A Mixed Reality-Based System for Upper Limb Motor Assessment in Stroke Patients with Reduced Cognitive Load

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Abstract—**Stroke ranks among the most prevalent neurological disorders worldwide, frequently resulting in substantial motor and cognitive deficits following acute cerebrovascular events. Post-stroke cognitive impairment (PSCI) affects 30 % to 60 % of survivors, not only limiting motor capacity but also impeding cortical reorganization through cognitive dysfunctions such as visuospatial deficits.**

Conventional motor assessments assume patients can comprehend and execute complex instructions, an ability often compromised in PSCI, leading to inconsistent or unreliable outcomes. Moreover, standard instruments exhibit pronounced floor effects in severely impaired individuals and ceiling effects in those with milder deficits, thus failing to sensitively capture true motor potential or rehabilitation progress.

Emerging technologies such as mixed reality (MR) environments and wearable sensors offer promising solutions. Wearable devices enable real-time, automated motion capture with high temporal resolution, while MR first-person guidance reduces cognitive load by providing immersive, intuitive visual cues. Evidence indicates that first-person perspectives preferentially engage the mirror neuron network, enhancing action imitation and sensorimotor integration; this shortens imitation latency and improves assessment fidelity. Additionally, iterative observation–execution cycles in MR contexts may further promote experience-dependent neuroplasticity.

This study proposes an automated motor evaluation framework tailored for PSCI patients by integrating the Unity engine with wearable motion sensors within an MR setting. The system employs segmented, first-person demonstrations and delivers real-time feedback to activate mirror neurons, minimize cognitive demands, and facilitate cerebral reorganization. Experimental comparisons with traditional assessments and video-based learning reveal that MR-assisted evaluation substantially improves efficiency, accuracy, and patient satisfaction, effectively mitigating floor effects and unlocking latent motor capacities. These findings advance assessment methodologies for PSCI and provide novel insights into neuroplastic mechanisms underpinning rehabilitation.

Keywords— **Stroke Assessment, Mixed Reality, Cognitive Load, Motor Rehabilitation**

I. INTRODUCTION

Stroke, a cerebrovascular disease caused by the rupture or blockage of cerebral blood vessels, is characterized by high incidence, recurrence, mortality, disability rates, and economic burden [1], leading to irreversible damage to the central nervous system. Influenced by population aging, China faces the highest stroke burden and lifetime risk globally (39.3%) [2]. In 2019, stroke became the leading cause of disability-adjusted life years (DALYs) in China [3], and in 2021, it was a major cause of premature death [4].

Stroke frequently induces upper limb motor impairment due to lesions in the central nervous system affecting sensory and motor cortices, resulting in damage to descending pathways and a decreased firing rate of motor units. This manifests as slowness of movement, muscle weakness, and joint coordination deficits [5, 6, 7]. World Health Organization data indicate that 66% of new stroke patients experience upper limb motor impairment [5]. Concurrently, post-stroke cognitive impairment (PSCI) affects 30% to 60% of patients [China Stroke Prevention and Treatment Report (2023)], caused by cerebral artery stenosis or occlusion leading to reduced cerebral blood flow, resulting in memory decline, attention deficits, and other cognitive issues [8].

Regular assessment is essential for tracking rehabilitation progress and promoting functional recovery by stimulating neuroplasticity [9]. Clinically, motor impairment assessment relies on scale-based methods, often structured according to the WHO's International Classification of Functioning, Disability and Health (ICF) framework, encompassing impairments in body function/structure, activity limitations, and participation restrictions. Assessment of body function/structure commonly employs the Brunnstrom stages (evaluating hemiplegic recovery in six stages [10]) and the Fugl-Meyer Assessment (FMA) (total score 100, with 66 points for the upper limb, assessing grasp, strength, etc. [11]). Activity limitations are assessed using the Box and Block Test (BBT) (evaluating grasping speed [12]) and the Action Research Arm Test (ARAT) (evaluating arm function [13]). Participation restrictions are often evaluated using the

