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Development and Testing of a Virtual Reality Mirror Therapy System for the Sensorimotor Performance of Upper Extremity: A Pilot Randomized Controlled Trial

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ABSTRACT Mirror therapy (MT) has been proposed as an essential component of upper limb neuro-rehabilitation, using mirror illusion of the unaffected hand movement and superimposing it on the affected hand to improve neuroplasticity for improving motor recovery in stroke patients. In this paper, we developed a virtual reality mirror therapy (VRMT) system, and examined the performance of the proposed VRMT system. The VRMT system consists of a motion-tracking device, a VR goggle, and a VRMT software. Young, healthy participants, and stroke patients with mild-to-severe hemiparesis were recruited in this study, to validate the effectiveness of the proposed VRMT system. Experimental results based on the pinch-holding-up activity (PHUA) test revealed a significant effect on the precision pinch performance of young-healthy participants receiving VRMT, whereas traditional MT could not improve the precision pinch performance in young-healthy participants (Wilcoxon signed-rank test, $Z = -2.693$, $p = 0.007$). For patients having suffered a stroke and being treated with VRMT, significant beneficial effects examined by mixed effect model were found on the total score of FMA ($p = 0.033$) and hand part of FMA ($p = 0.008$). The findings in this study indicate that the VRMT system has a potentially positive effects on the sensorimotor performance of hands in healthy participants. In addition, add-on effect of VR to MT provides beneficial effects on motor function of the upper extremity in chronic stroke patients.

INDEX TERMS Virtual reality, mirror therapy, stroke rehabilitation.

ABBREVIATIONS

VR	virtual reality
MT	mirror therapy
VRMT	virtual reality-based mirror therapy
LMC	leap motion controller
MMSE	mini-mental state examination
LOTCA	Lowenstein occupational therapy cognitive assessment
FMA	Fugl-Meyer assessment
PHUA	Pinch-holding-up activity
DH	dominant hand
NDH	non-dominant hand
BH	both hands
PPT	Purdue Pegboard test
MMDT	Minnesota Manual Dexterity Test

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I. INTRODUCTION

Neuroplasticity is the ability of the brain to remodel structure and function in response to external stimulation, activities, and experiences that result in compensation for age or disease-related brain changes [1]. Rehabilitation-induced neuroplastic changes provide improvement of sensorimotor function for brain damage patients. Enrichment in exercise and sensory inputs have been proposed as effective strategies to improve neuroplasticity, facilitating motor recovery for stroke patients [2]. Neurophysiologic studies [3], [4] reveal that using multisensory integration techniques on motor training increases the upper limb training benefit. The virtual reality (VR) [5] and mirror visual approaches [6] are effective strategies of driving multisensory inputs onto the motor system to help motor recovery.

Mirror therapy (MT) has been proposed to be an essential component of neuro-rehabilitation, using mirror illusion of the unaffected hand movement and superimposing it on the affected hand to improve neuroplasticity in stroke patients [7]. Recent research revealed that MT provides effects not only on motor impairments, but also on sensory and perception deficits for stroke patients [8]. Different from delivering high-intensity motor practice, MT is a priming technique for brain activation, to re-establish motor function of the affected limb. While looking at the image of the unaffected hand movement reflected in a mirror, multisensory feedback of vision and proprioception increases neuronal activation in cortex areas associated with self-awareness and spatial attention [9]. Visual mirror feedback also improved motor performance and enhanced the primary motor cortex excitation in healthy participants [10]. However, it is worth noting that asymmetry in sitting posture while conducting MT using a traditional mirror box would cause problems in movement learning and control [11].

Virtual reality (VR) technology creates an interactive simulated visual environment, presented via a head-mounted display. It leads to more functional outcomes of the affected arm compared with the traditional therapy, by providing more immersive feedback on movement training [12]. Besides, VR technology allows users to interact with a computer-generated scenario, which can motivate patients to participate in the rehabilitation program [13]. Through the repeated practice and performance shaping principles, VR appears to confer the great benefits for stroke rehabilitation among other treatments. Nevertheless, based on current research, the recruiting criteria for participants to receive VR training are limited to patients with mild to moderate impairment in upper extremities, and treatment effects have not been confirmed for patients with more serious injuries. Therefore, comprising the virtual image to mirror movements of the unaffected arm might be a possible strategy for enhancing sensorimotor function for patients with severe motor impairment [14].

