Camera-based Mirror Visual Feedback: Potential to Improve Motor Preparation in Stroke Patients

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***Abstract*— Mirror visual feedback (MVF) is used widely for motor recovery after stroke, but an optimal training setup and systematic procedure are lacking. New optimization strategies have been proposed, one of which is a camera technique. We investigated the effects of a camera-based MVF setup on motor function and motor processes upstream for upper-limb rehabilitation. Seventy-nine stroke patients were assigned randomly to the MVF group (MG; N = 38) or conventional group (CG; N = 41), which respectively received camera-based MVF and dosage-equivalent physiotherapy or/and occupational therapy for 1 h/day and 5 days/week for 4 weeks. Two clinical scales were used to quantify the effect of the intervention methods: the Fugl–Meyer Assessment-Upper Limb (FMA-UL) subscale and Barthel Index (BI). The hand laterality task was used to evaluate the ability of mental rotation, including the reaction time (RT) and accuracy (ACC). All measurements improved significantly for both groups following intervention. FMA-UL was improved significantly in the MG compared with that in the CG. In lateralization tasks, the RT of the MG was significantly shorter than that of the CG at the endpoint. For all patients, judgments for the affected side were significantly slower and less accurate than for the less-affected side. Subgroup analyses suggested greater benefits of motor function, the activities of daily life, and mental rotation were achieved in subacute patients after MVF. A trend towards greater improvements in motor function for patients with severe–moderate motor impairment and patients with right-hemisphere damage were also revealed. Camera-based MVF improved the motor function and ability of mental rotation for stroke patients, especially for patients in the subacute stage, which indicates the potential to improve motor preparation. Further studies might combine mental rotation with electroencephalography to investigate the neuro-mechanism of MVF.**

***Index Terms* — Mental rotation, mirror therapy, motor preparation, stroke**

I. Introduction

SINCE Ramachandran demonstrated that phantom pain could be relieved through mirror visual feedback (MVF) in 1992 [1], MVF has been the focus of much interest and debate in terms of stroke rehabilitation [2]–[6]. It is believed that MVF provides visual feedback, also called "mirror illusion", to promote motor recovery and the ability to undertake the activities of daily living (ADL), especially for upper-limb dysfunction in patients with hemiparesis [4]–[8]. Neural modulation of the motor cortex, facilitation of cortical spinal output and reversion of learned non-use syndrome are thought to be the underlying mechanisms of MVF [5], [7]–[9]. Studies which evaluated the instant effect of MVF showed that activity of motor cortex could be modulated directly by MVF, especially for the primary motor cortex [9]–[11]. As a long-term effect, repeated modulation of motor cortex could result in adaptive neural reorganization, including enhanced functional connectivity and reestablishment of interhemispheric balance, which was demonstrated in some functional magnetic resonance imaging (fMRI) studies in stroke patients who had a gain in motor function after MVF treatment [5], [7]. These instant and long-term effects indicated that neural modulation, adaptive reorganization, and facilitation of corticospinal projections might be the underlying neuromechanisms of MVF.

Currently, MVF is in wide use in neuro-rehabilitation based on the belief that the visual stimulus can cause cortical reorganization and enhance the performance of paretic limbs [4], [6]. In studies over the past two decades, a plain mirror or "mirror box" has been used as a conventional setup to form an illusionary hand. Patients were asked to perform unilateral or bilateral symmetric motor tasks and persuade themselves that the impaired hand could move as well as the active one [12], [13].

Recently, to provide better mirror illusion feedback, some scholars proposed new strategies for presenting MVF: mirror glasses, virtual reality (VR) and cameras/videos [14]–[18]. However, some of these new methods have two major limitations: an inadequate sense of ownership, and imperfect setup and procedure. Anamorphic or computer graphic-generated hands and the limited space of the device may not be

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able to enhance the perception of ownership. In addition, few studies have reported a systematic procedure or the effectiveness of these new strategies on stroke patients. Among them, camera technique-based MVF has been the focus of much interest. Giraux and Sirigu used a video-optical system to project the pre-recorded movements of the hand on the affected side to form a mirror illusion for patients with avulsion of the brachial plexus [15]. Increased activity of the contralateral motor cortex was reported, but the visual feedback coming from pre-recorded movements could not match real-time movements. Mehnert et al. used a video webcam to stream the patient's hand covered by a black box, and then displayed the real-time video as MVF [17]. However, unilateral visual feedback and the limited view field of this setup could affect the efficacy of the induced mirror illusion, and their study recruited only healthy subjects. More recently, additional camera-based mirror therapy (MT) equipment with bilateral visual feedback has been used, which has shown the feasibility of a camera technique [10], [15]–[17], [19]. Several studies have tried to ascertain the efficacy of camera-based MVF [15]–[17], [19]. Lee and colleagues reported enhancement of upper-limb function in a randomized controlled trial (RCT) on stroke patients using camera technology based on VR reflection apparatus, but asymmetric training was employed instead of the bilateral symmetrical movements of MT [19]. However, other studies were mainly small-scale case studies, exploratory studies, or studies recruiting healthy subjects, which had a low level of evidence for clinical practice [15]–[17]. To minimize bias and determine the casual relationship between camera-based MVF treatment and effect in stroke patients, RCTs which are recognized as the "gold standard" for clinical trials were used in the present study [20].

