Effectiveness of Immersive Virtual Reality-Based Hand Rehabilitation Games for Improving Hand Motor Functions in Subacute Stroke Patients

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***Abstract*—Stroke rehabilitation faces challenges in attaining enduring improvements in hand motor function and is frequently constrained by interventional limitations. This research aims to present an innovative approach to the integration of cognitive engagement within visual feedback incorporated into fully immersive virtual reality (VR) based games to achieve enduring improvements. These innovative aspects of interaction provide more functional advantages beyond motivation to efficiently execute repeatedly hand motor tasks. The effectiveness of virtual reality games incorporated with innovative aspects has been investigated for improvements in hand motor functions. A randomized controlled trial was conducted, a total of (n=56) subacute stroke patients were assessed for eligibility and (n=52) patients fulfilled the inclusion criteria. (n=26) patients were assigned to the experimental group and (n=26) patients were assigned to the control group. VR intervention involves four VR based games, developed based on hand movements including flexion/extension, close/open, supination/pronation and pinch. All patients got therapy of 24 sessions, lasting 4 days/week for a total of 6 weeks. Five clinical outcome measures were Fugl- Meyer Assessment-Upper Extremity, Action Research Arm Test, Box and Block Test, Modified Barthel Index, and Stroke-Specific Quality of Life were assessed to evaluate patients' performance. Results revealed that after therapy there was significant improvement between the groups ($p<0.05$) and within groups ($p<0.05$) in all assessment weeks in all clinical outcome measures however, improvement was observed significantly greater in the experimental group due to fully immersive VR-based games. Results indicated that cognitive engagement within visual feedback incorporated in VR-based hand games effectively improved hand motor functions.**

***Index Terms*—Stroke rehabilitation, virtual reality, cognitive, visual feedback, clinical outcome measures.**

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Holy Family Hospital Rawalpindi in the Physiotherapy Department and the Research Ethical Committee under Application No. BMES/REC/22/027, and performed in line with the Declaration of Helsinki.

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I. Introduction

STROKE is a neurological disorder that mainly reduces the quality of life of patients which unable to perform their daily living activities. By 2030, it was anticipated that the prevalence of stroke would have increased to 21.9% globally [1], [2]. The most prevalent disability that makes it difficult for stroke survivors to conduct daily living activities is Upper Extremity (UE) [3], [4]. Many stroke patients are left with functional impairments and incapable of moving their hands due to inadequate rehabilitation. Therefore, patients struggle with functional tasks that reduce their everyday life and social interaction. Regaining the motor function of the hand impact greatly on daily living activities. Hand impairments induced by stroke are frequently associated with challenges in motor rehabilitation requiring creative therapy for effective recovery [5], [6].

Neuroplasticity studies [7], [8], [9], [10] revealed that the brain tends to reorganize when the activities are repetitious and subjected to task-oriented which improves the impaired motion abilities. The existing concepts used in neurorehabilitation after stroke to assist motor relearning and subsequently function enhancement are repetitive, intense, and task-specific functional training [8], [11]. Demotivation to therapy due to exercise repetitions is generally happens in conventional therapy due to which patients are less attentive to perform limited repetitions [12]. Additionally, conventional practices do not offer enough learning challenges to foster the plasticity necessary for motor rehabilitation [13].

Conventional exercises could not be sufficient to benefit stroke patients' concentration because of extended therapy sessions. The task-specific aspect that must be organized for relearning motions is highlighted in Carr and Shepherd's study on motor relearning [14]. This approach encourages stroke patients to take part in their care more effectively by increasing their training and task adaptability [15], [16], [17].

Intervention techniques have been explored because conventional techniques take more therapy time along with resource intensive [18]. A relatively emerging intervention for stroke recovery is virtual reality gaming [19]. This encourages stroke survivors to use their affected limbs to the best of their abilities in an interactive setting. Virtual reality is a way to improve and assist in practicing motor skills in virtual settings that are like situations of real life [20], [21]. Treatment of the upper extremity after a stroke may be particularly effective when VR is combined with conventional therapy, according to the review of [20]. Gamification in VR during rehabilitation may encourage patients to practice for a longer duration to getbetter outcomes [22]. Fan et al. [23], found that VR gaming significantly enhanced motor recovery and promoted stroke patients' treatment plans. VR based games gaining popularity but still need to be explored for effective stroke rehabilitation. VR devices like IREX, X-box Kinetic, and Nintendo Wii patients used to play virtual reality games on screen and view the real environment out of the screen [10], [19], [24]. Many VR systems carry out exercises, but they commonly use computer games that are commercially available and not intended for rehabilitation purposes.

A study conducted by Hernández-Rodríguez et al. [25] on subacute stroke patients using HandTutor© glove system. Results showed improvement in hand recovery function. However, the system was semi-immersive and lack to engage the patient. In another intervention study, Yao et al. [26] investigated the virtual reality combined with transcranial direct current stimulation (c-tDCS) and the results presented significant improvement when VR combined with c-tDCS compared to VR alone showed efficacy in reducing motor impairment.

Most VR games use handheld VR controllers where patients are unable to experience substantial exercise based on VR game which decline their motivation to therapy. In recent years, studies have been conducted on the efficacy of VR based game rehabilitation depicted in [27]. However, most of the studies were conducted on non-immersive and semi-immersive VR technology [28], [29]. Askin et al. [30] assessed how semi-immersive VR training with the Kinect impacts patients' functional results and upper extremity motor recovery. According to the results, Kinect-based VR training enhances motor function and active range of motion in chronic stroke patients.