Upper extremity hemiparesis is the most common post-stroke disability, with about 55−75% of stroke survivors experiencing it [15]. Thus, developing an effective, therapeutic strategy for reducing disability after stroke is an important issue for clinicians, and also the research motivation of this paper. Traditional MT has been proven as a promising therapy with potential benefits for sensorimotor recovery on upper limbs [7]. Based on the finding of a previous brain image study, there was stronger activation in primary sensorimotor cortex for the VR-based MT compared to the traditional mirror box condition [16]. VR technology, delivering highly immersive environments for motor learning, provides optimal levels of evidence in the management of motor symptoms [17]. Integrating VR technology to MT can empower rehabilitation outcomes [18]. However, very limited data on their clinical utility of VR-mediated MT has been presented.

The first aim of this study is to develop a virtual reality mirror therapy (VRMT) system by integrating a motion-tracking device, virtual reality goggle, and in-house developed software. The expected improvement of the VRMT system, when compared to traditional MT, is that it can offer fully immersive mirror image of bilateral upper limb, provided by the VR goggle, to solve the problem of posture asymmetry of traditional MT. A second expected improvement is that VRMT can be a suitable intervention for patients with more severe hemiparesis to reduce the limitation of existing VR system.

The second aim of the study is to examine the performance of the proposed VRMT system, as evaluated by results derived from two groups: 1) young-healthy participants and 2) stroke patients with hemiplegia. The delicate sensorimotor control of the hand have received relatively little attention with regard to the investigation of mirror therapy. To understanding effects of VRMT on motor learning, in addition to several manual dexterity tests, a pinch-holding-up-activity (PHUA) test with sensitivity for determining both the sensibility and precision pinch performance of a hand was used for better understanding sensorimotor control in the hand [19]. We hypothesize that VRMT would provide better effects on sensorimotor function than traditional MT for participants in both groups of stroke and young healthy participants.

II. VIRTUAL REALITY MIRROR THERAPY SYSTEM

The usage scenario of the VRMT system is shown in FIGURE 1 and FIGURE 2. A participant is sitting in front of a desk, wearing the VR goggle. A motion-tracking device captures movement of the unaffected side of the participant. The virtual reality goggle and the motion-tracking device used in this study are Oculus Rift and Leap Motion Controller respectively. The self-developed software is responsible for continuously collecting data from the motion tracking device, and then mirroring it.

A. MOTION TRACKING DEVICE

A Leap Motion Controller is a tiny USB peripheral device that can be plugged into a computer and placed facing upward on a desktop or mounted onto a VR goggle. Leap Motion Controller uses three infrared (IR) LED transmitters and two monochromatic IR camera sensors to track ten fingers and palms on both hands. The overall estimated average movement accuracy of the Leap Motion Controller is 0.7 millimeter, as shown in a previous study [20]. The Leap Motion Controller can sense hand movement within a three-dimensional (3D) interaction space of about eight cubic feet above the device and a close-range around an inch above the controller. The VRMT participant is performing MT rehabilitation activities inside the eight cubic feet above the

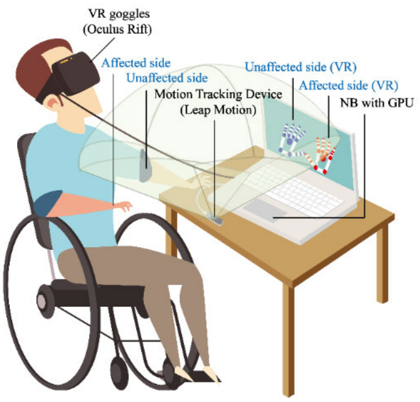

FIGURE 1. Usage scenario of the VRMT system.

FIGURE 2. Real usage scenario of the VRMT system.

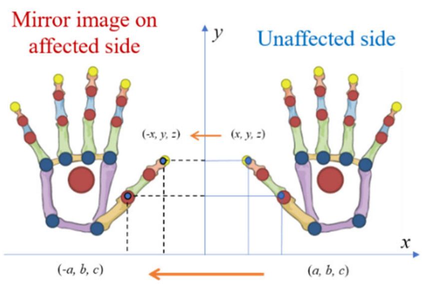

FIGURE 3. Nodes of leap motion controller in hand and mirroring from unaffected side to affected side.

Leap Motion Controller. The Leap Motion Controller enables the VRMT to precisely track the movements of the unaffected side without any visible delay. The joints can be captured by the Leap Motion Controller as shown in FIGURE 3.