We investigated the effects of a camera-based MVF setup on motor function and the ability of mental rotation for upper-limb rehabilitation for stroke patients. We hypothesized that camera-based MVF might improve the performance of motor function with the potential to modulate the motor process upstream.

II. Methodology

A. Camera-based MVF

A camera-based MVF setup (Figure 1), also called a "mirror box" (1200 mm × 940 mm × 702 mm), was used to present MVF instead of a plane mirror. Two cameras were mounted on the top of the mirror box to capture the movements of the less-affected hand of stroke patients [21]. A 23.8-inch light-emitting diode screen (resolution: 1920 × 1080 pixels) was fixed on the mirror box to present visual feedback. During the intervention, patients were seated in front of the mirror box at a comfortable height and placed their hands in the box. Both hands of the patients were placed underneath the screen so that the direct view of both hands was blocked. When using this setup, there was no need for patients to observe the hand from the side, which reduced cervical-posture tension and weight shifting [22]. The picture of the less-affected hand and its mirrored image were shown on the screen, which was superimposed just above the real hands. All the hand images presented on the screen were of similar size as the real hands. Based on the structural design and digital visual feedback, this setup should provide a better sense of ownership and reduce the posture pressure. Only one recent study used a similar setup to explore clinical feasibility [16], and used a different system to that in the current study. Besides, additional auto-verbal instructions and standard-motion guide videos were provided during training for more self-disciplinary training (guide videos appeared thrice at the start of training).

B. Participants

Patients were recruited from Huashan Hospital (Jing'an Branch), Fudan University (Shanghai, China). The inclusion criteria for this study were stroke patients: (i) diagnosed by computed tomography or MRI between 2 weeks and 1 year following stroke onset; (ii) aged 25–75 years; (iii) could identify the laterality of the hands. Patients were excluded if they had: (i) severe cognitive disorder (Mini-Mental State Examination <23); (ii) psychiatric disorder or expressive apraxia; (iii) severe spasticity in any joints of the affected side (Modified Ashworth Scale >2). Ninety patients matching the described criteria were enrolled in this study. This was a single-blinded, pretest–post-test, RCT (Figure 2). All assessments were conducted by an independent researcher blinded to the assignment. After baseline measurements, eligible patients were stratified using motor-deficit severity (cutoff point was a Fugl–Myer Assessment-Upper Limb (FMA-UL) score of 35) [23] and days from onset (cutoff point was 6 months) [24]. Patients were assigned randomly to the mirror visual feedback group (MG; N = 45) or conventional group (CG; N = 45). The allocation sequence was based on a computer-generated random-number table. Sealed and numbered envelopes were created to allocate patients to the MG or CG. An envelope was extracted for random grouping when an eligible patient was recruited. The randomization program and all the assignments were conducted by another independent researcher. Each participant was informed of the nature of the study and signed informed-consent forms approved by the Institutional Review Board of Huashan Hospital (KY2017-230).

C. Intervention Protocol

For patients in the MG, an experienced therapist helped them to relax muscles and sit in front of the mirror box with screen height adjusted for comfort when he/she placed both hands into the box. Patients were asked to symmetrically move both hands synchronously while watching the video feedback on the screen and persuade themselves that the moving hand on the affected side was the true image of their affected hand. The therapist needed to adjust the difficulties of the motor training tasks to avoid global synkinesis while the less-affected side was moving. A systematic procedure was employed during camera-based MVF training, which provided basic motor training and functional training. It contained 25 basic training items focusing on the hand, wrist, and forearm, of which four were employed in the current study: (i) forearm pronation/supination; (ii) wrist extension; (iii) thumb abduction; (iv) gripping (Figure 3). It also contained 24 tool-based items. Each item would be repeated 30 times per session for two sessions under verbal instruction. All patients in the MG received 1-h training (30 min for each session) per day, 5 days a week, for 4 weeks. After the MVF intervention, the therapist administered some stretching and massage to help patients relax. During training, the therapist gave the necessary instructions to help patients focus on the screen and persuaded them to imagine immersing themselves in the mirror illusion. Typical instructions were "Now, you need to keep your eyes on the screen, pay attention to the reflection of the hand and try to imagine and persuade yourself it is your affected one" and "During training, you are required to move both your hands synchronously. However, if you feel it is hard to move the affected limb, moderate trying or rest will be a recommendation for you."