Fully immersive VR-based games are more effective in stroke rehabilitation when combined with visual training feedback. Neural pathways related to motor functions are activated increasingly with VR games created with repetitive and task-specific [9], [31], [32]. However, these studies were only limited to visual and auditory feedback in their intervention and therefore could not be able to achieve enduring improvements. According to Choi et al. [33] when stroke patients used commercial VR based gaming intervention, they were able to regain mobility and do their daily routine tasks.

Virtual reality can build interactive settings with sensory feedback inputs [34] but it is not apparent what additional engagement should be offered to enhance motor learning tasks for enduring improvements in hand motor functions. However, there is an opportunity in VR research [34] that has not been taken advantage of that VR intervention games could be enhanced further by incorporating cognitive engagement within visual feedback elements. This combination has the potential to sustain neuroplastic changes and facilitates achieving better enduring improvements. It is necessary to conduct studies to determine whether VR games incorporated with innovative approaches of cognitive engagement within visual feedback are viable treatment options in stroke rehabilitation.

In this study, we develop and investigate the effectiveness of VR games incorporated with an innovative approach of cognitive engagement within visual feedback for enduring improvements in hand motor functions. These VR games comprise four activities designed for subacute stroke patients, including hitting rolling balls, grasping balloons, swapping hand positions, and gripping pencils. These varied ranges of activities targeted distinct hand movements encompassing flexion and extension, close and open, supination and pronation, and pinching respectively for promoting recovery of hand motor functions. Clinical outcome measures are evaluated at baseline, 4th week, 6th week, and 9th week (follow-up).

This research marks a valuable contribution to the innovative approach of integration of cognitive engagement within visual feedback in VR games to enhance motor learning tasks for enduring improvements in hand motor functions. Secondly, the sensory-cognitive engagement paradigm in VR games delivers more functional advantages beyond the subject's motivation to commence further repetitions of motor tasks.

II. Methodology

A. Virtual Reality Settings

The virtual reality settings in this study are illustrated in Fig.1. Therapeutic games for hand rehabilitation were developed with the Unity3D game engine. The Android Package Kit (APK) file was used to run the games on a standalone device Oculus Quest 2 Virtual Reality device. This device also uses hand-tracking technology allowing to use of the subject hands within the virtual environment which instantly responds to the patient's hand movements in real time.

B. VR Game Design Mechanics

VR based games were developed for centric hand rehabilitation for patients with subacute stroke. The four VR games as shown in Fig.2 are developed based on hand movements including flexion / extension, open / close, supination / pronation, and pinch. The VR games have three minutes of easy level and five minutes of difficult level. Fig.2 presents the developed VR hand games that are played with affected hand within the virtual reality.

C. Visual Training Feedback and Cognitive Engagement

The games were created with visually appealing and immersive VR settings with virtual table, balls, balloons, and pencils

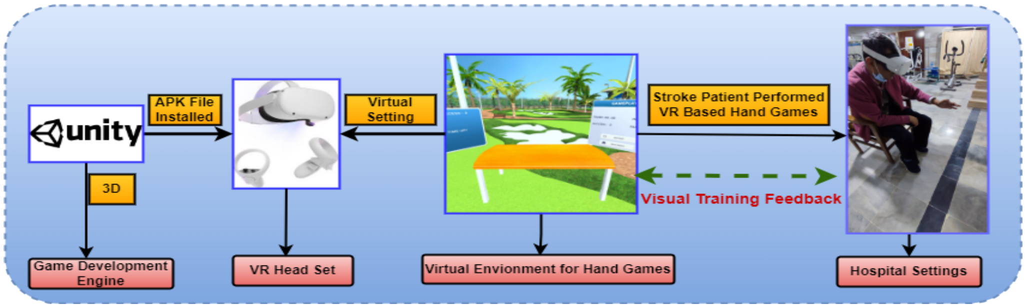

Fig. 1. Virtual reality settings for stroke rehabilitation. Games were developed in the Unity3d game engine and stroke patient employed Oculus Quest 2 VR headset to play VR based hand rehabilitation games.

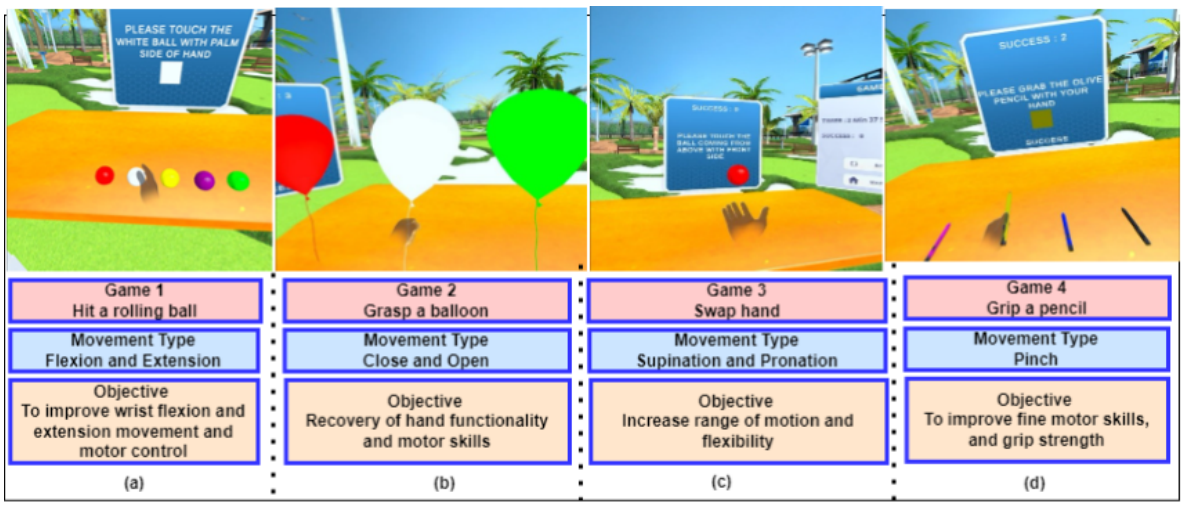

Fig. 2. Design mechanics of VR based hand rehabilitation games. (a) Hit a Rolling Ball, (b) Grasp a Balloon, (c) Swap Hand, (d) Grip a Pencil. Patients with affected hand were used to play these rehabilitation games within the virtual environment.

