary cause of increased risk for falling at advanced age. More than one-third of elderly people over 60 years have a gait disturbance. At 60–69 years, the prevalence of gait disorders is about 10.7%, increasing to 61.7% in 80-year-old patients. Gait disturbances are rooted in neurological causes in 75% of cases [1]. Among the leading causes of motor dysfunction are sensory ataxia, parkinsonism, brain damage, and cerebrovascular diseases such as Small vessel disease [2]. The latter usually manifests as gait disturbance (in up to 85% of patients with stage 2 small vascular disease), pyramidal disorders, akinetic rigid syndrome, loss of coordination, including declining ability to maintain balance, etc. [3].

The slowness of postural response to external stimuli is one of the factors affecting balance at advancing age. It is difficult for elderly patients to adequately cope with an unexpected balance disturbance; they typically respond with increased muscle coactivation and joint stiffening, which cannot ensure effective amortization [4]. In another study, elderly patients demonstrated a slow motor response when asked to lift a foot following a visual cue, and often shifted their body weight erroneously in preparation for a step. The difference in reaction times between the groups waned when the preparation stage was excluded from the analysis. Thus, a slow motor response may be associated not only with overall slowness but also with incorrect preparation to movement [5]. Apart from longer reaction time, postural stability is affected by slow braking. In an experiment involving a series of forward and backward movements, elderly participants demonstrated a higher forward velocity (2^{nd} movement) to compensate for overall motor slowness. Besides, their strategy of movement control was different from that of the young participants, and the braking process took longer. The authors concluded that attempts to adapt to overall motor slowness may lead to increased postural instability [6].

The risk of falls can be prevented or reduced through rehabilitation programs. Over the past two decades, a variety of high-tech methods have been introduced into routine rehabilitation. A substantial body of evidence has been accumulated confirming the effectiveness of robotic technologies, exoskeletons, brain-computer interfaces, non-invasive methods for brain stimulation, etc. [7–12]. In the age of technological abundance, a personalized approach to rehabilitation and the search for predictors of effectiveness of the applied technology and rehabilitation as such are becoming increasingly important [13]. In this light, it would be useful to identify methods for determining the effectiveness of the chosen rehabilitation approach for an individual patient. The aim of this study was to evaluate effects of the integrated rehabilitation program for better balance and faster motor response on postural and psychophysiological parameters.

METHODS

The study was conducted in 24 patients with small vascular disease (5 men and 19 women). The median age was 66 years (61; 72).

The following inclusion criteria were applied: patients of both sexes aged 60 to 70 years with Small vessel disease. Exclusion criteria: severe visual impairment preventing the patients from discriminating images on the screen; severe cognitive impairment preventing the patients from following the instructions; Montreal Cognitive Assessment (MoCA) score < 20 points; severe sensory or motor aphasia; co-morbidities causing static and dynamic balance impairments.

The patients underwent rehabilitation on a virtual reality Rehabunculus system (Intelligence and Innovations; Russia) fitted with a non-contact Kinect sensor (Microsoft; USA).

The rehabilitation course lasted for 10 days and comprised 5 30-min-long sessions per week. Exercises included in the course aimed at training static and dynamic balance function and the speed of motor reaction (Darts, Stepping over the board with the left and right legs, Dodging the ball by bending sideways, Dodging the ball by stepping sideways, Football for the left and right legs, Barley-Brick [14].

Psychophysiological parameters were evaluated using a Psychophysiologist UPFT-1/30 device (Medicom MTD; Russia).

Evaluation was based on the following battery of tests:

1. *A simple visuomotor reaction test* (SVMR). The patient was tasked to press Yes or No in response to a visual cue (a flashing LED indicator on the handheld console) as quickly as possible using their dominant hand.

2. *A complex visuomotor reaction test* (CVMR). The patient was tasked to press Yes (green light) or No (red light) in response to a visual cue as quickly as possible using their dominant hand.

3. *A simple visuomotor reaction to the movement of the pointer indicator* (SVMR -IM). The patient was tasked to press Yes or No as quickly as possible in response to the onset of pointer indicator movement on the "dial face".

4. *A simple audiomotor reaction test* (SAMR). Headphones were not worn during the test; the patient was tasked to press Yes or No as quickly as possible in response to a loud audio stimulus emitted from the console.

5. *A complex visuomotor reaction to a combination of colors* (CVMR-CC). The patient was tasked to press Yes or No as quickly as possible in response to a certain combination of 3 flashing light stimuli (green leftmost light, red rightmost light).