Patients in the CG also received dosage-equivalent treatments with the help of an experienced therapist, including the same repetitions of each item (60 times for each item, four items for each daily intervention) and training duration (1 h per day) as the MG. The training items for CG patients contained physiotherapy and occupational therapy focused on the hands, wrist, and forearm, such as passive supination of the forearm or active extension of the wrist, which were based on the motor tasks for MG patients. Furthermore, stretch and massage were administered for patients for muscle relaxation in the CG. Moreover, patients in the CG received 1 h of training per day, 5 days a week, for 4 weeks. All these therapies were in addition to routine treatments in the hospital for both groups.

D. Outcome Measurement

We included the clinical measurements of motor impairment and daily function. The ability of mental rotation was assessed by hand laterality tasks, as discussed below.

1. Clinical Measures

The FMA-UL subscale was used to assess motor impairment of the upper limbs [25]. This assessment focused on motor control with a three-point ordinal scale from 0 to 2 (0 = cannot perform; 1 = can perform partially; 2 = can perform fully). Moreover, the Barthel Index (BI) was employed to compare improvements in the performance of daily functions [26].

2. Ability of Mental Rotation

During the hand laterality task, patients were seated ≈50 cm in front of a screen. Photographs of two types of gesture (i.e., an open hand with all fingers extended and a closed fist) of right and left hands at four angles (0°, 90°, 180°and 270°) were displayed with equal probability on the screen (16 photographs in total; Figure 4).

The task contained two blocks of 320. In each block, there were 160 trials (16 judgment types × 10 repetitions). Patients were requested to judge whether the picture was a left or right hand, and to press the response button on the keyboard using their less-affected hand as quickly and accurately as possible. The overall response time (RT) and accuracy (ACC) of the judgment of the affected and less-affected hand were acquired separately.

E. Data Analyses

We compared the baseline characteristics of the MG and CG using chi-square tests (for sex, stroke types, and stroke locations), independent *t*-tests (for age, time after stroke onset) and Mann–Whitney *U*-tests (for Brunnstrom stages, distal and proximal parts). FMA-UL and the BI were calculated by repeated measures analysis of variance (ANOVA) taking time (two levels: before intervention and after intervention) as a within-subject factor and group (two levels: MG and CG) as the between-subject factor. Three-way repeated measures ANOVA taking hands (two levels: affected hands and less-affected hands) as another within-participant factor was done for ACC and RT in the hand laterality task. Spontaneous recovery is an important confounder of treatments in the first 6 months after stroke [24]. Hence, subgroup analyses based on the time since stroke onset (subacute (<6 months) *vs.* chronic (>6 months)) were done. Additional subgroup analyses were based on levels of impairment of upper-limb movement (severe–moderate, FMA-UL ≤34 *vs.* moderate–mild, FMA-UL ≥35) [23] and the side of the damaged hemisphere (left *vs.* right) to provide information about possible trends and guide future clinical trials. The underlying assumptions of our model were checked thoroughly by the Shapiro–Wilk's test for the normality of distribution, and Levene's test for the homogeneity of variances. Results are the mean with standard deviation (SD). Significant levels for all tests were set at 0.05. The Bonferroni procedure was used to adjust *p* values for multiple testing. All statistical analyses were done using SPSS v22 (IBM, Armonk, NY, USA).

III. RESULTS

Ninety patients matching the inclusion criteria were recruited. They were assigned randomly to the MG (N = 45) or CG (N = 45). Eleven patients (7 in the MG and 4 in the CG) could not complete all trials in the intervention in hospital due to logistical problems. Seventy-nine patients (MG, N = 38; CG, N = 41) completed the intervention with no adverse events. The MG and CG showed no significant differences in sex, age, side of stroke, months after stroke onset, stroke type or Brunnstrom stages [27] (Table I).