as presented in Fig.2. Stroke patients were used to getting feedback through visual training and cognitive engagement. The cognitive engagement paradigm within visual feedback experienced by patients includes attention, such as focusing on visual cues for the selection of object color, and decision-making, such as picking the right color object after the random appearance of the same objects of different colors on the table. The cognitive engagement within visual training feedback in VR-based hand games advances an optimistic learning involvement. This encourages patients to perform activities repeatedly and strengthen successful movements.

Involving visual training in VR games contains activities that enhance spatial perception. These activities help patients to control virtual objects in a three-dimensional environment to comprehend the orientation, position, and movement of objects in a virtual environment to patients themselves. Moreover, gameplay revealed whether the shown color cue was correctly being played for a specific task and was displayed as success or failure. Furthermore, a virtual scoreboard displayed the time and total, success, and failure to motivate the patient and monitor their development. Using a virtual reality headset with hand tracking, patients were able to view their own damaged hand and get closer to the target to complete the essential movements. Table I illustrates the role of VR visual feedback in each game.

TABLE I
ROLE OF VR VISUAL FEEDBACK IN EACH GAME

Games	Role of VR visual feedback in each game
Game 1: Hit a Rolling Ball	- As patients hit rolling balls with their affected hand, patients see how their affected hand movements influence virtual balls. - Stroke Patients improve their hand-eye coordination and movement precision by making quick transitions using visual feedback.
Game 2: Grasp a Balloon	- Through visual feedback on gripping actions, patients see their hand close around the balloon. - With visual feedback, patients can increase their grasp on virtual balloons and apply the required force and control.
Game 3: Swap Hand	- Patients receive guidance from visual cues as visual feedback to ensure that their hand is positioned appropriately during the supination and pronation movements. - Patients can improve their capacity to do rotating activities more efficiently when they are provided with visual feedback.
Game 4: Grip a Pencil	- Patients are provided with visual feedback to correctly grip and hold a virtual pencil with real-time observation of their hand grip. - Visual feedback helps patients refine their pinch grip, allowing them to grip virtual pencils more precisely.

D. Experiment Study Design

This study was conducted in Holy Family Hospital, Rawalpindi in the Physiotherapy Department. Approval for

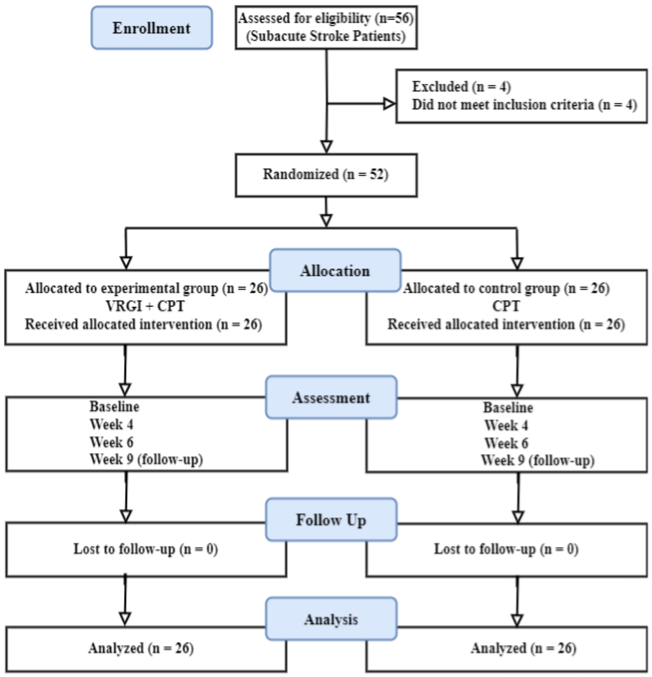

Fig. 3. CONSORT flowchart of experiment study design.

this study was granted by the Research Ethical Committee (Reference Number: BMES/REC/22/027) and accomplished according to the institutional regulations and principles of the Declaration of Helsinki. Each patient signed a written informed consent form to participate in the study. Fig.3 illustrates the Consolidated Standards of Reporting Trials (CONSORT) flowchart of experiment study design.

E. Inclusion and Exclusion Criteria

The patients were enrolled in this study based on inclusion and exclusion criteria. The inclusion criteria include (a) Montreal Cognitive Assessment (MOCA $\geq$ 21), this criterion ensures that patients have cognitive functioning, (b) Modified Ashworth Scale (MAS$<$ 4), criteria ensures that fewer spasticity patients may effectively be engaged, (c) Fugl-Meyer Assessment (FMA between 25 and 55), this confirm that patients have the required motor skills, (d) Age $\geq$ 18 years, this preferred to comply study measures and instructions regarding interaction with VR device, and (e) Stroke patient type (Subacute patients), at this stage brain's neuroplasticity are adaptable to rewiring and modifications.

The patients with the following are excluded from the study, (a) Wrist Impairments due to any muscular problem, (b) Contractures due to burns, (c) Patients with vestibular issues, and (d) Permanent external fixation.