6. *A functional activity of nervous processes test* (FMNP). The patient was tasked to press Yes or No as quickly as possible in response to a rapidly flashing light (red light — yes, green light or skipped yellow light — no).

7. *A reaction to a moving object test* (RMO). The patient was tasked to press Yes or No with their dominant hand to stop the pointer indicator before it reached the target position (indicated by the flashing light).

The total duration of psychophysiological testing was 30 min. Prior to each test, the patients received the instructions and verbally confirmed that the instructions were understood. The patients put their fingers in a comfortable position above the console. The stimuli were delivered at different time intervals to exclude the possibility of adjusting.

Static and dynamic balance at baseline and after the rehabilitation course was measured using a Stabilan-01-2 system (RITM OKB; Russia) and the Berg balance scale [15].

The obtained data were processed in Statistica v. 7.0 (StatSoft; USA) using the Mann–Whitney U test for independent samples, Wilcoxon test for dependent samples, and Spearman's correlation coefficient. The results are presented below as medians and lower and upper quartiles (25%, 75%). Differences were considered significant at $p < 0.05$.

RESULTS

Effects of virtual reality training on balance function in elderly patients

The median Berg score was 50 [45; 54] points at baseline, increasing by 3 ($p < 0.05$) points after the rehabilitation course and thus reaching 53 [52; 55] points. The baseline Berg score was negatively correlated with the Berg score after rehabilitation (the correlation coefficient was 0.823 at $p = 0.000005$).

Body sway was analyzed using standard parameters listed in Table 1.

After the rehabilitation course, the Romberg ratio (KoefRomb) was significantly lower ($p < 0.05$) than at baseline (Fig. 1); there was a significant increase in the LFS_c value (length to area ratio in the eyes-closed test) and the strength of correlation between COP position in the sagittal plane relative to the line connecting the lateral and medial malleoli and COP velocity in the eyes-open test (VFY_o).

The eyes-open test revealed a significant ($p < 0.05$) increase (in comparison with baseline values) in the mean COP velocity (V_o), an increase in the velocity index (IV_o), an increase in the time-normalized statokinesigram length on the Y axis (LY_o), a decline in the balance function quality (BFQ_o), an increase in the normalized vectorgram area (VA_o), an increase in the mean linear velocity (MLV_o), especially in the sagittal plane (MLV_o_sag), a trending increase in the COP excursion index (OD_o; $p = 0.055$) and in the time-normalized statokinesigram length on the X axis (LX_o; $p = 0.058$).

The eyes-closed test revealed a significant ($p < 0.05$) increase in the COP excursion index (OD_c), an increase in LFS_c, an increase in the coefficient of sharp velocity vector directional change (CSVVDC_c), an increase in the mean angular velocity (MAV_c), an increase in the mean angular velocity variation amplitude (MAVVA_c), an increase in the angular velocity asymmetry coefficient (AVAC_c), and an increase in total angular displacement (TAD_c).