A. Clinical Measurements

Repeated measures ANOVA on FMA-UL showed a significant time × group interaction ($F_{1,77}$ = 8.71, p = 0.004). Further analyses demonstrated a comparable baseline of FMA-UL between the MG and CG (MG = 25.66 ± 17.63, CG = 18.85 ± 16.38, p = 0.08). After intervention, FMA-UL was higher in the MG compared with the CG (MG = 32.66 ± 17.90, CG = 22.80 ± 17.37, p =0.02). This finding suggested that patients in the MG obtained better restoration of motor function than those in the CG (see Figure 5). For daily function, no significant interaction was found for the BI ($F_{1,77}$ = 1.60, p = 0.21), but a significant main effect of time ($F_{1,77}$ = 155.28, p = 0.03) and group ($F_{1,77}$ = 4.72, p = 0.03) was obtained. The BI measured after intervention was improved significantly compared with before intervention in the MG (BI_{pre} = 68.03 ± 22.7, BI_{post} = 82.53 ± 17.84, p < 0.001) and CG (BI_{pre} = 59.51 ± 22.04, BI_{post} = 71.34 ± 19.69, p < 0.001). The data were not powered sufficiently for subgroup analyses to detect treatment differences. Nevertheless, some trends and interesting results were obtained. Subgroup analyses suggested significant effects on FMA-UL in subgroups of subacute patients, patients with severe–moderate motor impairment, and those with a damaged right hemisphere (Table II). Further analyses indicated that FMA-UL scores were improved significantly for subacute patients (p = 0.047) or patients with severe–moderate impairment of movement (p = 0.006) after MVF intervention compared with the CG. However, no significant group differences were found for FMA-UL in the subgroup of patients categorized as having right-hemisphere damage. To investigate potential trends, the independent t-test was used, and it confirmed the significance of absolute changes of FMA-UL scores in the subgroup with right-hemisphere damage between the two groups (ΔMG: 7.25 ± 4.59; ΔCG: 3.00 ± 4.43; p = 0.004). This finding suggested that patients with right-hemisphere damage in the MG would achieve greater benefit in motor function. Moreover, a significant effect on the BI in the subacute subgroup was found ($F_{1,53}$ = 4.943, p = 0.03), and further analyses revealed that subacute patients in the MG improved more than those in the CG for the BI (p = 0.043). However, no significant effects were found on BI scores in the other two subgroups.

B. Behavioral Performance in the Hand Laterality Task

Repeated measures ANOVA on RTs suggested a significant time × group interaction ($F_{1,77}$ = 5.02, p = 0.03). Further tests showed that the main effect of time was significant only in the MG ($F_{1,37}$ = 6.91, p = 0.01) and not in the CG ($F_{1,40}$ = 0.07, p = 0.79). A significant main effect of group was found after intervention ($F_{1,77}$ = 5.803, p = 0.018), which demonstrated that RTs decreased significantly after intervention in the MG (pre: 4.21 ± 1.33 s, post: 3.75 ± 0.93 s), compared with the CG (pre: 4.48 ± 1.77 s, post: 4.52 ± 1.74 s). These results suggested that the behavioral performance in the hand laterality task after stroke could be improved by MVF. Further paired t-tests showed the RT improvement by MVF was more significant for the affected hand (p = 0.004) than for the less-affected hand (p = 0.12) (Figure 6). Moreover, a significant main effect of the hand on RTs ($F_{1,77}$ = 35.09, p < 0.001) was investigated, which indicated that patients took more time to recognize pictures of the affected hand than the less-affected hand (affected: 4.49 ± 0.18 s, less-affected: 4.00 ± 0.14 s). These results demonstrated a deficit to recognize the affected hand after stroke. Repeated measures ANOVA for ACC demonstrated no significant effects (all p > 0.146) (Figure 7). However, the significant main effects of time ($F_{1,77}$ = 73.78, p < 0.001) and hand (F1,77 = 81.32, p < 0.001) on ACC were shown, which indicated that all patients could complete the hand laterality task with higher ACC after the intervention (pre: 83.31 ± 1.47 %, post: 92.47 ± 0.90 %). Moreover, patients could recognize the pictures of less-affected hands more accurately compared with the affected hand (less-affected: 91.92 ± 0.94 %, affected: 83.84 ± 1.39 %). Subgroup analyses on RTs showed a significant interaction of time × group ($F_{1,53}$ = 4.354, p = 0.042) in the subgroup of subacute patients. A significant main effect of time was revealed in the subgroup of the MG ($F_{1,25}$ = 6.972, p = 0.014) and a main effect of group was found after intervention ($F_{1,53}$ = 5.563, p = 0.022). This finding indicated RTs decreased significantly only in subacute patients in the MG (pre: 4.64 ± 1.35s, post: 3.88 ± 1.14s) compared with the CG (pre: 4.99 ± 2.23s, post: 4.88 ± 2.21s). However, no significant effects on RTs were found in other subgroups; moreover, no significant differences in ACC between the two groups were established in subgroup analyses.