B. VIRTUAL REALITY GOGGLE

Oculus Rift is a virtual reality goggle developed and manufactured by Oculus VR. The Rift has two PenTile OLED displays, and offers 1080 × 1200 resolution per eye, a 90 Hz refresh rate, and a 110° field of view. The device also features rotational and positional tracking, as well as integrated headphones that provide a 3D audio effect. The separation of the lenses is adjustable, using a slider on the bottom of the device to accommodate a wide range of interpupillary distances. The Rift allows for full 6-degrees-of-freedom rotational and positional tracking. Tracking is performed by Oculus's Constellation tracking system and is precise, of low-latency, and accurate to the sub-millimeter level. Constellation is the goggle's positional tracking system, used to track the position of the user's head as well as other VR devices. It consists of external IR tracking sensors that optically track specially designed VR devices.

C. VIRTUAL REALITY MIRROR THERAPY SYSTEM (VRMT) SOFTWARE

An in-house developed VRMT software used in this study was developed by the Unity cross-platform game engine. The VRMT software collects data from Leap Motion Controller, representing a total of 22 joints from the unaffected side is shown in FIGURE 3. A mirroring function in VRMT system software is then mirroring all joints in the unaffected side, causing the center of the VR goggle view point to generate a coordination of all joints in the affected side. The fusion process is done by combining the joint coordinates of unaffected/affected side together. Finally, two capsule hands are formed in the VR goggles, as the VRMT scenario for participants.

D. REHABILITATION ACTIVITIES of VRMT

The VRMT software provided guidance of seven hand-rehabilitation-related activities to participants conducting VRMT, as shown in FIGURE 4, including a) supination or pronation (palm turn over), b) thumb-to-the-tip-of-the-finger movement, c) thumb circling, d) wrist flexion and extension, e) tendon gliding exercise (straight hand, hook fist, straight fist, and full fist), f) finger flexion and extension, g) key pinch. Participants were seated in front of the desktop with both upper limbs placed on the desk. Each movement was repeated 50 times for 30 minutes during intervention.

III. EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

A. PARTICIPANTS

To examine the effects of the proposed VRMT system regarding the sensorimotor control of hand function, two groups were included in the clinical trial, young-healthy participants and stroke patients with hemiplegia. The clinical trial was approved by the Institutional Review Board under IRB No. 8800-4-03-001 of National Cheng Kung University Hospital (Tainan, Taiwan).

1) YOUNG-HEALTHY PARTICIPANTS

30 young and healthy participants were recruited, based on the effects obtained regarding sensorimotor control of a hand using MT, an estimate with a 2-tailed alpha of 0.05 and power of 0.80 as shown in previous research of MT with an effect size of 0.86 [21]. All the participants in this research group were right-handed and had no history of neurological or psychiatric illness and abnormalities in the upper extremities. Participants with diagnosed neuro-musculoskeletal disorders, left-handedness, congenital anomalies of the wrist and hand,

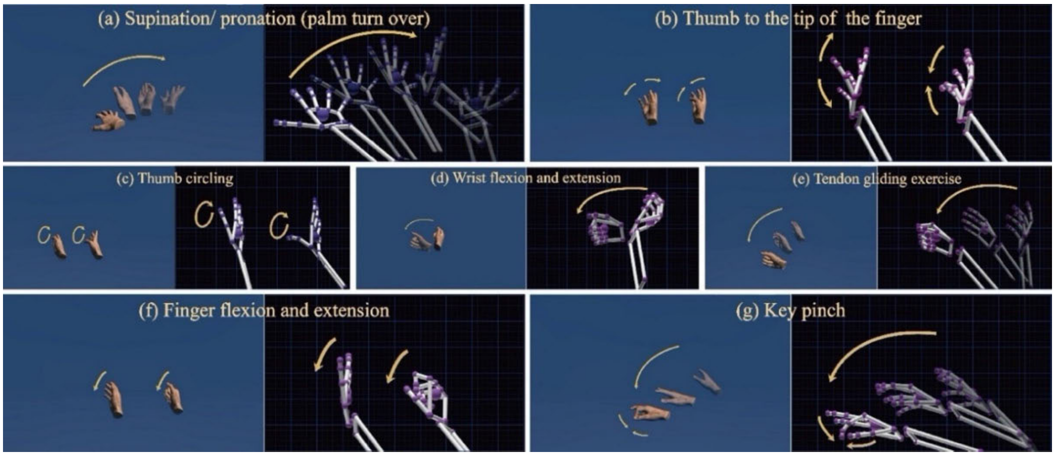

FIGURE 4. Guidance provided by the VRMT software: (a) Supination/ pronation (palm turn over), (b) Thumb-to-the-tip-of-the-finger movement, (c) Thumb circling, (d) wrist flexion and extension, (e) Tendon gliding exercise, (f) Finger flexion and extension, (g) key pinch.

cognitive deficits, and of age younger than 20 or older than 40 were excluded.