Barthel Index (assessing independence in daily living activities [14]).However, traditional scales exhibit poor applicability for PSCI patients. The FMA, for instance, lacks a cognitive dimension [15], is time-consuming (30-45 minutes), can induce fatigue, and suffers from floor effects in severely impaired individuals [16]. Furthermore, its sensitivity for moderate impairments is only around 62% [17]. While studies on virtual reality (VR) and MR show VR can promote limb recovery [18], its effectiveness in improving cognitive function remains debated [19]. Wearable devices have been primarily applied to gait rehabilitation [20] and often do not sufficiently address the cognitive needs of PSCI patients.This research, grounded in the principles of mirror neurons and neuroplasticity, utilizes motor imagery therapy concepts to improve function. Mirror neurons facilitate brain remodeling through observation-execution activation [21], and techniques like hand-mirror training and video observation tasks have proven effective [22]. MR has also been shown to enhance neuroplasticity [23]. The MR-based upper limb assessment system developed in this study aims to reduce cognitive load through virtual hand demonstrations and positive feedback, thereby overcoming floor effects. Preliminary experiments suggest that MR enhances assessment accuracy and engagement, making it particularly suitable for PSCI patients. Future work requires larger sample sizes and optimized device integration.

II. Materials and methods

This study focuses on developing a mixed reality (MR)-based instructional system designed to acquire multimodal data from patients with post-stroke cognitive impairment (PSCI) experiencing upper limb dysfunction. Utilizing Pico 4 Ultra glasses equipped with a depth camera, a data glove, and an electromyography (sEMG) armband, the system aims to achieve precise rehabilitation assessment and interactive guidance. The system employs the Unity engine to map virtual scenes onto the real environment, supporting action demonstration, data analysis, and rehabilitation progress tracking. The research emphasizes efficient assessment and interaction through the integration of the depth camera and sensors, rather than focusing on the hardware development of the data glove and sEMG armband.The hardware comprises commercially available data gloves and sEMG armbands integrated with inertial measurement units (IMUs), bend sensors, and surface EMG sensors to capture hand movements and muscle activity. The data glove acquires acceleration (±16g), angular velocity (±2000dps), magnetic field direction, and finger flexion using 6 IMUs and 5 bend sensors. The sEMG armband detects ±1.5mV myoelectric signals (amplified 1000 times) via 3 dry-electrode sEMG sensors, ensuring data precision. The depth camera scans the real environment, capturing 3D information of objects (e.g., tables, chairs, tennis balls) and hand movements to generate kinematic data (3D coordinates, velocity, acceleration, etc.), stored on a PC at a 100 Hz frequency for subsequent analysis.

The software architecture utilizes the Unity engine to construct the virtual scene. Patients interact with the real environment through the Pico 4 Ultra glasses, with the depth camera assisting in environmental and hand calibration to ensure accurate alignment between virtual objects and the real scene. The system includes four modules: Tutorial, Calibration, Assessment, and Report. The Tutorial module uses videos and interactive guidance to familiarize patients with tasks, reducing cognitive load. The Calibration module employs the depth camera to scan real objects (e.g., cotton swabs, tennis balls) and hand movements for accurate motion capture. The Assessment module features standardized actions based on the Fugl-Meyer Assessment (FMA) [25], utilizing first-person demonstrations and exaggerated movements to enhance engagement. Acquired kinematic and EMG data are analyzed by the StroReh-Net model (based on LSTM-CNN and DTW algorithms), which demonstrated excellent performance in validation on public datasets. The Report module generates visualized treatment curves and charts to aid in optimizing rehabilitation plans. The virtual scene incorporates everyday objects to reduce costs and enhance immersion.

The experimental design involves assessing kinematic and kinetic data from healthy subjects and PSCI patients performing the Box and Block Test (BBT) and FMA tasks within the MR environment to validate the rehabilitation effect of the instructional system. The study received approval from the Biomedical Ethics Committee of Beihang University (BM20180017) and was registered in the Chinese Clinical Trial Registry (ChiCTR2100042355). The FMA-Upper Extremity (FMA-UE), based on the Twitchell and Brunnstrom scales, comprises 113 items (total score 226), assessing upper limb movement, sensation, joint range of motion, and pain, with each item scored from 0 to 2 [26]. The BBT assesses upper limb dexterity by the number of blocks transferred within 60 seconds [26]. The Action Research Arm Test (ARAT) and Brunnstrom Stage (BS) evaluate finger pinch grip and gross motor movements, complementing the WHO-ICF framework to overcome the limitations of single scales. Subjective satisfaction and user experience were measured using the Subjective Experience Scale (SES), encompassing 7 dimensions like perceived difference and comprehensibility, scored from 1 to 7, to supplement objective data.