IV. Discussion

The present study confirmed the feasibility and effectiveness of camera-based MVF in improving upper-limb function and mental abilities in stroke patients. We showed a trend of the effect of MVF on motor preparation which will be helpful for future study. We also provided evidence of a standard, systematic procedure for MT in the clinic using camera-based MVF.

Compared with patients in the CG, the motor function of patients in the MG improved significantly after intervention, as indicated by FMA-UL (Figure 5). This finding is in line with other studies on MVF [2]–[4]. MVF has been recognized as a neurorehabilitation tool to promote motor recovery after stroke and unilateral pain relief over the past two decades [1], [7], [9], [18]. With the help of the mirror illusion and immersive experience created by MVF, a mechanism can be postulated: improvement in attention towards the affected limb, and a stronger sense of ownership and awareness of limb movements, increases the perception of the paralyzed limb, which reverses the learned non-use and contributes to better motor function [4], [7].

However, no significant difference was found in the BI between groups. Unimpaired hand functions are necessary for people to participate in the ADL. The Brunnstrom stages of motor recovery consist of six sequential stages, with a higher stage indicating better motor recovery [27]. In the present study, distal and proximal parts (upper limb and hand) were used. According to the baseline evaluation (Table I), patients recruited in the present study might have had upper-limb spasticity and synergic movement patterns. Moreover, they had minimal voluntary movements of the upper limbs, which could hinder their motor performance and improvements in the ADL. This might be an interpretation for the non-significant comparison of the ADL evaluated using the BI between the two groups. Camera-based MVF was designed to promote recovery of function of the hands and upper limbs, but the baseline status of motor function might limit improvement of performance of the ADL. In addition, the modified BI would be more sensitive to small changes in functional activities because the scoring and number of categories have been changed [28].

Although the data presented here could not be used to detect treatment differences in subgroups, subacute patients in the MG showed significant improvements in motor function, ability to undertake the ADL, and performance of the hand laterality task, compared with the CG. According to other studies [2], [7], [27], [29], subacute patients seem to achieve more from MT. As visual-guided motor-imagery therapy [30], MVF could hinder the development of learned non-use in the subacute stage by increasing the perception of the affected limb. Besides, spontaneous recovery should also be taken into account because it is an important confounder of interventions in the subacute stage [24]. Some studies have reported that spontaneous recovery has great individual variability and limited impact on motor-function recovery [31], [32]. Moreover, in the present study, FMA-UL gains in subacute patients after MT exceeded those estimated in the spontaneous-recovery patterns reported by Duncan et al. [33]. Therefore, in the present study, spontaneous biologic recovery might have accounted for some of these improvements, but a camera-based MVF intervention may also have had a role. Significant improvements in motor function were also observed in the subgroup of patients with severe–moderate motor impairment in the MG. Dohle et al. reported that patients with severe hemiparesis gained more function after MT than after conventional therapy [7]. This finding could be because there was a stronger experience of mirror illusion when patients could not move their limbs or hands, resulting in a greater therapeutic effect of MT. Moreover, subgroup analyses also suggested a trend towards greater improvement of motor function for patients with right-hemisphere damage in the MG. Bernspng and Fisher [34] reported that patients with right-hemisphere lesions had greater impairment in coordinating two body parts. The observed trend could be interpreted to be due to the potential of MVF for improving inter-limb coordination *via* bilateral movement exercises [9]. A larger parieto-frontal network in the right hemisphere for visuospatial tasks [35] might have also contributed to motor recovery after MVF.

MVF is effective visual stimulation for sensorimotor rehabilitation, and a real mirror is usually employed to provide MVF [1], [9]. Conventional MT, whereby a plain mirror is employed, is convenient and inexpensive treatment for upper-limb rehabilitation, but its design has disadvantages: weight shifting, balance control and postural pressure [22]. The lack of standard and systematic procedures/protocols during conventional MT could be circumvented by better supervised training. Besides, a real mirror can present only the perceptual and motor reflection of the right hand simultaneously and *vice versa*. Independent and randomized transformations of visual feedback, such as delayed MVF, could activate the relevant cortical structures, including the primary motor cortex, occipito-parietal cortex (especially the precuneus for visuo-motor transformation), and supplementary motor areas [10], [17], [36]. Thus, we used a novel camera-based MVF system for optimal setups, standard protocols, systematic procedures, and better-immersing mirror illusion. With evidence of improved motor performance, camera-based MVF could be an effective tool or adjunct treatment for upper-limb rehabilitation after stroke, a hypothesis that is consistent with a similar study [16]. Our results might also aid future applications as well as standard and systematic procedures of camera-based MVF in the clinic. We did not measure the sense of body ownership of patients specifically, but most of them reported the realism of both hands on the screen, and the feeling of illusionary feedback.