2) STROKE PATIENTS

To determine if there was motor improvement in a hand that has undergone VRMT, a sample size estimation was made using a 2-tailed alpha of 0.05, a power of 0.80, as shown in previous research in MT with an effect size of 1.28 [22]. A minimum number of nine patients per condition was identified as a sample size. A convenience sample of stroke survivors was recruited for the study, referred from the Department of Physical Medicine and Rehabilitation of a medical center in southern Taiwan. The inclusion criteria for stroke patients were as follows: patients of chronic stroke with unilateral cerebral infarction or hemorrhage and whose disease duration was more than six months following the stroke, a score for the Fugl-Meyer upper extremity motor assessment ranging from 23 to 60 (corresponding from too poor to notable arm-hand capacity), and score of a mini mental state examination (MMSE) not lower than 24. Participants who did not meet the inclusion criteria, or showed Wernicke's aphasia or global aphasia leading to difficulty of following instructions were excluded.

TABLE 1 summarizes the demographic characteristics, disease duration, and severity of affected upper extremities for stroke patients selected for this study. 18 chronic-stroke patients with mild to severe motor impairment were randomly allocated in either a MT or VRMT group. The characteristics of age, disease duration, and severity of affected upper extremity did not statistically differ between the two groups, hence the effect of the MT or VRMT is not influenced by these factors. In addition, there were no reported adverse effects in the current work.

B. STUDY DESIGN

The study consisted of two experiments. Experiment 1 investigated the difference in immediate effects on sensorimotor function of the hands between VRMT and MT in the healthy, young adults used a crossover randomised controlled design. Except for the baseline measurement (TH1), the same measurement on outcome was conducted immediately after (TH2), and then two hours after (TH3) each session (FIGURE 5, blue part). Experimental 2 investigated the difference in effects of 18 sessions of VRMT/ MT on sensorimotor function of the hands in the stroke patient used a single-blinded, randomized controlled trial with baseline (TS1) and endpoint (TS2) assessments (FIGURE 5, red part). Therapists providing intervention in both conditions did not perform outcome measurement. Two external evaluators blinded to the participant's condition were employed. One being an occupational therapist (for FMA, Purdue Pegboard and Minnesota Manual Dexterity test measures), and the other being a technician (for baseline characteristics collection and Pinch-Holding-Up Activity test).

C. INTERVENTION

1) YOUNG HEALTHY PARTICIPANTS

The VRMT clinical trial in healthy, young participants group consisted of two one-session interventions, 30 minutes of VRMT (or traditional MT), separated by a washout period of two weeks. The healthy, young participants received either 30 minutes of MT, or VRMT in each treatment session. After the two-week wash-out period, the participants changed intervention group.

2) STROKE PATIENTS

The recruited stroke patients were randomized to either a traditional MT or a VRMT group. Treatment intensity, equal for each group, was 50 minutes/day, two days/week, for nine weeks. Patients in the experimental group (VRMT group) received 30 minutes of VRMT each, followed by 20 minutes of regular motor task-specific training in each treatment session. The controls (patients in MT group) received 30 minutes of traditional MT each, followed by 20 minutes of motor task-specific training in each treatment session. The session

TABLE 1. Demographics and baseline clinical characteristics of stroke participants.

	MT group (*n*=9)	VRMT group (*n*=9)	*p*-value
Demographic data			
Gender (Male/ Female)	6/3	7/2	0.06
Age (years)	58.8 ± 9.6	49.7±13.4	0.14
Affected hand: Dominant / Non-dominant hand	5/4	3/6	0.64
Period from onset to 1^{st} evaluation (months)	48.2±32.4	42.2±21.3	0.86
Clinical Characteristics			
Fugl-Meyer motor assessment for upper extremity	28.3±18.1	43.4±14.5	0.14