F. Participants

A total of 56 participants with subacute stroke were recruited in this study. Only 52 patients who met the eligibility requirements for the trial were included. 4 patients dropped out due to not fulfilling the eligibility criteria requirements. An independent person who was not participating in any aspect of the study carried out the randomization procedure for the remaining 52 patients. Each participating patient was given a serial number as identification.

G. Intervention

Patients were randomly assigned to an experimental group referred to as (VR Based Game Intervention plus Conventional Physical Therapy, (VRGI+CPT)) and a control group referred to as (Conventional Physical Therapy (CPT)). Both groups undertook six weeks of intervention and two weeks of follow-up. The patient played each game level twice. In each VR game, easy and difficulty levels were divided into durations of 3 min and 5 min respectively.

1) Experimental Group: The VRGI+CPT group initially got VR intervention by playing all four easy-level games twice for three minutes each (i.e., 3min + 3min) during the first and second weeks. The VRGI+CPT group again underwent VR intervention playing all four same games with a difficulty level twice 5 min (i.e., 5min + 5min) duration for the third, fourth, fifth, and sixth weeks. The VRGI+CPT group had an intervention of 24 sessions, lasting 4 days/week for a total of 6 weeks. During the first two weeks, patients received 24 minutes of VR hand games and 24 minutes of therapy sessions per day which accounts for a total of 48 minutes, and for the next four weeks, this group received 40 minutes of VR hand games and 40 minutes of conventional therapy session per day which accounts for a total of 80 minutes. For virtual reality, intervention blinding was not conceivable because both the patients receiving virtual reality-based therapy and the therapist supervising it were aware of the intervention.

2) Control Group: The CPT group received conventional physical therapy, which consists of Range of Motion (ROM), stretching, resistance, and strengthening exercises. The CPT group had a conventional intervention of 24 sessions, lasting 4 days/week for a total of 6 weeks. The CPT group was given 48 minutes of conventional physical therapy sessions per day for weeks 1 and 2 followed by 80 minutes of conventional physical therapy sessions per day for the next 4 weeks. To further elaborate on the conventional physical therapy protocol; these therapy sessions consisted of ROM exercises for joints (such as shoulder, elbow, and wrist), muscle stretching (shoulder flexors; abductors; external rotators, elbow and wrist extensors, hand musculature), strengthening exercises and resistive exercises for weak muscles (using power web and gym equipment) and motor skills training for the upper limb (Thera putty and occupational therapy equipment). The time allocated for conventional therapy in the CPT group is equal to the total time spent on VR training and conventional therapy duration in the VRGI+CPT group.

H. VR-Based Hand Games Contents

The contents of each virtual reality game for hand rehabilitation are described below.

1) Game 1: Hit a Rolling Ball: Fig.2(a) shows the hit a rolling ball game. A patient flexed their affected wrist to contact the randomly generated color balls with the palm of their hand as it approached them on the virtual table. For the next, a patient taught to extend their same wrist to contact the balls with the back of their hand when it advanced them on the virtual table. In the easy level, the balls approached with slow speed with an appropriate wide gap between the balls whereas in the difficulty level the balls moved closer together at a slightly faster pace. This VR game is like activities in real-life scenario of reach and grab objects.

2) Game 2: Grasp a Balloon: Fig.2(b) illustrates the grasp of a balloon game. In easy level, randomly generated three color balloons appeared at equal distances. A patient closes their affected hand to pick up the balloon and holds that indicated color balloon for 5 secs. After the grasping time, the balloon was released, and the hand was open. The same procedures were performed for difficult level with more balloons placed closer together with little space in between the balloons. This VR game imitates situations to pick up objects for a specific amount of time in a real-life scenario.

3) Game 3: Swap Hand: Fig.2(c) presents the swap hand game. During the first half of each time duration, a patient extends their affected hand in a supination position. A randomly generated virtual ball from the top descended at an appropriate low speed and touched the palm side of the patient's hand. A patient then instantly swaps their hand for transition movement from a supinated to a pronated position. Another virtual ball descended and touched the back side of the patient's hand. In the second half, a virtual ball came from the opposite direction from bottom to top with appropriate speed and touched the palm side of the patient's hand. A patient then again promptly switched their hand from a pronated to a supinated position and another virtual ball touched the back side of the patient's hand. The same procedures were performed for difficult level with increased ball speed. This VR game can be useful for real-life activities requiring hand rotation.

4) Game 4: Grip a Pencil : Fig.2(d) illustrates the grip a pencil game. At an easy level, randomly colored pencils appear on the virtual table with wide gaps, a patient move their affected hand close to the virtual pencil and close their thumb and index finger to pick up a pencil with a specific color and hold for 5 sec and then placed nearby on the virtual table. The same procedures were performed for difficult level with more pencils placed closer together. This VR game emphasizes gripping small objects in real-life scenarios.

I. Outcome Measures

To assess the effectiveness of motor function of hand based on VR game intervention, Fugl-Meyer Assessment's- Upper Extremity (FMA-UE), Action Research Arm Test (ARAT), Box and Block Test (BBT), Modified Barthel Index (MBI) and Stroke-Specific Quality of Life (SSQOL) are the clinical outcome measures in this study for experimental (VRGI+CPT) group and control (CPT) group. Primary outcome measures were FMA-UE, ARAT, and BBT whereas MBI and SSQOL were considered as secondary outcome measures. These sets of clinical outcome measures are widely used in research and clinical settings [10].

The outcome measures FMA-UE, ARAT, BBT, MBI, and SSQOL were evaluated before the intervention and defined as "baseline", the 4th week and 6th week defined as "postintervention" and the 9th week defined as "follow-up". Patients were evaluated at follow-up for retention to perceive how long treatment benefits last and whether the intervention makes a difference in the desired outcomes. The use of these outcome measures is explained below.