Mental rotation, as an implicit motor imagery, is associated with motor preparation [30], [37], [38]. Mental rotation was assessed by the hand laterality task, which was used to evaluate mental abilities, motor preparation, and activation of the motor cortex in a study on motor imagery [39]–[41]. Based on electroencephalography (EEG) and fMRI studies, motor preparation is impaired, besides the deficits of motion execution, for stroke patients [37], [45], [46]. Moreover, impairments of motor preparation remain even in patients with nearly normal motor function [45], [47]. Thus, we emphasized the training of mental abilities and motor preparation in stroke patients. Studies have demonstrated that motor imagery can enhance motor preparation by increasing activation within the prefrontal cortex and premotor cortex, which have important roles in motor preparation and planning [46], [48]–[50]. Recognized as visually guided motor imagery [30], MVF can activate cortical areas, which is similar to motor imagery and motor preparation [9]. Therefore, we postulated that camera-based MVF could mediate motor preparation via the component of motor imagery, which has been recognized as an underlying neuro-mechanism. In the present study, the increased performance of mental rotation, as suggested by the improvement of ACCs and reduction of RTs in the MG, indicated that MVF can increase motor preparation.

Studies on mental rotation have demonstrated that it is less accurate and/or slower to identify laterality of the hands for stroke patients [42], which was also investigated in the present study (RTs: affected, 4.49 ± 0.18 s, less-affected. 4.00 ± 0.14 s; ACC: less-affected, $91.92 \pm 0.94\%$, affected, $83.84 \pm 1.39\%$). The insufficient abilities of implicit motor imagery or impairments of motor preparation could explain the results for RTs of hand judgments [37]. In the current study, we showed significant reduction of RTs in the MG compared with the CG after intervention (Figure 6), which suggested that camera-based MVF had a better ability to enhance mental abilities and motor preparation in stroke patients.

Parietal lobes have critical roles in mental rotation, but the contributions of left and right lobes are controversial [37], [41], [43], [44]. Studies of patients with posterior right-hemisphere damage have shown impairments in mental rotation [43]. However, other studies have reported reduced abilities of mental rotation after left-hemisphere damage, and have suggested that activation of the left hemisphere is more closely related to the complexity and familiarity of the stimulus during mental rotation [44]. In the present study, subgroup analyses based on the side of hemisphere damage suggested no significant differences on RTs or ACCs between the MG and CG. One possible interpretation was the varying types and sizes of lesions, which hindered precise localization.

Recent studies have proposed that corticospinal output and more upstream motor processes (e.g., attention) and motor preparation are disrupted after stroke [45], [47]. However, clinical studies and clinical practices largely focus on motor execution/performance, which can hinder therapeutic efficacy. In the present study, increased performance of motor function and mental rotation ability were reported, which indicated the effectiveness of camera-based MVF and potential to mediate the motor process, especially motor preparation.

V. Conclusion

This study was the first to explore the feasibility and effectiveness of camera-based MVF for stroke patients and to use the hand laterality task to evaluate the capacity of mental rotation. Our results demonstrated the possibility of applying camera-based MVF for stroke patients and providing a systematic procedure of MT. Moreover, it also suggested the potential of camera-based MVF to mediate motor preparation for enhancing motor execution in stroke rehabilitation and data that could be used for further studies on the neuro-mechanism of MVF. Subgroup analyses suggested greater benefits of motor function, ability to carry out the ADL and mental rotation were achieved in subacute patients after MVF. Moreover, patients with severe–moderate motor impairment in the MG gained greater improvement in motor function. A trend towards greater improvements in motor function for patients with right-hemisphere damage in the MG was observed, which provides guidance for future studies of MVF.

As a limitation, only the RT and ACC of the hand laterality task were measured to evaluate the capacity of mental rotation. Event-related potential has been used in some EEG studies on motor imagery to evaluate the process of motor preparation and execution based on the high temporal resolution of EEG signals [37], [48], [51]. Exploring what has been altered in the rotation-related performance of the hand laterality task and in the motor process after MVF using EEG merits further study.

VI. References

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Fig. 1. The camera-based mirror visual feedback setup.

