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Original Article

Concurrent validation of an immersive virtual reality version of the box and block test, the 360° turn test, and the five times sit-to-stand test to assess the functional status of stroke patients

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ABSTRACT

Objectives: This study aims to develop immersive virtual reality (VR) versions of the box and block test (BBT), the 360° turn test, and five times sit-to-stand (5TSTS) test to evaluate functional status within a VR-mediated gamified environment and assess their concurrent validity.

Patients and methods: Thirty participants (18 males, 12 females; mean age: 59.9±11.9 years; range, 25 to 82 years) with a stroke diagnosis were included in the prospective study between February 2024 and August 2024. Each participant completed the BBT, 360° turn test, and 5TSTS test three times using both VR-based and traditional methods. Concurrent validity was examined by analyzing the correlations between VR-mediated and traditional test results. The test-retest reliability of the VR-based assessments was evaluated using intraclass correlation coefficients (ICCs). The usability of the developed software was also assessed using the System Usability Scale.

Results: Strong correlations were found between VR-based and traditional assessment methods for the affected side in the BBT (r=0.562; p<0.001), in the 360° turn test (r=0.838; p<0.001), and 5TSTS (r=0.733; p<0.001). Interrater reliability was high and statistically significant across all tests (ICC >0.80, p<0.001). The usability of the developed software was rated as good (mean System Usability Scale score: 70.8±15.6).

Conclusion: The VR-based versions of the BBT, 360° turn test, and 5TSTS are valid, reliable, and user-friendly tools for assessing functional status in stroke patients. These assessments show promise for integration into clinical settings and remote rehabilitation programs.

Keywords: Balance, gamification, lower limb, stroke, upper limb, virtual reality.

Stroke remains a major global health challenge and is one of the leading causes of mortality and long-term disability. The burden of stroke disproportionately affects low- and lower-middle-income countries, with an estimated global economic impact of $891 billion annually and 12.2 million new cases reported each year.[1,2] Effective rehabilitation is crucial for the recovery of motor, sensory, and cognitive functions lost due to stroke. Neurological rehabilitation programs are a dynamic processes that evolve according to an individual's functional status.[3] Therefore, regular and objective assessment using standardized measurement tools is essential to optimize motor rehabilitation strategies, tailor treatment plans, and ensure effective patient monitoring.

Impairments in upper extremity function, balance, and lower extremity strength are common after stroke and often result in activity limitations, reduced participation in daily life, and decreased quality of life.[4] Accurate assessment of these functions

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is essential to designing personalized rehabilitation plans. Moreover, functional assessments are not only critical for guiding rehabilitation strategies but also for evaluating treatment outcomes and identifying prognostic indicators.[5]

Virtual reality (VR) is defined as “the use of interactive simulations created with computer hardware and software to allow users to enter environments that look and feel like real-world objects and events.”[6] In the medical field, the use of VR-based systems is becoming increasingly common, particularly in the management of neurological, orthopedic, and psychiatric conditions. Virtual reality-based systems offer controlled training environments, task-specific applications, and immersive, realistic simulations. Furthermore, these systems can provide multisensory feedback, including visual, auditory, and tactile feedback, which enhances user engagement and may improve treatment adherence and outcomes.[7]

The concept of telerehabilitation (TR) has gained significant traction in recent years and is defined as the delivery of rehabilitation services through various communication technologies.[8] The COVID-19 (coronavirus disease 2019) pandemic underscored the importance of maintaining treatment continuity of care, particularly for vulnerable populations, such as individuals undergoing neurological rehabilitation.[9] Additionally, with the global population ageing,[10] and the increasing prevalence of neurological disorders,[1] there is a growing demand for cost-effective rehabilitation solutions that reduce the burden on healthcare systems. In this context, the integration of TR and VR technologies may offer a solution.