1) Fugl-Meyer Assessment-Upper Extremity(FMA-UE): The FMA-UE subscale was used to assess the motor function recovery of stroke patients in the upper extremity following interventions. The FMA-UE has 33 items with a total score between 0-66 to assess motor function impairment [35].

2) Action Research Arm Test (ARAT): The ARAT is used to measure stroke patients' upper extremity's functional abilities, particularly about reaching, grasping, pinching, and general movement tasks. Every item is assigned a 4-point rating score, and the possible total scores range from 0 to 57 [10].

3) Box and Block Test (BBT): The BBT assessed the hand dexterity of stroke patients. In this test, within a time frame of one minute, blocks must be moved from one compartment to another [35].

4) Modified Barthel Index (MBI): The MBI evaluates a person's capacity to carry out both instrumental and everyday activities. The MBI contains ten items, and each one is scored either on the amount of help needed or the degree of independence shown by the patient [32].

5) Stroke-Specific Quality of Life (SSQOL) : The health quality of life of stroke survivors was assessed using SSQOL measure. SSQOL scale has 49 entire items, and it rates according to existing condition life of stroke patients [36].

J. Data Analysis

To analyze the data of the experimental group and control group, SPSS 21 statistical software (IBM Corp. Release 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.) has been utilized. $p < 0.05$ was set as the statistical significance criterion. To analyze the homogeneity of variances for patient demographic and clinical data Levene's test was performed. The Shapiro-Wilk test was used to perform the variables for normality. The Mann-Whitney U test was performed to evaluate the difference comparison between the experimental group (VRGI+CPT) and the control group (CPT). The Wilcoxon Signed Ranks test was performed to assess the difference comparison within the experimental group and the control group. These tests were performed for outcome measures FMA-UE, ARAT, and BBT. Due to the normality of MBI and SSQOL assessment data, ANOVA was performed.

III. Results

n=52 subacute stroke patients who met the eligibility requirements were included in this study. A randomized controlled trial was conducted. These patients are equally randomized in the VRGI+CPT group and CPT group. Each group was assigned 26 patients. Fig.4 presents the experimental paradigm employed in this study for hand rehabilitation games.

TABLE II
DEMOGRAPHIC AND CLINICAL DATA OF STROKE PATIENTS

Demographic and Clinical Data	Experimental Group (VRGI + CPT) n=26	Control Group (CPT) n=26	*p*-value*
Gender			
Male (n%)	16(61.5)	18(69.2)	0.564
Female (n%)	10(38.5)	8(38.8)	
Age (years), Mean ± SD	51.8 ± 12.9	49.8 ± 9.9	0.775
Affected Hand			
Right (n%)	11(42.3)	15(57.7)	0.272
Left (n%)	15(57.7)	11(42.3)	
MOCA, Mean ± SD	22.6 ± 1.4	22.5 ± 1.9	0.584
FMA-UE, Mean ± SD	40.84 ± 8.6	36.6 ± 7.4	0.190
MAS			
Grade 0	10(38.5)	7(26.9)	0.319
Grade 1	7(26.9)	7(26.9)	
Grade 1+	5(19.2)	6(23.1)	
Grade 2	4(15.4)	6(23.1)	

Mean ± SD: Mean ± Standard Deviation, VRGI: VR Based Game Intervention, CPT: Conventional Physical Therapy,
* Mann-Whitney U Test

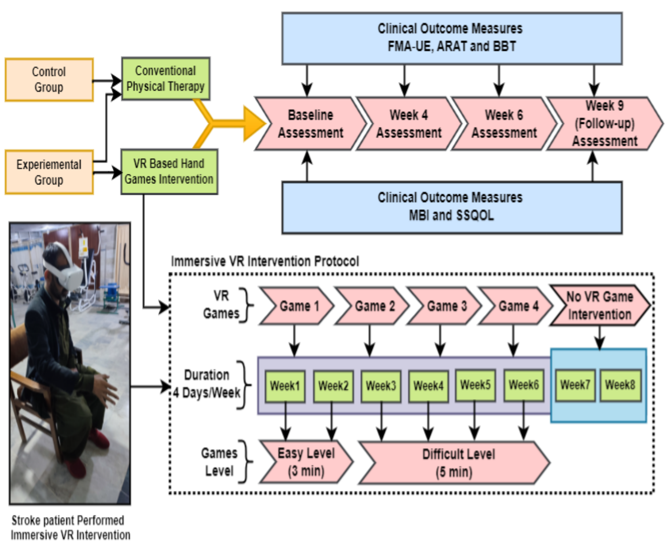

Fig. 4. Experimental paradigm employed for stroke patients' rehabilitation. The control group only employed conventional physical therapy whereas the experimental group underwent both VR intervention and conventional physical therapy.

A. Patient Demographic and Clinical Data

The patient demographic and clinical data are listed in Table II. For both groups data are presented in percentages (n%) for gender, affected hand, and MAS whereas age, MOCA and FMA-UE data are expressed in Mean ± SD. The p-values (all, $p > 0.05$) in the table depicted that baseline demographic and clinical features of the two groups did not significantly differ from one another. This illustrates that demographic variables at the baseline for both groups are evenly distributed. To ensure that the variances among the groups were homogeneous, Levene's test was run. The findings demonstrated that all p-values for demographic and clinical data are higher (all, $p > 0.05$), reflecting similar variations between the groups.