The experimental setup integrates the Pico 4 Ultra MR headset, data glove, and sEMG armband to create a comprehensive BBT and FMA assessment system. The BBT module uses the depth camera to capture interactions with a virtual cube container and dynamic blocks, simulating real interaction with a grip force threshold of 0.2N. The FMA module includes 21 standardized actions (e.g., flexor synergy, fingertip touching). The depth camera and sensors analyze movement trajectories, angles, and stability in real-time, while the system provides auditory and visual feedback. Python scripts process kinematic data to generate quantitative reports, including dimensions such as tremor severity and coordination.

Participants were recruited from Beihang University and tertiary hospitals in Beijing, totaling 95 healthy subjects and stroke patients. Healthy subjects were required to be ≥18 years old, have visual acuity ≥4.8 (likely referring to a Snellen equivalent like 20/25 or 0.8 decimal), MMSE score ≥24, and be free from conditions affecting upper limb function. Stroke patients needed a confirmed diagnosis ≥3 months prior, be right-handed, and have no history of visual impairment or epilepsy. All participants provided signed informed consent and received compensation.

The experimental procedure employed a two-stage crossover design. Healthy subjects completed the BBT, FMA-UE, and SES questionnaire, with a retest after 4 weeks to verify stability. Stroke patients sequentially completed the MMSE, BS, FMA-UE, and BBT, focusing on assessing motor control and functional task performance. Testing was paused immediately if fatigue occurred, ensuring ethical compliance.

Figure 1 comprehensively illustrates the neural mechanisms and system design of mixed reality technology in stroke rehabilitation assessment: A shows the real-world scenario where a user wearing the headset begins the rehabilitation assessment, interacting with real objects on a desk. B displays the mixed reality scene from the user's perspective, where the user sees themselves and the surrounding environment, along with a virtual hand demonstrating actions segmentally. Target objects (yellow blocks) are highlighted, a progress bar indicates completion status, and audio cues are provided. Visual and auditory feedback enhances immersion and engagement, promoting motor learning through audio-visual integration. C depicts the visual feedback loop: visual information travels from the retina via the thalamus to the primary visual cortex (V1), is processed by higher visual areas for color, shape, and motion, and finally reaches the posterior parietal cortex (PPC) where it is transformed into action-related signals. This subsequently activates mirror neurons in the premotor cortex, causing them to fire during action observation, thus integrating action perception and execution. D illustrates the tactile feedback loop: the MR-based assessment provides realistic force feedback through direct contact, stimulating peripheral nerves. Somatosensory information travels from the dorsal root ganglia to the ventral posterolateral nucleus (VPL) of the thalamus, and then to the primary somatosensory cortex (S1). S1 projects to the motor cortex in the frontal lobe, ultimately establishing synaptic connections in the premotor cortex, enhancing rehabilitation outcomes. E demonstrates that completing a single movement relies on the coordinated interaction of various parts of the nervous system. Cortical areas in the frontal, parietal, temporal, and occipital lobes, along with the basal ganglia, cerebellum, and pontine nuclei, provide input to descending pathways like the reticulospinal and vestibulospinal tracts projecting to spinal motor neurons. Afferent inputs from the visual, vestibular, and somatosensory systems are integrated in the brainstem and cortex to update the body schema and inform future postural commands. It also shows the hierarchical and parallel processing of motor commands, with the cerebellum fine-tuning movements and the basal ganglia modulating motor planning, as indicated by the different pathways shown.