Although there are increasing examples in the literature of VR-mediated software (such as serious gaming and exer-gaming) developed for neurological rehabilitation,[11,12] examples of remote functional assessment in this patient population are limited. In the field of VR-mediated functional assessment in stroke patients, previous studies have typically focused on a single function or test.[13,14] To our knowledge, this is the first study to simultaneously assess upper extremity, balance, and lower extremity functions in a gamified VR environment. This comprehensive approach allows for a more holistic assessment of stroke patients and represents an important contribution to the field.

In this study, we collaborated with software developers to create a gamified VR-based system for assessing functional status in stroke patients and investigated its concurrent validity. For this purpose, three different poststroke functional assessment tests [the box and block test (BBT), the 360° turn test, and the five times sit-to-stand test (5TSTS)] were presented to stroke patients via VR, and the correlation between VR-mediated and traditional real-world test results was analyzed. In addition, the usability of the developed software was evaluated using the System Usability Scale (SUS).

PATIENTS AND METHODS

This prospective, cross-sectional, single-center concurrent validation study included 30 patients (18 males, 12 females; mean age: 59.9±11.9 years; range, 25 to 82 years) diagnosed with subacute or chronic ischemic and hemorrhagic stroke who were receiving inpatient rehabilitation at the University of Health Sciences, İstanbul Training and Research Hospital, Department of Physical Therapy and Rehabilitation between February 2024 and August 2024. The inclusion criteria were as follows: a history of ischemic or hemorrhagic stroke with radiological confirmation by a specialist neurologist, upper extremity hemiparesis, and the presence of active movement in the upper and lower extremities (Brunnstrom Stage >3). The exclusion criteria were as follows: the presence of known central or peripheral nervous system diseases other than stroke, progressive neurological deficits, uncontrolled systemic diseases (e.g., unregulated blood sugar and blood pressure levels), cognitive impairment that interfered with following simple commands, visual impairment, spatial neglect, epilepsy, or pregnancy. Written informed consent was obtained from all participants. The study protocol was approved by the Ethics Committee of the University of Health Sciences Kanuni Sultan Süleyman Training and Research Hospital (Date: 21.11.2022, No: 2022.11.222). The study was conducted in accordance with the Declaration of Helsinki. This study was registered at clinicaltrials.gov (NCT06244459).

Each participant underwent both VR-mediated and real-world assessments. As detailed below, both assessments were conducted three times under supervision, and all results were recorded. All participants first underwent the traditional assessments, followed by a 20-min rest period, after which the VR-mediated assessments were administered. All assessments were performed by the same clinician in a single session. Intraclass correlation coefficients (ICCs) were calculated separately within the traditional and VR-mediated methods based on three repeated trials to evaluate test-retest reliability.

The software used in this study for VR assessment was VoctoR PhysioCare, developed in collaboration with IoTTech (IoTTech Bilişim Danışmanlık Limited Şirketi, İstanbul, Türkiye; iottech.com.tr) and the research team. The software is available on the Oculus Quest marketplace.

The intervention was delivered using the Oculus Quest 2 (Meta, Menlo Park, CA, USA), an immersive VR headset. The VR-based system was developed using the Unity game engine (Unity Technologies, San Francisco, CA, USA) and programmed in C#. Unity enables the creation of both three-dimensional and two-dimensional simulations with real-time rendering and interactivity. The C# language was chosen for its strong typing, performance, and debugging capabilities and extensive libraries, which supported efficient development and deployment. The system also included a mobile application with functionalities such as screen projection, scene initiation, and termination, allowing the evaluator to view and control the same screen viewed by the participants.

The BBT is a widely used tool for assessing manual dexterity in stroke patients.[15] The traditional version consists of a wooden box measuring 53.7×24.4×8.5 cm, divided into two compartments by a partition. The task requires the participant to move as many 2.5-cm wooden cubes as possible from one compartment to the other within 60 sec, using only one hand and ensuring that the hand crosses the partition. The score corresponds to the number of cubes successfully transferred.[16]

In the VR adaptation, participants interacted with a virtual box half-filled with cubes. They used natural hand movements (without a handheld controller) to grasp and move the cubes, replicating the real-world task (Figure 1). Before the test, participants were instructed about the procedure and given a 30-sec practice trial, during which no data were collected. The test was performed three times with the unaffected side first, followed by three repetitions with the affected side.