B. Effect of Virtual Reality Game Intervention on Motor Function Recovery

Motor function recovery of subacute stroke patients was assessed by Fugl-Meyer Assessment-Upper Extremity at time points of baseline, week 4, week 6, and week 9. From Table III, at the baseline assessment point, it was observed that there was no significant difference between the experimental group and control group scores, with ($p>0.05$) that is $p=0.190$ preceding to VR-based game intervention. When assessed at time points of week 4, week 6 and week 9, significant differences (all, $p<0.05$) were observed among the two groups. When comparing the differences within the experimental group, a significant difference was observed between all assessment time points. The significant difference between baseline and week4 was ($Z = -4.481$, $p=0.000$) with an improvement of 4.34± 2.2. Between week4 and week6 ($Z= -4.478$, $p=0.000$) with improvement of 5.11±2.6. Among week 6 and week 9 (follow-up) was ($Z=-4.175$, $p=0.000$) with 5.61±3.5 improvement, and between baseline and week 9 (follow-up) was ($Z=-4.464$, $p=0.000$) with an overall improvement of 15.07±34.9. On the other hand, when comparing the differences within the control group, a significant difference was observed between all assessment time points. The significant difference between baseline and week4 was ($Z=-4.410$, $p=0.000$) with an improvement of 1.65± 1.0, between week4 and week6 ($Z=-4.527$, $p=0.000$) with the improvement of 2.11±0.8, between week 6 and week 9 (follow up) was ($Z=-3.952$, $p=0.000$) with 1.84±1.5, and between baseline and week 9 (follow up) was ($Z=-4.469$, $p=0.000$) with 5.61±2.4.

C. Effect of Virtual Reality Game Intervention on Functional Abilities

Functional abilities, especially those related to reaching, grasping, pinching, and general movement tasks were assessed at time points of baseline, week 4, week 6 and week9. The experimental group (VRGI+CPT) and control group (CPT) were not significantly different in ARAT at the baseline assessment point, with ($p>0.05$) that is, $p=0.132$ before the VR based games intervention whereas Table III, also revealed that between the two groups there was a significant difference ($p<0.05$) in ARAT at time points of week 4, week 6 and week 9 because experimental group underwent effective VR intervention. When examined the within group, both groups depicted improvement. However, the VRGI+CPT group shows better improvement in ARAT than the CPT group in all assessment weeks. The significant difference of VRGI+CPT group between baseline and week4 was ($Z= -2.009$, $p=0.045$) with improvement of 2.69±6.3, between week4 and week6 was ($Z=-4.185$, $p=0000$) with improvement of 5.23±3.8 and between week6 and weeek9 was ($Z=-4.470$, $p=0.000$ with improvement 5.30±2.8. The within CPT group significant difference between baseline and week4

TABLE III
EFFECT OF VIRTUAL REALITY GAME INTERVENTION ON CLINICAL OUTCOME MEASURES (FMA-UE, ARAT AND BBT)

Group	Assessment Time points				Difference between Week 6 and follow-up	Difference between Baseline and follow -up
	Baseline (Mean ± SD)	Week 4 (Mean ± SD)	Week 6 (Mean ± SD)	Week 9 (Follow up) (Mean ± SD))	p-value[b]	p-value[c]
FMA-UE						
VRGI+CPT	40.84± 8.6	45.19± 7.5	50.30± 7.3	55.92± 7.3	0.000	0.000
CPT	36.61± 7.4	38.26± 7.6	40.38± 7.7	42.23± 7.86	0.000	0.000
p-value[a]	0.190	0.003	0.000	0.000		
ARAT						
VRGI+CPT	24.23±4.9	26.92±9.3	32.15±10.9	37.46±9.1	0.000	0.000
CPT	21.23±8.2	21.69±8.4	24.34±6.7	25.50±6.7	0.000	0.002
p-value[a]	0.132	0.037	0.009	0.000		
BBT						
VRGI+CPT	15.11±6.7	22.61±8.8	31.00±12.43	39.50±12.8	0.000	0.000
CPT	11.76±8.6	13.26±9.0	14.65±8.5	15.69±8.4	0.007	0.000
p-value[a]	0.088	0.000	0.000	0.000		

VRGI: VR Based Game Intervention (n=26), CPT: Conventional Physical Therapy (n=26), FMA-UE: Fugl-Meyer Assessment-Upper Extremity, ARAT: Action Research Arm Test, BBT: Box and Block Test.
[a] Mann-Whitney U Test, Difference comparison between experimental group (VRGI+CPT) and control group (CPT)
[b]Wilcoxon Signed Ranks Test, Difference comparison within experimental group and control group between Week 6 and follow up.
[c]Wilcoxon Signed Ranks Test, Difference comparison within experimental group and control group between Baseline and follow up.

was (Z=−3.464, p=0.001) with an improvement of 0.46±0.5, and between week4 and week6 was (Z=-2.149, p=0.032) with an improvement of 2.65±5.6 and between week6 and weeek9 was (Z=−4.416, p=0.000) with a mean difference of 1.15±0.67.

D. Effect of Virtual Reality Game Intervention on Hand Dexterity

Hand dexterity was evaluated for fine motor skills at time points of baseline, week 4, week 6, and week 9. From Table III, improvement was observed within the groups in both the experimental group and the control group. However, the improvement was more significant in the experimental group than in the control group. The significant difference of VRGI+CPT group between baseline and week4 was (Z=−4.463, p=0.000) with improvement 7.5±2.8, between week4 and week6 was (Z=−4.462, p=0.000) with improvement 8.38±4.7 and between week6 and weeek9 was (Z=−4.473, p=0.000) with improvement 8.50±2.8. The CPT group significant difference between baseline and week4 was (Z=−3.849, p=0.000) with improvement 1.50±1.6, between week4 and week6 was (Z=−3.503, p=0.000) with improvement 1.83±1.4 and between week6 and weeek9 was (Z=-2.717, p=0.007) with 1.03±2.4.