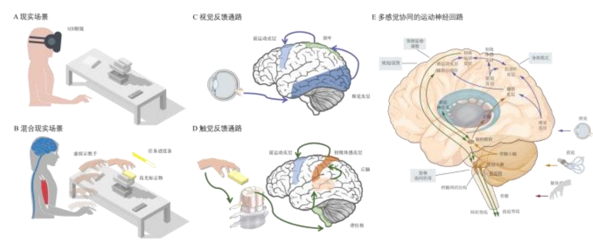

Fig. 1 A: Real-world scenario of a user wearing the headset starting the rehabilitation assessment. B: Mixed reality scene from the user's perspective. C: Visual mirror neuron pathway. D: Tactile feedback neural pathway. E: Schematic of parallel processing circuits for motor commands.

III. Results

This study employed various statistical methods to evaluate the effectiveness, stability, and clinical applicability of the MR-based automated assessment system. Data from the initial test and retest of 95 healthy subjects and 16 patients with PSCI were analyzed to assess system reliability, validity, and specificity for upper limb functional deficits.

Firstly, system reliability was assessed using the Intraclass Correlation Coefficient (ICC) and Standard Error of Measurement (SEM). A two-way mixed-effects model was used to calculate single-measurement ICC values, quantifying test-retest consistency. The results indicated high precision of the system in tracking rehabilitation changes. A bar chart was generated to visualize consistency (Fig. 2).

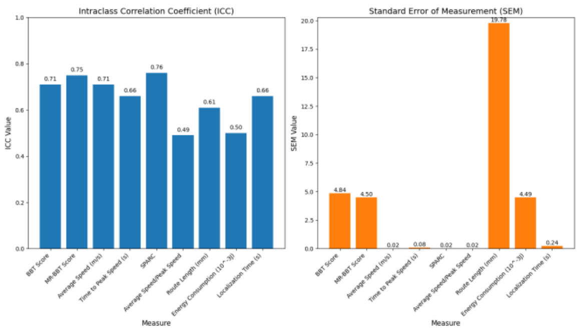

Fig. 2 ICC and SEM

Based on data from 95 healthy subjects (aged 18-87), the reliability and normal range of motion parameters for the MR-BBT system were analyzed. Reliability analysis of MR-BBT parameters showed good reliability for the real-world BBT score, and excellent reliability for the MR-BBT score and SPARC (Spectral Arc Length). Parameters including average velocity, time to peak velocity, average velocity/peak velocity ratio, movement path length, energy consumption, and positioning time demonstrated good reliability (Table 1: Reliability of MR-BBT Parameters).

Table 1 Reliability of MR-BBT Parameters

	Initial Test (mean ± SD)	**Retest (mean ± SD)**	**Difference (Initial - Retest, mean ± SD)**	**ICC (95% CI)**	**SEM**
BBT Score	72.20 ± 9.37	74.23 ± 8.50	-2.03 ± 6.59	0.71 (0.59–0.80)	4.84
MR-BBT Score	30.49 ± 7.92	34.45 ± 9.59	-3.65 ± 6.25	0.75 (0.38–0.88)	4.50
Mean Velocity (m/s)	0.18 ± 0.04	0.19 ± 0.05	-0.37 ± 0.08	0.71 (0.56–0.81)	0.02
Time to Peak Velocity (s)	0.47 ± 0.15	0.42 ± 0.13	0.04 ± 0.11	0.66 (0.50–0.77)	0.08
SPARC	-0.12 ± 0.05	-0.11 ± 0.05	-0.01 ± 0.03	0.76 (0.63–0.84)	0.02
Mean/Peak Velocity Ratio	0.26 ± 0.02	0.26 ± 0.02	-0.003 ± 0.02	0.49 (0.32–0.63)	0.02
Transfer Path Length (mm)	250.49 ± 33.84	237.65 ± 28.10	12.84 ± 25.65	0.61 (0.39–0.75)	19.78
Energy Expenditure ($\times 10^{-3}$ J)	16.93 ± 6.88	14.89 ± 5.63	2.02 ± 6.16	0.50 (0.32–0.64)	4.49
Targeting Time (s)	1.35 ± 0.43	1.21 ± 0.37	0.15 ± 0.31	0.66 (0.46–0.78)	0.24

Pearson correlation coefficient analysis indicated a high correlation between test and retest data for the real-world BBT score and all MR-BBT parameters (Fig. 3: Test-Retest Correlation Plot).