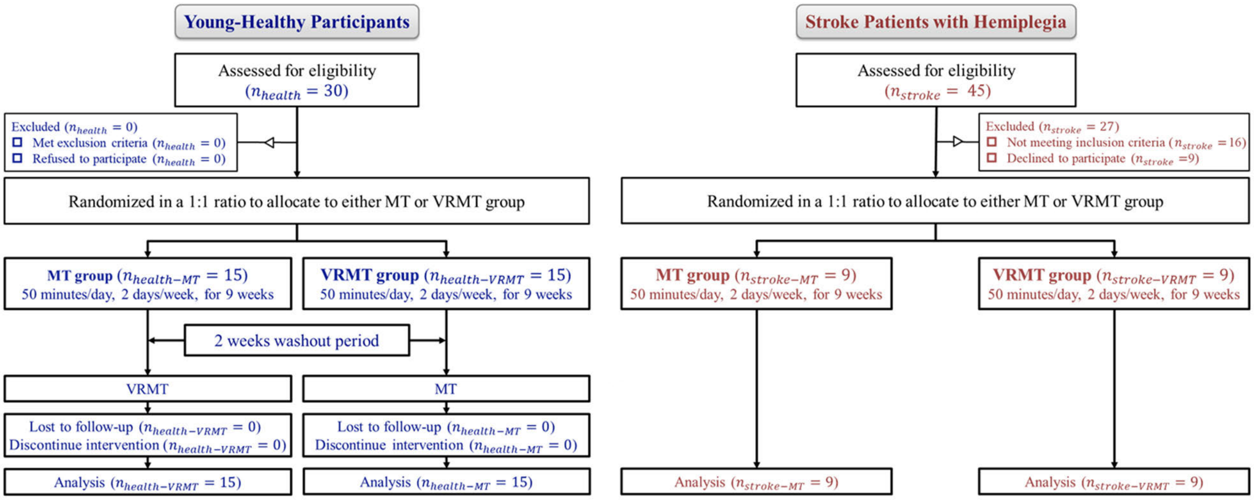

FIGURE 5. Flow chart showing the enrollment of patients/healthy participants and completion of the study.

dose of VRMT or MT in our study was chosen based on the characteristics of recruited studies in a systematic review article concerning mirror therapy with stroke patients [7].

D. ETHICS STATEMENT

The study protocol was approved by the National Cheng Kung University Hospital Institutional Review Board (A − ER − 105 − 213). Prior to participation, each subject was informed about the aims and the related procedures of the experiment, and then asked to sign a consent form.

E. RANDOMIZATION AND ALLOCATION CONCEALMENT

Following eligibility screening and consent, patients meeting the inclusion criteria were randomly allocated to conditions, using opaque envelopes with computer-generated random numbers, which were opened by the investigator upon receiving a consented participant. Eligible patients were randomly allocated until all available envelopes had been exhausted, resulting in a 1:1 ratio into either the experimental or control group.

F. HAND EXERCISES OF MIRROR THERAPY PROGRAM

The participant was sitting in a comfortable chair in front of a desk, with either a traditional mirror box or VRMT system during the treatment (MT or VRMT). During the treatment, an occupational therapist guided the participants to perform a series of hand movements in the real or VR environment. The sequences of hand exercises consisted of the movements shown in FIGURE 4. Each hand exercise was repeated 50 times. The participants were instructed to look at the motion of the virtual hand through VR goggle in VRMT condition, or at the motion of the mirror illusion in traditional MT.

G. OUTCOME MEASURES

1) PRIMARY OUTCOME

Fugl-Meyer Assessment (FMA) for motor function of the upper extremity for stroke patients: The assessment included items dealing with the shoulder, elbow, forearm, wrist, and hand in the upper extremity of patients. The overall reliability was high (overall intra-class correlation coefficient was 0.96), and the intra-class correlation coefficient for the subsections of the upper extremity assessment was 0.97 [23]. Each item was rated on a three-point ordinal scale (two points for the detail being performed completely, one point for the detail being performed partially, and zero for the detail not being performed). The maximum motor performance score was 66 points for the upper extremity.

Pinch-Holding-Up Activity (PHUA) test for healthy participants: The PHUA test was considered a valid test to evaluate sensorimotor control of a hand [24]. A pinch apparatus (a cuboid mounted with two load cells and one accelerometer) was used to conduct the PHUA test. The load cells and accelerometer registered the pinch force exertion of the participant and the acceleration of the pinch apparatus in space respectively. According to Newton's second law, the load of the lifting object is equal to the product of mass (m) and the vector summation of gravity (g) and lifting acceleration (a). The ratio between the pinch force exertion and the load of the lifting object during a dynamic pinch performance was considered a sensitive parameter to evaluate the sensorimotor control capability of a hand. The test was conducted using the following two phases. Holding phase: participants pinched the pinch apparatus with a weight of 480 g, then lifted it at about 5 cm height above the table and then held the device in this position for 5 seconds. Lifting phase: participants were asked to lift the pinch-apparatus from 5 cm height above the table to the height of 30 cm and slowly lower it down to the initial position at their preferred speed. The total duration of data collection was 15 seconds, recording the maximum upward acceleration and peak pinch force during the lifting phase of the test. The peak pinch force during the lifting phase was defined as FP_{peak}, and the maximum load of the object was defined as FL_{max}. The ratio between FP_{peak} and FL_{max} was defined as the force ratio, a sensitive parameter for evaluating the capability of a hand to adjust pinch force regarding changes in load of the lifting object.