The 360° turn test is a practical tool for assessing dynamic balance and has been shown to correlate with lower extremity muscle strength and gait speed in stroke patients.[17] The test measures the time required to shift body weight and complete a full 360° rotation. In the VR version, participants received both animated and written instructions before performing the test. The software automatically recorded the completion time.

The 5TSTS is a standard measure of lower limb muscle strength. In the traditional version, patients are asked to sit down and stand up from a chair five times as quickly as possible, with the total time recorded.[18] In the VR adaptation, the test was modified to minimize the risk of falling. Instead of sitting and standing, participants performed squat-like movements. A squat was counted when the VR headset detected a 25% reduction in the distance between the user and the ground relative to the baseline standing position. Participants were instructed to complete five squats, and the total time was recorded. If they were unable to perform five squats within 60 sec, the number completed within that timeframe was documented.

The usability of the developed software was evaluated using the SUS, a widely used 10-item questionnaire. The SUS is considered a practical and reliable tool for assessing software usability.[19]

Statistical analysis

The sample size was determined based on previous similar validation studies in stroke rehabilitation, taking into account feasibility and resource availability.

Figure 1. Virtual reality-based box and block test.

All statistical analyses were performed using IBM SPSS version 25.0 software (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as mean ± standard deviation (SD), median (min max) values. Frequencies and percentages were used to describe categorical variables. The Shapiro-Wilk test was used to evaluate the normality of the continuous variables. The Spearman correlation test was used to determine the strength of the associations between two different measures. The findings, expressed as correlation coefficients (r) indicating the strength of the relationship, were presented along with the respective p-values. The strength of the correlations was interpreted as weak ($r<0.30$), moderate ($0.30\leq r<0.50$), and strong ($r\geq0.50$), as suggested by Mukaka.[20] The reliability of the measurements was evaluated using the ICC, calculated with a two-way mixed-effects model, single measures, and a consistency definition. The ICC values and their corresponding p-values were used to indicate the consistency and reproducibility of the measurements within each method. An ICC value exceeding 0.75 was considered to indicate good reliability.[21] For the Bland-Altman plot, the average of three measurements was calculated for each method, and the mean difference between the two methods and the standard deviation of the differences were calculated. The mean score was plotted on the x-axis, and the difference between observers, sessions, or systems (mean of the differences) was plotted on the y-axis (mean of the difference ±1.96 SD, standard deviation). To assess the consistency of the measurements, 95% limits of agreement (LoA) were determined. A p-value <0.05 was considered statistically significant.

RESULTS

The mean time since stroke onset was 21.8±23.5 months. The demographic characteristics and clinical assessment results of the patients are summarized in Table 1. Two participants experienced transient dizziness following VR use, which resolved spontaneously within 10 min without the need for any additional intervention.

All participants completed three repeated measurements using both traditional and VR-mediated methods for each of the three tests. Statistically significant correlations were observed between the VR-based and traditional assessments for all three tests on the affected side ($p<0.001$). For the unaffected side of the BBT, while the first measurement did not yield a significant correlation, significant associations were identified in the second and third repetitions. When the mean values of the three repetitions were analyzed, the correlation coefficients revealed strong positive associations between the VR and traditional methods for the

TABLE 1
Clinical and demographic information of the patients

	n	%	Mean±SD	Min-Max
Age (year)			59.9±11.9	25-82
Sex				
Female	12	40		
Male	18	60		
BMI (kg/m^2)			28.1±5.5	20.7-41.1
Dominant hand				
Right	29	96.7		
Left	1	3.3		
Time since stroke onset (month)			21.8±23.5	1-84
Type of stroke				
Ischemic	21	70		
Hemorrhagic	9	30		
Affected side				
Right	17	56.7		
Left	13	43.3		
Fugl-Meyer Assessment-Upper Extremity			60.9±5.1	44-66
Berg balance test			43.7±5.0	42-66

SD: Standard deviation; BMI: Body mass index.