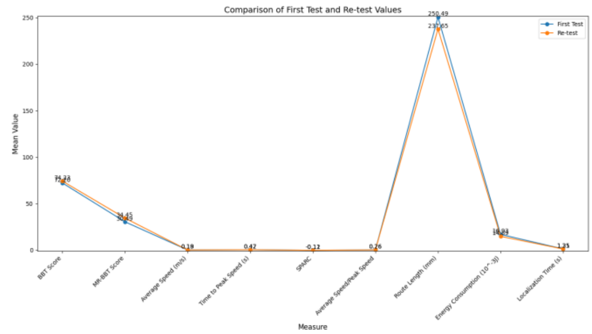

Fig. 3 Comparison of First Test and Re-test Values

Bland-Altman plots showed acceptable limits of agreement, e.g., (10.88, -14.95) for the real-world BBT score and (6.15, -14.06) for the MR-BBT score, with similar results for other parameters (refer to supplementary figures). Performance on the retest was generally better than the initial test, possibly due to learning effects, suggesting the MR-BBT system provides stable, reliable parameters, potentially superior to the traditional BBT.

To validate system validity and specificity, 16 stroke patients were recruited and compared with 16 age- and gender-matched healthy subjects. Inter-group comparison revealed significant differences between healthy subjects and stroke patients in BBT scores, MR-VBBT scores, and various parameters (average velocity, SPARC, etc.).

Receiver Operating Characteristic (ROC) analysis indicated high discriminative ability for most parameters, with high Area Under the Curve (AUC) values.

Table 2 Correlation with Clinical Scales

Variable	**BBT**		**ARAT**		**FMA-UE**	
	R^2	p value	R^2	p value	R^2	p value
Mean velocity	0.591	<0.001	0.247	0.050	0.354	0.015
Time to peak velocity	0.368	0.008	0.351	0.016	0.437	0.005
SPARC	0.393	0.006	0.444	0.005	0.503	0.002
Mean/peak velocity ratio	0.246	0.029	0.134	0.164	0.171	0.112
Transfer path length	0.179	0.102	0.420	0.007	0.067	0.333
Energy expenditure	0.061	0.357	0.353	0.015	0.063	0.347
Targeting time	0.512	0.002	0.493	0.002	0.505	0.002

Spearman rank correlation analysis showed strong or moderate correlations between MR-VBBT score, SPARC, positioning time, and traditional clinical scales (BBT, ARAT, FMA-UE).

Table 3 Results of multiple regression analysis

Dependent Variable	Independent Variable	Standardized β	Adjusted R^2	F	Model p-value
BBT Score	Mean velocity	0.763	0.725	20.778	<0.001
	Transfer path length	-0.413			
ARAT Score	Targeting time	-0.633	0.708	19.176	<0.001
	Energy expenditure	-0.508			
FMA-UE Score	Targeting time	-0.711	0.469	14.275	0.002

Correlation analysis with FMA-UE scores revealed moderate correlations for MR-VBBT score (r=0.607, p=0.013), average velocity (r=0.604, p=0.013), SPARC (r=0.560, p=0.024), and positioning time (r=-0.641, p=0.007). Multiple regression analysis indicated that positioning time explained 46.9% of the variance in FMA-UE scores.

Overlaying the MR-VBBT parameters of the 16 stroke patients onto the normal range derived from healthy subjects showed that 93.75% of patients' BBT scores, 68.75% of MR-VBBT scores, 87.5% of SPARC values, and 100% of positioning times deviated from the normal range.

Analysis of individual patients (P4, P13, P16) demonstrated the system's ability to specifically reflect impairments in upper limb dexterity, speed, and smoothness, supporting precision rehabilitation.

IV. Discussion

This study developed an automated assessment system based on mixed reality (MR) for evaluating upper limb function in patients with post-stroke cognitive impairment (PSCI). By integrating the Unity engine with wearable devices, the system utilizes first-person perspectives and segmented demonstrations to activate mirror neurons, reduce cognitive load, and provide real-time feedback to promote brain functional remodeling. Compared to traditional methods, this system offers automated operation, scientifically designed movements, comprehensive data collection, and suitability for cognitively limited patients.