2) SECONDARY OUTCOME

Purdue Pegboard Test (PPT) for healthy participants: PPT is used to evaluate hand manual dexterity and bimanual coordination of participants [25]. Participants are timed as they arrange and assemble pins, washers, and collars. It contains four subtests, involving the ability of participants to place pins in holes with the dominant hand, non-dominant hand, or with both hands simultaneously, as well as their ability to a pin-assembly task.

Minnesota Manual Dexterity test (MMDT) for healthy participants: In this study, the placing and turning subset of MMDT were used for measuring the speed with which a subject put the chess pawn from the top board into the bottom board and pick up chess with one hand and turn them with the other hand respectively. MMDT is considered a valid test for gross motor coordination assessment with test-retest reliability [26].

H. ADVERSE EFFECTS STUDY REPORT PROTOCOL

An adverse event in this study was defined as a headache, dizziness, nausea, or blurred vision, which could be attributed to the intervention and required a visit to a hospital. The increased risk was stated in the consent sheet participants were asked to sign.

I. STATISTICAL ANALYSIS

IBM SPSS 20.0 (IBM Corp., Armonk, NY, USA) for Windows was used for the statistical analyses conducted in this study. Statistics were used to describe the means and standard deviations of the characteristics of input data and outcome measurements. Normality in data distribution was examined with a Shapiro-Wilk's test. As normality assumptions were not met, the Mann-Whitney U test was used for continuous variables and the Fisher's Exact Test for categorical variable to compare data of patients at baseline. For stroke patients, the mixed-effect model was used to compare the difference in effects between the two interventions over time. The main effects of time, group, and the group-by-time interaction were evaluated. Gender was adjusted in this model as a confounding factor. The Wilcoxon signed-rank test was used to compare the difference between TS1 and TS2 for each treatment condition for stroke patients and the difference in change between the two interventions for healthy participants. The Friedman test was used to compare the testing outcomes at TH1, TH2 and TH3 time points for each intervention. The statistical significance level was set at $p < 0.05$. The Wilcoxon signed-rank test post hoc test was used to examine whether any differences existed between the time points. After correction, the statistical threshold was adjusted to $p < 0.016$.

IV. RESULTS

A. CHARACTERISTICS OF THE PARTICIPANTS

15 male and 15 female healthy adults between the ages of 20 and 39 (21.7 ± 2.2 years old) and 18 chronic-stroke participants were recruited in this study. TABLE 1 summarizes age characteristics, disease duration, and severity of affected upper extremities. The 18 chronic-stroke patients with mild to severe motor impairment were randomly allocated in either a MT or VRMT group. Age characteristics, disease duration, and severity of affected upper extremity did not differ statistically between groups, hence the effect of the MT or VRMT is not considered influenced by the demographics of the two groups. In addition, there were no reported adverse effects in this work.

B. EFFECTS OF VRMT ON YOUNG HEALTHY PARTICIPANTS

1) EFFECT OF VRMT ON PRECISION PINCH PERFORMANCE (PHUA TEST)

A statistically significant difference was detected in the force ratio using the PHUA test, in between treatments, between FP_{peak} and FL_{max} (Wilcoxon signed-rank test, $Z = -2.693, p = 0.007$). Also, a significant treatment effect was detected for the precision pinch performance (Wilcoxon signed-rank test, $Z = -3.293, p = 0.004$) of the young, healthy participants who received VRMT, based on the PHUA results shown in TABLE 2.

2) EFFECT OF VRMT ON THE HAND FUNCTION

Results of the subtests in the PPT and MMDT revealed significant within-group differences in both the VR-based treatment and traditional MT. However, the change in the results of hand function tests for both hands did not show a statistically significant between-group difference (TABLE 2).

TABLE 2. Effectiveness measures using PHUA, PPT, and MMDT for each intervention group for young healthy participants.