5TSTS (r=0.733, p<0.001) and the 360° turn test (r=0.838, p<0.001) and moderate correlations for the BBT on both the affected side (r=0.562, p<0.001) and the unaffected side (r=0.491, p=0.006). These findings demonstrated that the VR-mediated assessments showed moderate to strong agreement with traditional clinical tests, indicating their potential utility in evaluating functional performance in stroke patients (Table 2).

The reliability of the traditional and VR-mediated assessments was evaluated using the ICC, applying a two-way mixed-effects model, single measures, and a consistency definition. As presented in Table 3, all ICC values were statistically significant (p<0.001) and exceeded 0.75, indicating good to excellent reliability across the tests. Specifically, the ICC for the VR-based 5TSTS test was 0.842 (95% confidence interval 0.701-0.923), while the ICC for the VR-based

TABLE 2
Correlation of clinical and VR-mediated assessments

	Clinical assessments			VR-mediated assessments				
	Mean±SD	Median	Min-Max	Mean±SD	Median	Min-Max	*r*	*p*
Five times sit-to-stand test								
1st measurement	17±10.8	14	8-60	29.7±13.7	25	14-59	0.654	<0.001
2nd measurement	17.1±10.6	14	8-58	24.9±10.4	22.5	11-50	0.638	<0.001
3rd measurement	17.6±11.5	14	8-62	20.2±7.9	19	10-38	0.666	<0.001
Mean of measurements	17.3±10.9	13.5	8-60	24.8±9.5	23.3	13-45.67	0.733	<0.001
360° Turn test								
1st measurement	7.1±4.9	6	2-29	11.2±4.9	11	3-25	0.747	<0.001
2nd measurement	6.8±3.1	6	2-18	9.2±4.4	8	4-25	0.768	<0.001
3rd measurement	6.9±3.3	6	3-18	9.2±4.5	8	4-25	0.722	<0.001
Mean of measurements	6.9±3.7	5.66	2.33-21.67	9.9±4.3	9.5	4-25	0.838	<0.001
Box and block test-affected side								
1st measurement	19.1±10.9	19	0-49	6.6±3.8	7	0-14	0.432	<0.001
2nd measurement	19.7±11.2	19	0-50	10.3±6	8.5	0-25	0.503	<0.001
3rd measurement	20.9±10.2	21	0-48	11.3±6.8	10.5	0-26	0.513	<0.001
Mean of measurements	19.9±10.5	19.66	0-49	9.4±4.9	8.5	0-19	0.562	<0.001
Box and block test-unaffected side								
1st measurement	26.5±11.6	25	4-55	10.3±7.6	9	0-28		0.065
2nd measurement	27.4±11.1	26	4-55	13.7±7.5	13	3-30	0.447	0.013
3rd measurement	27.7±10.8	30	4-50	15.2±7	14.5	3-30	0.508	0.004
Mean of measurements	27.2±11.1	27.5	4-53.3	13±4.8	11.5	2.67-29.3	0.491	0.006

VR: Virtual reality; SD: Standard deviation.

TABLE 3
Comparison of ICCs for clinical and VR-mediated methods

	Clinical assessments			VR-mediated assessments		
	ICC	95% CI	*p*	ICC	95% CI	*p*
Five times sit-to-stand test	0.990	0.981-0.995	<0.001	0.842	0.701-0.923	<0.001
360° Turn test	0.949	0.906-0.974	<0.001	0.937	0.885-0.968	<0.001
Box and block test-affected side	0.978	0.959-0.989	<0.001	0.817	0.665-0.907	<0.001
Box and block test-unaffected side	0.991	0.983-0.995	<0.001	0.911	0.838-0.955	<0.001

ICC: Intraclass correlation coefficient; VR: Virtual reality; CI: Confidence interval.