E. Effect of Virtual Reality Game Intervention on Activity of Daily Livings

To assess the activities of daily living, MBI was evaluated at two time points baseline and week9. At baseline, there was no significant difference (p>0.05) between the experimental group and control group as depicted in Table IV. The follow-up revealed a significant difference between the two groups

TABLE IV
EFFECT OF VIRTUAL REALITY GAME INTERVENTION ON CLINICAL OUTCOME MEASURES (MBI AND SSQOL)

Group	**Assessment Time points**		**Difference between Base-line and follow up**
	Baseline (Mean ± SD)	Week 9 (Follow up) (Mean ± SD))	p-value[b]
MBI			
VRGI+CPT	10.84±4.51	16.26±2.30	0.000
CPT	9.19±2.48	10.57±2.84	0.000
p-value[a]	0.108	0.000	
SSQOL			
VRGI+CPT	133.2±25.43	168.5±18.37	0.000
CPT	122.23±20.87	135.11±19.36	0.000
p-value[a]	0.093	0.000	

VRGI: VR Based Game Intervention, CPT: Conventional Physical Therapy, MBI: Modified Barthel Index, SSQOL: Stroke-Specific Quality of Life.
[a] ANOVA Test, Difference comparison between the experimental group (VRGI) and control group (CPT).
[b]Paired Sample t-Test, Difference comparison between baseline and follow-up

(p<0.05). Evaluation within the experimental group revealed an improvement in activities of daily living with a mean improvement of 5.42±3.65 whereas the mean improvement within the control group was 1.38±0.89. This illustrated that improvement in activities of daily living within the experimental group was higher than within the control group.

F. Effect of Virtual Reality Game Intervention on Quality of Life

Quality of life was assessed with SSQOL questionnaire at baseline and week9. From the results of Table IV, among the experimental group and control group the results found no significant difference ($p>0.05$). On the results of the follow-up, it was found that there was a significant difference between the two groups ($p<0.05$). SSQOL was also assessed within both groups and results show that there was an improvement in quality of life within both groups with a mean improvement of 35.23±16.0 and 12.88±4.8 respectively. However, improvement within the experimental group was much better than within the control group.

IV. Discussion

In this study, the aim was to develop and examine VR-based games incorporated with an innovative approach of cognitive engagement within visual feedback to improve hand motor functions. The fully immersive VR games employed in this study were created for subacute stroke patients and are not commercially available. The clinical outcomes of these VR games present significant improvements in hand motions as compared to conventional physical therapy. Each measurement's mean and standard deviation expressed as Mean ± SD are shown together with the statistical significance (p-value).

From Table III, the results of FMA-UE and ARAT show no significant difference between the two groups at the baseline which illustrates that randomization was effective. However, after VR-based game intervention significant differences were observed among both groups at the remaining three evaluation points with (all, $p<0.05$) in FMA-UE and ARAT. It is also perceived from the table that there were significant differences within both groups. Within the experimental group, the FMA-UE score increases from baseline to week4 and week4 to week6 with mean values of 4.34± 2.2 and 5.11±2.6 respectively. The FMA-UE also increases in the control group in assessment weeks from baseline to week4 with a mean value of 1.65± 1.0 and week4 to week6 with a mean value of 2.11±0.8. However, it was noticed that within the experimental group, the FMA-UE was improved significantly than within the control group in all assessment weeks due to VR intervention that substantially improved motor recovery. During the follow-up, results demonstrated an increase in mean values of 5.61±3.5 from week6 to week9 was observed. However, as compared to a control group with a mean value of 1.84±1.5, the experimental group indicated a potential improvement when evaluated at week9. Results between baseline and follow-up demonstrated a notably better improvement in the experimental group as compared to a control group with 15.07±34.9 and 5.61±2.4 respectively. This illustrates that VR-based games intervention was effective in substantially sustaining the motor recovery of subacute patients.

The ARAT results from Table III illustrate the assessment within groups. In the VRGI+CPT group the mean score of ARAT was 2.69±6.3 from baseline to week4 and from week4 to week6 the mean value was 5.23±3.8. This shows that there was considerable improvement within the VRGI+CPT group. On investigating within the CPT group, the ARAT mean score also increases from baseline to week4 and week4 to week6 with mean values of 0.46±0.5 and 2.65±5.6 respectively. The ARAT within the experimental group improved significantly in all assessment weeks when compared to within the control group. When evaluating the assessment between baseline and follow-up significant improvement was observed in the experimental group with 13.23±7.6 as compared to a control group with 4.26±5.4. This improvement implied that VR-based game intervention has effectively been underwent to promote functional abilities.

Results from Table III show that within the experimental group, the BBT mean score from baseline to week4 was 7.5±2.8 and from week4 to week6 the mean score was 8.38±4.7. The rise in mean score of BBT indicated that the hand dexterity within the VRGI+CPT group was improved. Within the control group comparison, the BBT score also rises from baseline to week4 and week4 to week6 with mean values of 1.50±1.6 and 1.83±1.4 respectively. Within the experimental group, hand dexterity was greatly improved than within the control group in all assessment weeks. Hand dexterity improvement has also been noticed between baseline and follow-up with a significant difference ($p<0.05$) among the experimental group and control group. However, the improvement of hand dexterity was greater in the experimental group with 24.38±7.2 than the control group with 3.92±2.4 because of the task-specific and repetitive VR-based pinch game.

Table V illustrates the comparative analysis of VR games interventions with our developed VR based hand games. Targeting subacute stroke patients and exhibiting promising outcomes, results demonstrated significantly improved hand motor functions such as increased dexterity, improved range of motion, hand strength and griping, and enhanced quality of life. The International clinical guidelines have demonstrated that task-specific training is effective in the recovery of the upper extremities [38].