Effectiveness (index)	VRMT (n = 30)				MT (n = 30)				Difference between treatments			
									TH1-TH2		TH1-TH3	
	TH1	TH2	TH3	p-value	TH1	TH2	TH3	p-value	p-value	z-score	p-value	z-score
PHUA (FRpeak)	2.42±.16	2.31±.15*	2.36±.14†	.004	2.42±.16	2.40±.14	2.39±.15	.561	.007	-2.693	.673	-.422
PPT (DH)	16.6±1.5	17.8±1.4*	18.0±1.6†	.000	16.6±1.5	17.4±1.5	18.0±1.6	.000	.276	-1.089	.706	-.377
PPT (NDH)	15.4±1.6	17.2±1.3*	16.9±1.5†	.000	15.4±1.6	16.7±1.4*	16.8±1.8†	.000	.173	-1.364	.726	-.350
PPT (BH)	13.3±1.3	14.4±1.4*	14.4±1.5†	.000	13.3±1.3	14.3±1.3*	14.8±1.4†	.000	.939	-.076	.176	-1.352
PPT (Assembly)	43.3±5.5	48.0±5.6*	48.6±5.6†	.000	43.3±5.5	47.3±6.2*	49.3±5.8†	.000	.782	-.276	.621	-.494
MMDT (Placing)	111.8±10.1	104.9±9.07*	100.7±8.31†	.000	111.8±10.1	106.5±10.3	101.2±9.1	.000	.490	-.690	.326	-.981
MMDT (Turning)	91.8±12.9	83.0±11.5*	75.3±8.3†	.000	91.8±12.9	82.0±10.6	75.6 ±9.0	.000	.544	-.606	.968	-.040

Values are presented as mean±SD
Wilcoxon signed-rank test was used to compare the effects of the different interventions. The level of significance was set at $p<0.05$.
The Friedman test was used to detect the significance of training effects for each group. Wilcoxon signed-rank test post hoc test was used to examine whether any differences existed between the time points. The level of significance was set at $p<0.016$.
FR_{peak}: Force ratio (FP_{peak}: FL_{max}); PPT: Purdue Pegboard Test; DH: Dominant hand; NDH: Non-dominant hand; BH: Both hands; MMDT: Minnesota Manual Dexterity Test.
n: indicates the number of participants.
*: Significant difference between TH1 and TH2.
†: Significant difference between TH1 and TH3.

C. EFFECTS OF VRMT ON STROKE PATIENTS WITH HEMIPLEGIA

1) EFFECTS OF THE INTERVENTION ON MOTOR PERFORMANCE OF UPPER EXTREMITY MEASURING BY THE FMA FOR STROKE PATIENTS

A significant group-by-time interaction effect estimated by mixed effect model was found on the total score of FMA (p = 0.033) and hand part of FMA (p = 0.008) TABLE 3. Compared to the MT group, the participants who received VRMT has better improvement on motor function of the upper extremity. Results for the total score and hand component of FMA showed significant improvement in the VRMT group. The score of the wrist component revealed a tendency that failed to reach significance within group differences at endpoint (Wilcoxon signed-rank test, $Z = -1.890, p = 0.059$). However, there was a lack of significant within-group differences in the total and sub-score of the FMA test in the MT group.

V. DISCUSSION

A VR-based mirror neuro-rehabilitation system suitable for sensorimotor control training was developed in this study. Results of this study supported that VRMT feasibly enhances the sensorimotor performance of a hand for both healthy participants and patients having suffered a stroke. Subjects who received VRMT showed a better improvement in motor performance compared to those who received traditional MT.

Our findings suggest that VRMT resulted in better clinical effects for upper limb motor facilitation than traditional MT, including hand FMA sub-score and total score. A recent review identifies that using VR technology as a medium to deliver motor rehabilitation is a new direction for leading to functional gains in the paretic upper limb [27]. In our study, the add-on of VR to MT with task-specific training shows superior treatment effects on motor performance than the effect of MT with task-specific training alone. This added effect might be attributed to the immersive and immediate visual representation of the bilateral hand movement provided by the VRMT program. In addition, VRMT applied for a large amount of hand movement training might be the main reason leading to benefit for the recovery in the entire upper limb, particularly in the hand part. However, the observed change in the FMA score did not reach the value of minimal detectable change [28]. This might be due to the limited sample size recruited in this study. It is noteworthy that an earlier VR-based MT research did not reveal significant improvement for the FMA score of Upper Extremity [29]. As MT involving bilateral movement aids motor recovery by rebalancing cortical activation between hemispheres in stroke patients, thus, the image of the non-paretic upper limb suppressed in their system seemed to be the reason to weaken effect of VRMT on upper extremity motor facilitation [30].

TABLE 3. Effectiveness measures using FMA test for each intervention group for the stroke patients.