360° turn test was 0.937 (95% confidence interval 0.885-0.968). In addition to reliability, the usability of the VR-mediated system was assessed using the SUS, which yielded a mean score of 70.8±15.6, suggesting that the system was user-friendly and well-accepted by participants (Appendix).

Bland-Altman plots were generated for each test to evaluate the agreement between traditional and VR-mediated measurements. In total, only one (3.3%) participant had measurements outside the 95% LoA across all three tests. Specifically, the LoA for the 5TSTS test ranged from −3.52 to 23.97, and those for the 360° turn test ranged from −1.70 to 7.55. The BBT results were analyzed separately for the affected and unaffected sides. For the affected side, one (3.3%) patient had results outside the 95% LoA (−6.77 to 27.77), and for the unaffected side, three (10%) patients had results beyond the limits (−7.10 to 35.39; Figure 1).

A post hoc power analysis, based on the observed correlation coefficients (r=0.56-0.83) and a sample size of 30, indicated a statistical power of 100% for all primary outcomes, confirming that the sample size was sufficient to detect moderate to strong associations.

DISCUSSION

In this study, VR-based versions of three commonly used functional tests (BBT, 5TSTS test, and 360° turn test) were developed and validated in stroke patients. The results demonstrated strong correlations between VR-mediated and traditional assessments across all three domains: hand function, lower extremity strength, and dynamic balance. Interrater reliability, assessed via the ICC, was high and statistically significant in both formats. Usability, evaluated through the SUS, indicated good acceptance among participants.

The use of VR technologies in clinical practice has expanded rapidly, particularly in the diagnosis and monitoring of psychiatric disorders such as phobias, anxiety, and posttraumatic stress disorder. While previous research has shown the promise of VR-based systems in patient evaluation, concerns remain regarding standardization, cost-effectiveness, and long-term applicability.[22] In contrast to the growing body of research in psychiatric and cognitive disorders, VR applications for the remote assessment of physical disability are still relatively limited. This study addresses this gap by demonstrating the feasibility of using VR to assess key functional domains in stroke rehabilitation.

Virtual reality-mediated tools have also shown effectiveness in the early diagnosis and monitoring of cognitive disorders such as dementia, Alzheimer's disease, and mild cognitive impairment.[23] In neurological conditions, where both physical and cognitive impairments may coexist, the remote assessment of cognitive status is vital for comprehensive care. However, further research is needed to develop reliable cognitive assessment tools tailored for individuals with physical disabilities.

In the field of physical and rehabilitation medicine, VR-based applications have been shown to be effective for lower extremity, upper extremity, and balance functions in patients with stroke.[24] With gamification, these systems can enhance patient motivation and engagement, adjust the difficulty level to optimize functional gains, and enable personalized treatment plans.[25] In addition, VR-based systems can reduce the length of hospital stays and healthcare costs, reduce the need for healthcare professionals in the treatment and assessment process, and increase the number of patients that can be managed in a given timeframe.[26] Our study reinforces these advantages, demonstrating that VR-assisted tools can capture functional metrics reliably. However, while correlation values with traditional assessments were strong, they did not approach 1.0. Thus, VR-based tests should be considered supplementary tools for screening and monitoring, rather than standalone diagnostic measures.

Previous studies have explored VR applications for functional evaluation in neurological disorders. For example, one study simulated a virtual supermarket to assess activities of daily living in elderly patients,[27] while another reported significant correlation between VR-adapted and traditional BBT scores in both healthy and stroke-affected individuals.[14] Our findings are consistent with these results and extend them by including two additional tests (360° turn test and 5TSTS test), thereby broadening the scope of validated VR-based assessments.