The current study has various implications that have the potential to shape existing practices of stroke rehabilitation and provide a new VR-based games approach to research in the field of stroke rehabilitation. This research finding makes it possible to stimulate the incorporation of innovative sensory-cognitive engagement, functionally challenging tasks, and targeted movements into the rehabilitation procedures. This would adjust patients' abilities, promoting continuous challenge and enduring improvement. Due to the innovative design of the VR hand games, the transition between the hand movements also enhanced the patient's active involvement in the VR hand games making hand rehabilitation more engaging and adhering to the treatment regimen. The goal of playing proposed hand rehabilitation games is to increase the patient's ability to function independently. For those who have survived a stroke, this may involve regaining the ability to feed and dress themselves or engage in other activities that require self-care. These VR games enable stroke patients to persist with their hand recovery outside clinical settings by utilizing hand-tracking technology and have the potential to be used at home. These combined implications may lead to improvements in stroke rehabilitation practices and advancement of VR based game applications in healthcare.

Virtual reality (VR) games have the potential to be more motivational and interesting than conventional therapy due to functional engagement. Enhancement in neuroplasticity and

TABLE V
COMPARATIVE ANALYSIS OF VR BASED REHABILITATION WITH OUR DEVELOPED VR BASED HAND GAMES

	Reference [35] / 2023	Reference [19] / 2021	Reference [10] / 2022	Reference [37]/ 2023	**Our Proposed**
Games Employed	(1) Elevator Firefighters, (2) Apple Farmer Highway Ferry, (3) Chicken and Worm Get Green	(1) Butterfly, (2) Space War, (3) Snow, (4) Tubes and (5) Virtual Home	1. Reach game 2.Sequence game 3. Flip game 4.Opening/closing game	No VR games	1. Hit a Rolling Ball, 2. Grasp a Balloon, 3. Swap Hand, 4. Grip a Pencil
Semi Immersive/ Fully Immersive	Semi Immersive	Semi Immersive	Semi Immersive	Semi Immersive	Fully Immersive
System Used for VR intervention	PABLO Wearable sensor-based VR	Kinect sensor (Xbox 360)	Leap Motion Controller system-based VR	HTC Vive-VR, wireless controllers	VR Oculus Quest 2
Participants	37 Chronic	10 Chronic	10 chronic	40 subacute	52 subacute
Movement Type	Shoulder, elbow and hand.	Shoulder, elbow and wrist	Shoulder joint, pronation/supination of forearm, wrist flexion/extension of elbow, palmar grasp and finger extension /flexion.	Upper Extremity (No specific movement)	Flexion/extension of the hand, close/open of hand, supination/pronation of hand and pinch.
Outcome Measures	FMA-UE, AROMs, BBT, SIS and M-PAES	Goniometer, MMAS and Brunnstrom's stages	Grip Strength, ARAT, BBT, SF-36 and Likert-type scale	FMA-UE, BI and fMRI	FMA-UE, ARAT, BBT, MBI and SSQOL
Rehabilitation Outcomes	- No significant motor function improvement, grip strength and QOL. - VR group improved shoulder flexion and pronation AROMs. - No sensory-cognitive engagement	- Improvements in ROMs only. -No sensory-cognitive engagement	- Significant improvements in the grip strength - No significant changes were observed in SF-36 (QOL) - No sensory-cognitive engagement	Improvements in UE motor impairment and daily living activity. - Activities were performed using external controllers. - No sensory-cognitive engagement	- Improvement in hand motor functions due to innovative approach of integration of cognitive engagement within visual feedback in VR games. - No external sensors and controllers were used.

VR: Virtual Reality, COT: Conventional Occupational Therapy, EG: Experimental Group, CG: Control Group, FMA-UE: Fugl–Meyer Assessment Upper Extremity, AROMs: Active Ranges of Motion, BBT: Box and Block Test, SIS: Impact Scale Strength, M-PAES: Modified Physical Activity Enjoyment Scale, QOL Quality of Life, MMAS: Modified Ashworth Scale, ARAT: Action Research Arm Test, SF-36: Short Form Health Survey-36, BI: Barthel Index, fMRI: functional Magnetic Resonance Imaging, MBI: Modified Barthel Index, SSQOL: Stroke-Specific Quality of Life.

improvement in motor function was due to the effective utilization of our innovative approach. This made the rehabilitation for subacute stroke patients more encouraging. Furthermore, patients playing VR games observed their movements while receiving therapy. This impacts promising results due to the visual training feedback. This study has some limitations, Firstly, some additional clinical outcome measures may require to be considered for further assessment of VR-based hand games. Secondly, VR games in this study are limited to a set of exercises, therefore some stroke patients might require exercises for their specific needs.

V. CONCLUSION

This article presents the development and evaluation of the effectiveness of VR games incorporated with an innovative approach to the integration of cognitive engagement within visual feedback. In the results of follow-up assessments, significant differences ($p<0.05$) were observed between the groups in all clinical outcome measures, which illustrated that fully immersive VR-based games intervention was effective in substantially sustaining the motor recovery of subacute stroke patients. Stroke patients showed increased dexterity, improved range of motion, hand strength, and griping. The outcome of this research reinforces the notion that fully immersive VR based rehabilitation games intervention offers an efficient platform for hand motor improvement in stroke rehabilitation. To improve the patient's ability to synchronize their hand motions with visual stimuli, cognitive engagement within visual training aspects was incorporated into the games. This study paves the way for the new application of VR based hand games to enhance stroke patients' functional independence and quality of life.

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