Reliability analysis demonstrated the MR-BBT system's high precision in tracking rehabilitation changes. ICC and SEM values indicated excellent reliability for MR-BBT scores and SPARC, good reliability for real-world BBT scores, and excellent reliability for other parameters. High test-retest correlations and favorable Bland-Altman plots confirmed consistency. Improved performance on retest, likely due to learning effects, highlights the system's sensitivity to adaptive changes. Validity analysis revealed significant differences in MR-BBT parameters between 16 PSCI patients and healthy controls. High ROC AUC values indicated strong discriminative power. Spearman correlations showed moderate to strong associations between MR-BBT metrics (score, SPARC, positioning time) and traditional scales, with positioning time explaining 46.9% of FMA-UE score variance. Specificity analysis, showing 93.75% of patient BBT scores and 100% of positioning times deviating from the normal range, confirmed the system's ability to accurately identify specific upper limb functional deficits, supporting personalized rehabilitation.

Compared to traditional methods often limited by subjectivity and inefficiency, and existing immersive technologies that may lack cognitive considerations or require assistance, our system offers automation, ecologically valid scenarios, rich quantitative metrics, and intuitive heatmap visualizations of consistency.

Clinically, the system reduces cognitive load, provides quantitative motor metrics, integrates training elements, overcomes floor effects, and supports potential home monitoring, offering efficient support for PSCI rehabilitation. The MR system utilizes haptic feedback to simulate physical properties like weight and texture, enabling patients to experience near-realistic action execution in the virtual environment. This feedback enhances immersion and helps build confidence in rehabilitation tasks. For instance, feeling resistance when grasping virtual objects simulates daily activities and aids upper limb recovery. The presence of force feedback allows patients to perceive the reality of virtual objects within the MR environment, reducing uncertainty and fear associated with virtual scenarios. Consistent and predictable tactile feedback during interaction makes participation more natural, boosting confidence. This increased sense of security is particularly crucial for cognitively impaired patients, effectively lowering psychological barriers. Compared to traditional VR, MR reduces aversion to virtual environments through realistic physical feedback, facilitating faster adaptation similar to real-world interactions. This familiarity enhances acceptance, thereby increasing engagement and adherence, especially for long-term rehabilitation. The force feedback feature enhances the clinical utility of MR. Therapists can design life-like training scenarios (e.g., grasping a cup, moving objects), aiding the transfer of training gains to daily life. Furthermore, system automation combined with quantitative data (e.g., task completion time, accuracy) provides objective evidence for clinical assessment. Force feedback also increases training realism, helping maintain patient motivation and supporting long-term rehabilitation.

Limitations include a small sample size, homogenous patient group, insufficient control over cognitive variables, and limited age distribution. Future work should involve larger, more diverse samples (including various pathologies), refined cognitive assessments, optimized task design, integration of AI for analysis, and development of a home-based version.

V. Conclusion

This study developed an automated upper limb functional assessment system based on mixed reality (MR), specifically designed for patients with post-stroke cognitive impairment (PSCI), which reduces cognitive load during assessment by integrating wearable devices with the Unity engine. Utilizing a first-person perspective and segmented demonstrations, the system activates the mirror neuron network and provides real-time feedback to promote brain functional remodeling, offering a more scientific and automated approach suitable for cognitively limited patients compared to traditional methods.

Validation results from tests on 95 healthy subjects and 16 PSCI patients demonstrated high reliability and validity. ICC and SEM analyses confirmed its precision in tracking rehabilitation changes, with excellent ICC values for MR-BBT and SPARC. Validity analyses showed the system effectively discriminates between healthy individuals and patients, with high ROC AUC values. Positioning time explained 46.9% of FMA-UE score variance, confirming assessment accuracy.

Clinically, the system enhances patient acceptance through features like force feedback, supports personalized rehabilitation, overcomes floor effects, and is suitable for home monitoring. However, limitations such as small sample size and patient homogeneity exist. Future research should expand the sample size, optimize assessment protocols, and explore potential applications in pediatric populations to promote its widespread use in rehabilitation medicine.

Acknowledgment

This research was supported by the Beijing Natural Science Foundation (QY24143).

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