Table 1. Romberg and stability tests

Parameter	Definition
Romberg test	
Romberg ratio (KoefRomb)	The ratio of the confidence ellipse areas in the eyes-open and eyes-closed tests. This parameter is used to quantify the extent to which the patient uses their vision for standing balance control
Statokinesigram density (LFS_c)	The ratio of the COP path (the length of the statokinesigram) to its area in the eyes-open test. The parameter reflects COP excursion per unit area
VFY_o	The correlation between COP position in the sagittal plane relative to the line connecting the lateral and medial malleoli and COP velocity in the eyes-open test. The parameter describes the distance from the experimental regression curve between the COP coordinate in the sagittal plane and COP velocity
Mean COP velocity (V_o)	Mean COP velocity during the trial
COP velocity index (IV_o)	This parameter is used to calculate mean COP velocity in the sagittal or frontal planes
Time-normalized length of the statokinesigram on the Y axis (LY_o)	The total COP sway path in the vertical plane during the trial
Time-normalized length of the statokinesigram on the X axis (LX_o)	The total COP sway path in the horizontal plane during the trial
Balance function quality (BFQ_o)	This parameter is calculated as the percentage ratio of the area confined by the velocity vector length distribution function and the constant equaling to the area of the square confined by the X and Y axes, the horizontal asymptote of the velocity vector length distribution function and the vertical line. The parameter is used to evaluate how minimal COP velocity is
Vectorgram area (VA_o)	The total area of the vectorgram during signal recording. The higher COP velocity and the sharper velocity vector turns, the higher VA
Mean linear velocity (MLV_o)	Mean linear velocity during the trial
COP excursion index (OD_o)	The ratio of statokinesigram length to the mean COP excursion range during the trial
Coefficient of sharp velocity vector directional change (CSVVDC_c)	Percentage of sharp COP velocity vector turns (over 45°) relative to the total number of vectors
Mean angular velocity (MAV_c)	Mean rate of COP velocity directional changes
Mean angular velocity variation amplitude (MAVVA_c)	Mean absolute value of angular velocity changes at local peaks
Angular velocity asymmetry coefficient (AVAC_c)	Average direction of COP velocity vector rotation
Total angular displacement of vectors (TAD_c)	Total angular displacement of the velocity vector during the trial
Stability test	
Total sway zone (SZone)	The area of the squares with sides equaling to the sum of A/P and M/L displacements
Frontal displacement (MO)	COP displacement in the frontal plane
Mean COP displacement radius (R)	Mean radius of COP displacements
Mean COP velocity (V)	Mean COP velocity during the trial
Rate of statokinesigram area change (SV)	Mean rate of statokinesigram area change
COP velocity index (IV)	Mean COP velocity index
Coefficient of displacement asymmetry in the frontal plane (KAssM(x))	Shows histogram deviation relative to the independent value (the mid-point of the histogram interval which covers most of the values)
Mean linear velocity (MLV)	Mean linear velocity during the trial
Total angular displacement of vectors (TAD_c)	Total angular displacement of the velocity vector during the trial

The stability test revealed a significant ($p < 0.05$) increase in SZone (Fig. 2), an increase in frontal displacement (MO) ($p < 0.01$), an increase in the mean COP displacement radius (R), an increase in the mean COP velocity (V), an increase in the rate of statokinesigram area change (SV), an increase in the velocity index (IV), a reduction in the coefficient of displacement asymmetry in the frontal plane (KAssM(x)), an increase in the mean linear velocity (MLV), and an increase in the total angle of vector displacement (TAD_c).

Effects of virtual reality training on psychophysiological parameters in elderly patients

The simple visuomotor response test showed a trending decrease ($p = 0.052$) in the average reaction time (SVMR_MO) and a trending reduction ($p = 0.061$) in the squared deviation of the reaction time (SVMR_SD). According the statistical analysis, there was a trending increase ($p = 0.069$) in the error rate, which is below referred to as the integrated reliability index (SVMR_IRI) after the training program.

The complex visuomotor response test revealed a significant ($p < 0.05$) increase in sensorimotor performance (CVMR_CNSAL), quantitative CNS activation index (CVMR_P) and reaction time mode amplitude representing the percentage of the shortest reaction times (CVMR_AMODA).

The test of the simple visuomotor reaction to the movement of the pointer indicator demonstrated a trending increase ($p = 0.053$) in the integrated reliability index after the training course (SVMR-IM _IRI).

Changes were the most pronounced for the simple audiomotor reaction ($p < 0.05$): there was an increase in the integral reliability index (SAMR_ IRI), a reduction in the mean