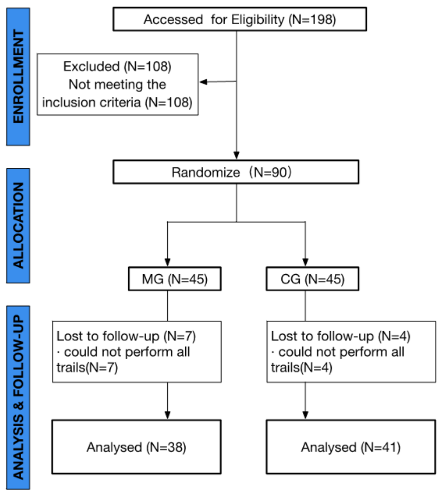

Fig. 2. Consort flow chart shows the study sample and procedures over the mirror visual feedback group (MG) and the conventional group (CG).

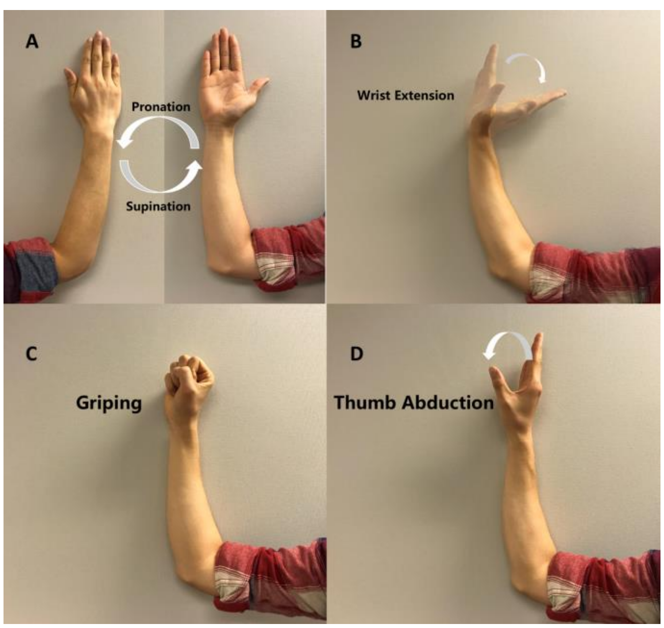

Fig. 3. The camera-based mirror visual feedback training items. **A:** forearm supination/pronation; **B:** wrist extension; **C:** thumb abduction; **D:** griping.

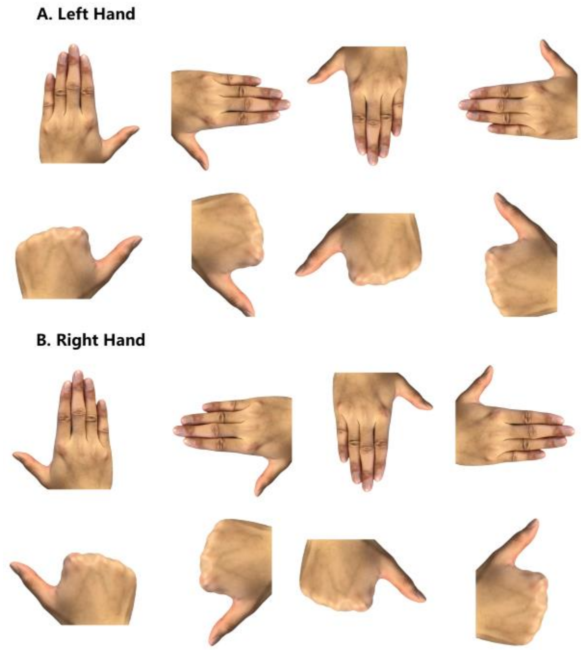

Fig. 4. Photos of hand laterality task. A: Left hand photos of the hand laterality task; B: Right hand photos of the hand laterality task

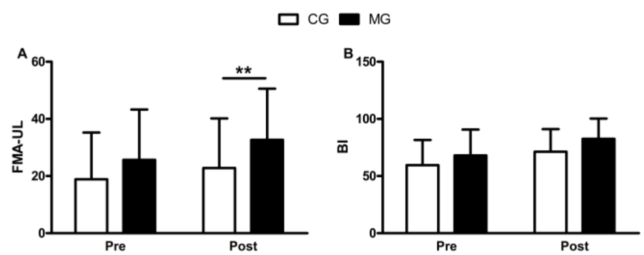

Fig. 5. Clinical measurements. **A:** the comparison of Fugl-Meyer Assessment Upper-Limb (FMA-UL) subscale between groups before and after the intervention. There was a significant difference in FMA-UL after intervention between mirror visual feedback group and conventional group. **B:** the comparison of the Barthel Index between groups before and after the intervention. Error bars represent the standard deviation of the mean. ** = $p < 0.01$.