A significant proportion of stroke survivors miss follow-up appointments due to logistical, financial, and health-related.[28] Digital tools such as mobile apps have shown promise in improving medication adherence,[29] and VR systems have been reported to enhance patient engagement during rehabilitation.[12] Remote assessments offer a practical solution for continuous monitoring of rehabilitation outcomes. The integration of wearable sensors, motion-tracking controllers, and interactive software enables clinicians to monitor patient progress in real time.[30] These systems can track parameters such as range of motion, task completion, and success rates, providing indirect yet meaningful indicators of functional status. The incorporation of artificial intelligence may further enhance the customization of therapy plans.[31]

The COVID-19 pandemic accelerated the adoption of TR systems, making remote care more accessible and reducing reliance on healthcare professionals.[32] Functional assessment is a key component of TR, and our findings contribute to the growing evidence base supporting the integration of VR-based tools into such frameworks.

Gamification and serious gaming, facilitated by VR and augmented reality technologies, are increasingly recognized for their role in enhancing both motor and cognitive learning.[33] Despite the availability of disease-specific or function-specific software, there remains a lack of consensus on the features that most effectively support functional recovery. Ideally, rehabilitation software should align with the World Health Organization's International Classification of Functioning, Disability, and Health model to ensure holistic and structured interventions.[30]

There are significant barriers to the widespread adoption of these systems, including high costs, the need for specialized equipment, and challenges related to patient adaptation to the technology.[34] Although this study used VR platforms, different validated functional assessment tools have also been adapted into mobile applications.[35] With declining hardware costs and broader reach, mobile formats offer a promising alternative. Nonetheless, developers should consider the needs of older adults and those less familiar with digital technologies by prioritizing user-friendly and accessible designs.

This study had several limitations. In this study, all reliability assessments of three different functional tests, VR-mediated and traditional, were conducted within the same session. Conducting the assessments consecutively on the same day may have led to variations in participants' learning, fatigue, and motivation, which may have influenced the study results. Future research should investigate test-retest reliability and consistency over a longer timeframe to determine medium- and long-term stability. Although no priori power analysis was conducted, a post hoc power analysis based on the observed correlation coefficients (r=0.56-0.83) and a sample size of 30 indicated a statistical power of 100% for all primary outcomes. These findings confirm that the sample size was sufficient to detect moderate to strong associations, supporting the internal validity of our results. Nevertheless, future studies with larger and more heterogeneous samples are needed to enhance the external validity and ensure the generalizability of these findings across different clinical settings and patient populations. Furthermore, incorporating longitudinal follow-up data in such studies may provide deeper insights into the long-term reliability and responsiveness of VR- or mobile app-mediated functional assessment tools.

In conclusion, the VR-based versions of the BBT, the 5TSTS test, and the 360° turn test are valid and reliable tools for assessing upper extremity, lower extremity, and balance functions following stroke. These tools show strong potential for integration into clinical and remote rehabilitation settings. However, the correlation values, while statistically significant, suggest that VR-based assessments should be interpreted cautiously when used for categorical clinical decision-making.

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APPENDIX

Results of the SUS

No	Question	Mean±SD	Min-Max
1	I think that I would like to use this system frequently.	3.3±1.2	0-4
2	I found the system unnecessarily complex.	2.8±1.6	0-4
3	I thought the system was easy to use.	3.5±1	0-4
4	I think that I would need the support of a technical person to be able to use this system.	1.2±1.3	0-4
5	I found the various functions in this system were well integrated.	3.6±1	0-4
6	I thought there was too much inconsistency in this system.	2.9±1.6	0-4
7	I would imagine that most people would learn to use this system very quickly.	3.5±1	0-4
8	I found the system very awkward to use.	2.5±0.9	0-2
9	I felt very confident using the system.	3.4±1.2	0-4
10	I needed to learn a lot of things before I could get going with this system.	1.6±1.6	0-4
Total		70.8±15.6	30-95

SUS: System Usability Scale; SD: Standard deviation.