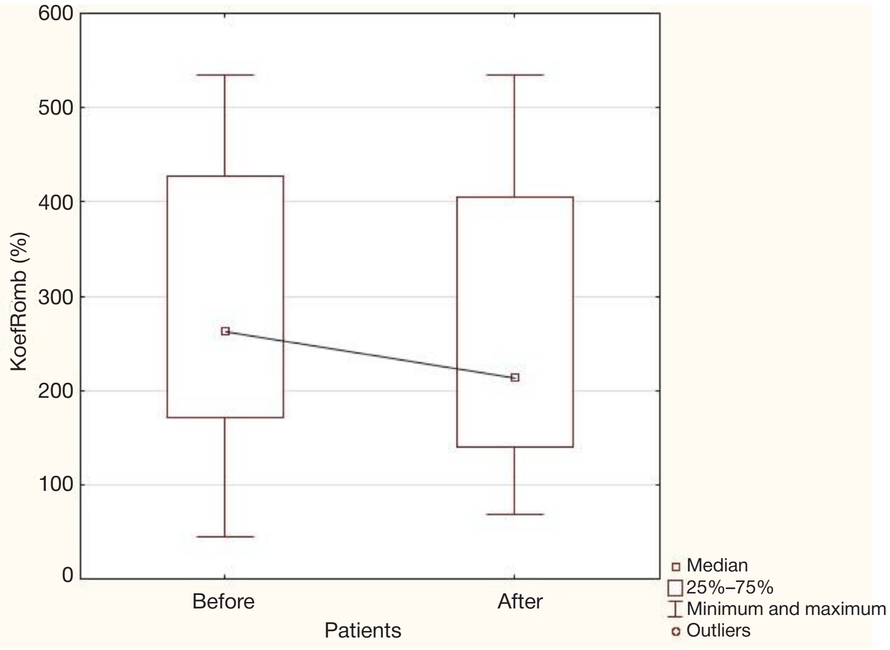

Fig. 1. Romberg ratio before (266 [199.5; 478.5]) and after (221 [149.25; 404]) rehabilitation ($p < 0.05$)

reaction time (SAMR_MO) (Fig. 3) and a reduction in the median value (SAMR_Me).

The reaction to a moving object test conducted after the training course demonstrated a significant ($p < 0.01$) rise in the number (RMO_NS) and percentage (RMO_PS) of successes and a reduction in the number (RMO_ND) and percentage (RMO_PD) of delays (Table 2).

No significant differences were observed between the results of the tests evaluating the complex visuomotor reaction to a combination of colors and the functional activity of nervous processes at baseline and after training.

The correlation analysis showed that the initial number and percentage of delayed RMO were positively correlated with changes the angular velocity asymmetry coefficient ($r = 0.53$; $p < 0.05$) and total angular displacement ($r = 0.57$; $p < 0.05$) measured in the Romberg eyes-closed test. This indicates that patients with initially slower response to a moving object had to adjust their COP position to maintain their balance more frequently and to a greater extent.

Changes in the Berg score were significantly ($p < 0.05$) correlated with the baseline integrated reliability index in the SAMR test (SAMR_IRI), CNS activation level (SAMR_CNSAL), quantitative CNS activation index (SAMR_QCNSAI), number of the classification square (SAMR_CSN), mean SAMR time (SAMR_MO), quickness of response (SAMR_QR), quickness of response in relative units (SAMR_QRR), mean squared deviation of speed (SAMR_MSD), median SAMR time (SAMR_Me), SAMR time mode (SAMR_Mo), and the longest SAMR time (SAMR_MaxT) (Table 3).

These correlations may be explained by the fact that the most pronounced changes on the Berg scale were observed in patients with the worst baseline balance parameters; according

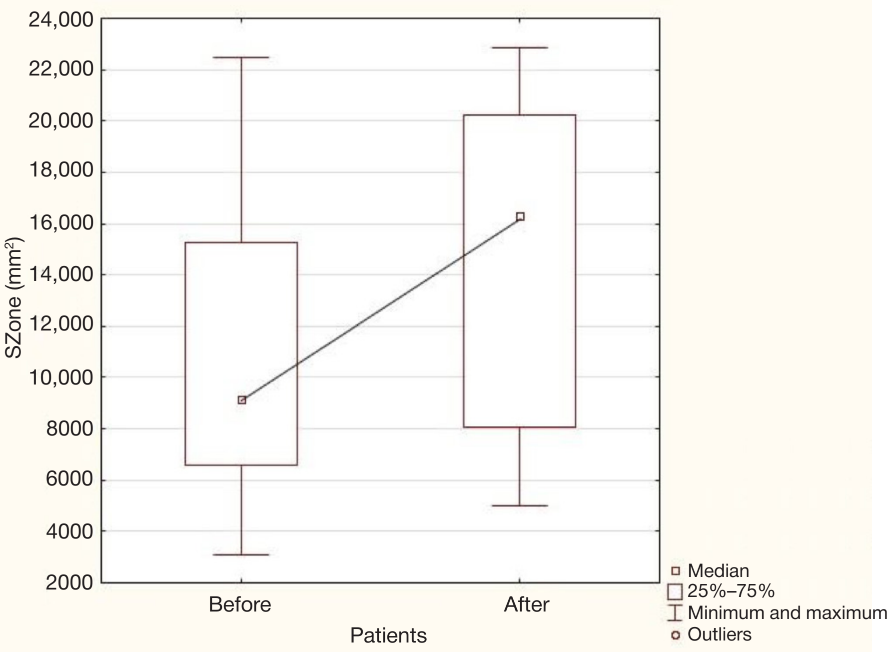

Fig. 2. Total sway zone before (9153 [7251.5; 14,805]) and after (16,289 [9006.5; 19,830]) rehabilitation ($p < 0.05$)