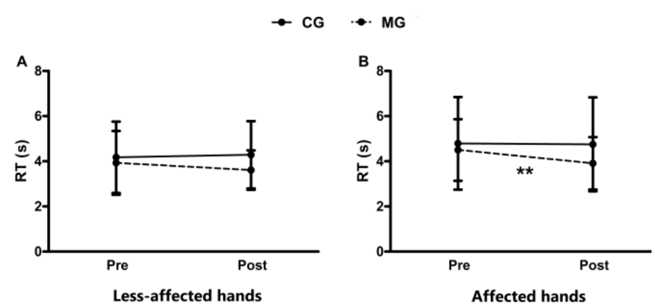

Fig. 6. The reaction time of (less)affected hands in hand laterality task within two groups. A significant improvement of affected hand RT was observed in MG. **A:** the comparison of less-affected hand RT before and after the intervention. **B:** the comparison of affected hand RT before and after the intervention. Error bars represent the standard deviation of the mean. ** = $p < 0.01$.

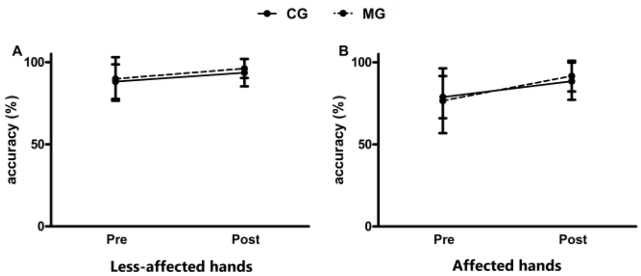

Fig. 7. The accuracy of (less)affected hands in hand laterality task within two groups. **A:** the comparison of less-affected hand ACC before and after the intervention. **B:** the comparison of affected hand ACC before and after the intervention. Error bars represent the standard deviation of the mean.

TABLE I
BASELINE CHARACTERISTICS OF PATIENTS

Characteristics	MG	CG	*P* - VALUE
Gender, N (%)			0.082
Male	23 (60.53)	33 (80.49)	
Female	15 (39.47)	8 (19.51)	
Age (SD), y	55.13 ± 8.67	53.47 ± 7.33	0.364
Side of Stroke, N (%)			1
Right	47.37	46.34	
Left	52.63	53.66	
Months after Stroke Onset (SD)	5.55 ± 5.17	4.88 ± 3.03	0.478
Stroke Type, N (%)			0.178
Ischemic	60.53	43.9	
Hemorrhagic	39.47	56.09	
Brunnstrom Stages (SD)			
Proximal	3.16 ± 1.15	2.95 ± 1.16	0.341
Distal	2.18 ± 1.29	2.26 ± 1.40	0.801

Abbreviations: MG, mirror visual feedback group; CG, conventional group.

TABLE II
RESULTS OF THE FUGL-MEYER ASSESSMENT UPPER-LIMB SUBSCALE FOR THE THREE SUBGROUPS

Subgroup	MG		CG		F	$p^{\#}$
	pre	post	pre	post		
Time after Stroke Onset						
	n = 26		n = 29			
Subacute (< 6m)	27.50 (17.58)	34.73 (17.21)	20.45 (17.67)	24.79 (18.66)	5.577	0.022
	n = 12		n = 12			
Chronic (> 6m)	21.67 (17.83)	28.17 (19.29)	15.00 (12.56)	18.00 (13.25)	3.140	0.090
Level of Function Impairment						
	n = 27		n = 33			
FMA-UL (0-34)	16.11 (8.72)	23.22 (10.53)	12.18 (8.80)	15.73 (9.97)	9.599	0.003
	n = 11		n = 8			
FMA-UL (35-66)	49.09 (10.12)	55.82 (8.16)	46.38 (10.20)	52.00 (7.75)	0.213	0.651
Side of Brain Damage						
	n = 20		n = 22			
Right	18.80 (15.71)	26.05 (15.97)	19.73 (17.29)	22.73 (18.55)	9.324	0.004
	n = 18		n = 19			
Left	33.28 (16.86)	40.00 (17.43)	17.84 (15.67)	22.89 (16.41)	1.183	0.284

Abbreviations: MG, mirror visual feedback group; CG, conventional group; FMA-UL, the Fugl-Meyer Assessment Upper-Limb subscale. # *p* values for interaction, according to repeated measures ANOVA