Measurement \ Group		VRMT group (n=9)		Traditional MT group (n=9)		Mixed-effect model						
						Group			Time			Group*Time
	Variables	TS1	TS2	TS1	TS2	β	SE	*p*-value	β	SE	*p*-value	*p*-value
Fugl-Meyer score	Total Motor Score	43.4±14.	46.7±12.7*	28.3±18.1	29.2±18.4	15.3	8.0	.074	0.9	0.7	.228	.033
	Shoulder/Elbow/ Forearm	26.7±6.2	27.3±6.0	17.2±9.2	17.8±9.1	9.7	3.8	.022	0.6	0.4	.194	.850
	Wrist	4.7±3.4	5.4±3.1	2.1±3.3	2.6±3.9	2.8	1.6	.108	0.4	0.3	.140	.422
	Hand	8.4±5.3	9.7±4.4*	4.9±6.1	4.9±6.1	3.4	2.8	.236	0.0	0.3	1.00	.008
	Coordination	3.7±1.2	4.2±.8	4.1±.3	4.0±.0	-0.5	0.4	.307	-0.1	0.3	.665	.079

Values are presented as mean±SD. β= estimation; SE= standard error.
Mixed effect model was used to compare the effects of the different interventions.
Wilcoxon signed-rank test was used to compare the difference between TS1 and TS2 for each treatment condition.
The level of significance was set at $p<0.05$.
*: Significant difference between TS1 and TS2.

Previously reported positive effects by MT on dexterous hand performance [31] and bimanual skills in healthy people [32] were supported by the obtained results of PPT and MMDT following both the VR-based and traditional MT of this study. The visual mirror feedback is a strategy for improving motor function, based on the theory of motor network boosting in the brain, potentially enhancing top-down motor facilitation during action observation of a hand [33], [34]. Furthermore, visual mirror feedback might promote the recruitment of ipsilateral motor pathway of the trained hand [35]. Both MT and VRMT provide both sensory and motor input, with positive effects on the motor responses [36], such as motor planning and spatial efficiency in movement execution [37], leading to facilitation of bimanual skills [38], [39].

The force ratio detected by the PHUA test (the capability of participants to force adjustment through interaction between the object and hand), improved drastically with the add-on effect of VR to MT, compared to the traditional MT. Our result was similar to the findings of a recent study, which showed that use of a VR-based mirror training system was capable of improving hand performance significantly for young participants [40]. Recent evidence from neuroimaging shows that the functional brain connectivity for a patient was changed after receiving AR-based mirror training, through the examination of functional magnetic resonance imaging [41]. Either augmented or virtual reality is a computer-generated graphical environment that offers an immersive environment to affect engagement of the user. In the current study, a VRMT neuro-rehabilitation system was verified in a sample of healthy participants and revealed clinical feasibility. Compared to MT itself, VRMT, a kind of augmented multisensory feedback, facilitates neuroplasticity through more convincing vision illusion, leading to a better effect on sensorimotor control. As far as we know, there is little available research investigating the feasibility of immersive VRMT for upper limb training [29]. In combination with related techniques of VR and MT, the system optimized neuro-rehabilitation practice through multisensory stimulation. Motor cortex priming could, therefore, enhance motor control.

In the current study, a VRMT system was developed as a remedial approach for motor impairment. Of note, hand function and precision pinch performance of healthy young participants has been improved even receiving VR-based MT intervention once. Moreover, the current study showed beneficial effects of a newly developed treatment paradigm, compared to the traditional MT, on the controlling of motor performance for chronic stroke patients. Despite the cost of VR-mediated MT being much higher than traditional mirror box training, using VR could add a level of limb presence and perception for the patients [42], which increases effectiveness in motor learning [43]. However, obtained results cannot be generalized, because of the limited number of recruited stroke patients, which is the main limitation of this study. In addition, the limited sample size might be the key to why the improvement in sub-score of shoulder, wrist and coordination did not reach statistical significance for stroke patients in both treatment conditions. Another limitation of this work is the difference between baseline FMA scores for MT and VRMT group (28.3 ± 18.1 and 43.4 ± 14.5 respectively), which might affect the expected effect of VRMT training. Moreover, the not so realistic visual representation of bilateral hand displayed on the goggle is the third limitation of this work. Future VRMT studies should investigate the long-term effects of VRMT on the motor deficit of the upper extremity of brain-injury patients, and it would be also necessary to determine the optimal dose of VRMT therapy. The next step in the current research topic would be to create a more realistic virtual scene, in order to improve patients' engagement in the intervention.

VI. CONCLUSION

The findings in this study indicate that the VRMT system has potentially positive effects on the functional performances of hands for healthy participants. In addition, applying VR technology to MT, can help restore motor capability of the upper extremity in chronic stroke patients, using the experience of immersive virtual feedback and visual illusion of unaffected hand movements.

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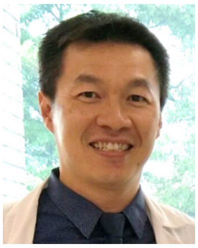

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