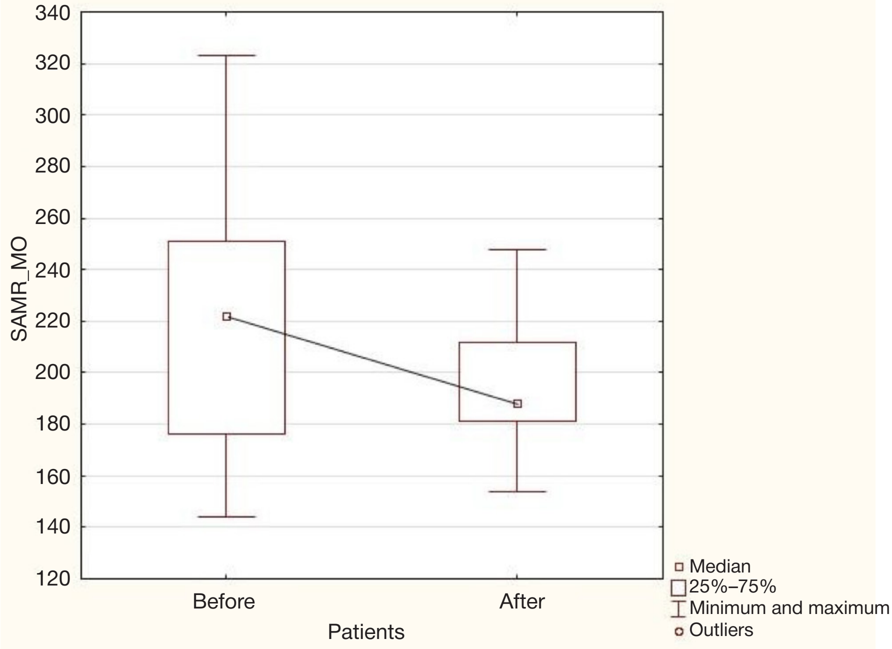

Fig. 3. Mean SAMR time before (210 [174.25; 245.5]) and after (180.5 [170.5; 208]) rehabilitation ($p < 0.05$)

to the SAMR test, the initial functional CNS state was also worse in these patients.

No correlations were established between the changes in the psychophysiological parameters and sway dynamics in the Romberg and stability tests.

The change in the Berg score was significantly ($p < 0.05$) correlated with the SAMR_IRI value ($r = 0.72$; $p < 0.05$), changes in the mean reaction time ($r = –0.73$, $p < 0.05$) and the SAMR median ($r = –0.69$; $p < 0.05$).

DISCUSSION

Based on the dynamics of the Romberg ratio, we conclude that after the rehabilitation course the patients were guided less by their vision and more by their proprioception to maintain balance. This can be explained by the necessity to use biological feedback in the virtual reality environment, which required that the patients compared proprioceptive inputs with the current position of their COP projected on the screen. The 3-D avatar on the screen allowed the patient to use the horizon in the virtual reality environment as a feedback source and to improve proprioception.

The increase in statokinesigram density (LFS_c) indicates a higher density of COP positions within a smaller area, suggesting an improvement in balance function. The correlation between COP positions in the sagittal plane relative to the line connecting the lateral and medial malleoli and COP velocity (VFY) changed from negative to positive, suggesting a change in the balance control strategy. The positive values indicate a reduction in triceps surae muscle tension and a forward COP displacement, which is a sign of a more physiologically sound strategy for balance control.

The increased values of various velocity parameters in the Romberg test may be linked to a reduction in rigidity and adoption of a more robust balance control strategy instead of a compensatory one. Giving up the compensatory strategy is essential for gaining the sufficient degree of freedom for COP movement needed to improve balance. As seen from the results of the stability test, motor control significantly improved after the rehabilitation course; the velocity and magnitude of COP excursions were much greater and easier to achieve after the course [16, 17].

The higher Berg score after the rehabilitation program suggests an improvement in the static, dynamic and functional balance. The patients with the worst balance parameters at baseline made the greatest progress during the course.

Thus, the proposed 10-day rehabilitation program had a positive impact on balance function in patients with small vascular disease, which is consistent with the findings of other studies [18–20] and corroborates the effectiveness of virtual reality as a tool for balance training [21].

The applied psychophysiological tests demonstrated that VR-based rehabilitation led to a reduction in mean SAMR and SVMR times and an increase in the integrated reliability index. The latter estimates the percentage of errors for each response. It is calculated as a mean of the reliability coefficients (RC1) for each response. No rehabilitation-related improvement in response times was registered during complex sensorimotor response tests, but the number of different error types became lower and the functional state of CNS improved. Complex sensorimotor reactions studied in the experiment were represented by recognition and choice behaviors. Not all of the applied tests revealed statistically significant changes after the rehabilitation course: changes were not while testing

Table 2. Results of the RDO test

Parameter	Baseline	After training	*p*
RMO_NS	7,5 [4,75; 9,25]	9 [7,75; 11,25]	0,003
RMO_PS (%)	25 [16; 30,75]	30 [26; 37,75]	0,002
RMO_ND	2 [1; 5]	1 [0; 2]	0,007
RMO_PD	7 [3; 17]	3 [0; 7]	0,005

Table 3. Correlations of SAMR parameters at baseline with score changes on the Berg scale

Parameter	SAMR_IRI (%)	SAMR_CNSAL	SAMR_ QCNSAI (rel.un.)	SAMR_CSN
Changes on the Berg scale	–0,72323	–0,731143	–0,694082	–0,694082
	SAMR_MO (ms)	SAMR_QR	SAMR_QRR (rel.un.)	SAMR_MSD (ms)
Changes on the Berg scale	0,659752	–0,731143	–0,731143	0,529675
	SAMR_Me (ms)	SAMR_Mo (ms)	SAMR_MaxT (ms)	
Changes on the Berg scale	0,662874	0,507568	0,554416	

Note: Significance level $p < 0.05$

the functional activity of nervous processes and the complex visuomotor reaction to a combination of colors. Perhaps, this may be due to the fact that these tests were the most difficult and required involvement of substantial cognitive resources. Overall, improved reaction time after the rehabilitation program is consistent with the literature data [22–24]. However, some researchers report slower reaction times [25] while others do not detect any effect of training on the quickness of motor response [26]. To our knowledge, there has been no analysis of correlations between VR-based rehabilitation and the reliability of testing, erroneous responses and other similar parameters. This is probably due to the choice of the device used for psychophysiological testing.

The patients with the best progress on the Berg scale (i.e., those who had worse results at baseline) also demonstrated a greater improvement in SAMR IRI, mean SAMR speed and median. This suggests that the VR-based rehabilitation program is effective in improving both balance and cognitive functions and demonstrates a predictive value of the SAMR test. The integrated reliability index and the mean SAMR speed allow identification of patients with initially worse parameters who may benefit the most from VR-based rehabilitation.

It is known that balance control depends on the afferent integration of visual, vestibular and proprioceptive inputs. Although the auditory system provides the patient with accurate and precise spatial reference, its auxiliary role in balance control is not acknowledged [27]. Nevertheless, some authors hypothesize that the role of auditory stimuli may increase if one of other involved systems is impaired [28]. The established correlation between changes in audiomotor response speed and the dynamics of balance function after rehabilitation may be linked to the increased role of auditory afferentation associated with changes in the compensatory strategy.

So far, no reliable predictors of motor recovery have been identified; however, the SAMR test may be a potential candidate. Perhaps, the absence of a unified predictor in our study may be linked to the diversity of balance impairment mechanisms in the included patients. Besides cognitive impairment, balance disorders can be caused by sarcopenia, motor deficit, proprioceptive disorders, etc.

Further research should be conducted on a larger patient sample; subgroups should be formed based on the cause of balance impairment. Larger patient samples and the analysis of vestibular function accounting for the physiological characteristics of study participants will allow us to identify different patterns of balance impairment and develop a working tool for determining therapeutic targets in balance training.

CONCLUSIONS

Based on the preliminary results, we conclude that 1) balance impairment in elderly patients may be associated with both CNS activation and inhibition impairments and postural or motor disorders; 2) a combination balance and reaction virtual reality training is an effective rehabilitation method for elderly patients that improves static and dynamic balance control; the training program helps the patient to give up the compensatory strategy and adopt a new, more physiologically robust one (in terms of biomechanics); 3) virtual reality-based balance training improves balance control and CNS activation and stimulates the patient to use additional afferent sources for balance control; 4) patients with initially more pronounced balance disorders make better progress in improving the accuracy and speed of response to visual and auditory cues during the program. Thus, the combination balance and reaction virtual reality training has a potential to become an effective rehabilitation method. However, in order to identify reliable psychophysiological and stabilometric predictors of its effectiveness, further research is needed involving patient grouping by the cause and degree of balance impairment.

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