Development of an Innovative Robotic Mirror Therapy Device for Individuals with Hand Impairments

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***Abstract*—Mirror therapy is a widely recognized therapeutic method in rehabilitation, but its effectiveness is limited by the inability to move the weak hand of the patient during training. Additionally, research has highlighted the importance of haptic feedback and games for patient motivation, aspects that are missing in conventional mirror therapy. Therefore, this paper presents a robotic mirror therapy device for individuals with hand impairments, integrating vibration feedback and VR games. Utilizing sensors and actuators, the device measures the movement of the healthy fingers and mirrors it to the affected ones, creating the same movement trajectories on both hands. A screen on top of the device can be used to cover the hands of the patient during training while visualizing the VR games.**

The results of the device evaluation show that patients can execute finger curling movements with the index, middle, ring, and pinkie fingers (range of motion of 170°), along with upward and downward movements with the thumb (range of motion of 90°). Additionally, the delay time of the device that shows how fast it responds to the movements of the healthy fingers and mirrors them to the affected fingers was assessed and equals 118.6 ms. Furthermore, the user study showed that 91.67 % of the participants perceived a greater mirror therapy effect when using the MIRAπ device than performing conventional mirror therapy. Also, the clinical study revealed patient acceptance of the device, with high feasibility and usability ratings. Therefore, the proposed device indicates its potential for facilitating hand and finger rehabilitation and inducing patient outcomes. Also, the VR interface might be beneficial for patient motivation, which is often challenging in conventional mirror therapy.

***Index Terms*—Finger rehabilitation, mirror therapy, haptic feedback, VR interface**

I. INTRODUCTION

STROKE is a significant global health threat, ranking as the second-leading cause of death [1]. Approximately 47% of individuals survive the stroke but nearly 90% of those stroke survivors experience various types of disabilities [2]. Those include hand and finger paralysis, significantly impacting the quality of life of those affected by hindering their ability to perform everyday tasks. Together with nerve injuries, brain bleeding, and hand surgeries, a stroke is the cause of a large part of the motor function impairments in humans. To regain the function of the affected fingers, mirror therapy (MT), first described by Ramachandran et al. [3] is widely used. This technique is effective because it operates on the principle of visual illusion to deceive the brain. In combination with robotic technology, MT has become popular in rehabilitation. Advanced robotic systems can replicate the principles of conventional MT by employing motorized mechanisms and sensor-based feedback to create the visual illusion in combination with physical movements and haptic stimulation. In addition, games and virtual reality (VR) further enhance these devices to encourage active participation from patients. This advantage was highlighted with a study by Rapolinė et al. [4], which demonstrates that motivated patients tend to achieve better treatment outcomes compared to their unmotivated counterparts. Also, Howard et al. [5] demonstrated through a meta-analysis that VR rehabilitation programs are more effective than traditional physical rehabilitation programs. Many authors have published papers on rehabilitation devices, but there is a lack of robotic MT devices for finger training including games and haptic feedback.

In [6], Hernandez-Santos et al. present a wearable finger exoskeleton that features a linkage mechanism capable of generating flexion and extension movements of the fingers. Their design is capable of withstanding forces up to 40 N exerted by a linear actuator [6]. Lambercy et al. [7] engineered a robotic sensory trainer used to improve the sensory function of the hand and fingers. Stimulation devices on the device stimulate the index finger [7]. Stimuli were applied to 13 healthy people and their localization performance was evaluated. An average correct detection rate of 99.6% (± 0.6% standard deviation) was observed [7]. Decker and Kim [8] developed a hand exoskeleton rehabilitation device designed to enhance motor function and sensory training with additional tactile feedback and a VR environment. It was found that the device generates feedback forces up to 14 N for each finger and a joint angle of maximum 62 ° [8]. In contrast to exoskeletons, Li et al. [9] introduced a soft robotic glove equipped with sensors and force feedback for rehabilitation in combination with VR. This innovative design offers users tactile feedback, enabling them to perceive the force exerted by virtual objects. Their tests showed that within the tested current limit each motor can provide a maximum force of 3.14 N [9]. An exoskeletal hand aimed at facilitating MT was also introduced by Chang et al. [10]. Control of the exoskeletal hand is achieved through a sensor glove worn on the healthy hand. This device can also be used for home training and is already commercially used. An alternative approach to implementing MT was devised by Cisnal et al. [11] with a hand rehabilitation robot driven by electromyographical (EMG) signals. Their user performance test showed that there is an increase in the user's control over the movement of the robot due to the visual feedback [11].

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In [12], Chen et al. combined a wearable hand rehabilitation system with task-oriente MT. Their setup synchronizes a sensor glove with a motor glove to mimic natural hand gestures. The device can be used in combination with a user interface and a VR environment. The device allows patients to perform MT due to 16 finger gestures (accuracy of 93.32%) [12]. Mazzola et al. [13] introduced another innovative approach for MT using VR technology. Their research showcased a VR environment equipped with gesture-level hand tracking for a block stacking task [13]. A test they performed revealed that the speed to complete a task decreased in the virtual environment due to the difficulty of control in that environment [13].

The above-mentioned hand rehabilitation systems mostly concentrate on the development of the mechanism responsible for moving the affected hand. The mechanism for measuring the movements of the healthy hand is often neglected, and a sensor glove is used. However, it could be preferable to create a device capable of mirroring the movements of the healthy fingers onto the affected fingers, replicating the same movement trajectories on both hands. Furthermore, current devices often include either haptic stimulation or VR but rarely integrate both in combination with MT. Therefore, it is a clear opportunity to enhance rehabilitation outcomes by combining these modalities in a single device.

In this paper, an innovative robotic mirror therapy device for the rehabilitation of individuals with hand impairments creating the same movement trajectories on both hands for MT is introduced. To encourage the motivation of the patient, VR games are implemented which can be used with a portable screen. Furthermore, the device also provides vibration feedback to increase haptic sensitivity.

II. MIRAπ System

A. Hardware

The device consists of two main parts: one designed for the healthy hand, serving as the passive side, and another one for the affected hand, functioning as the active side. Figure 1 presents the two parts of the device with the electronics, including the PCB, housed within the two boxes. As the active and passive side look the same from the outside, their internal structures vary. The active side is equipped with linear actuators (PQ12-63-12-P, Actuonix) to move the affected fingers, while the passive side contains rotary position sensors (3382G-2-104G, Bourns) to measure the movement of the healthy fingers. The device can be reconfigured to accommodate patients who have weakness in either their left or right hand. This adjustment ensures accessibility for individuals regardless of their affected hand. The device is made of aluminum parts that are easy to clean, as it is intended to be used for study purposes in the future. To enhance the comfort of the patient during training, it has a 3D-printed arm support made of polylactide (PLA). It is covered with soft material, providing an ergonomic shape that stabilizes the forearm of the patient.

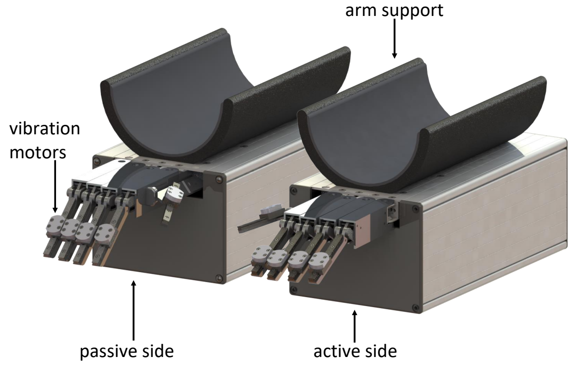


Fig. 1: CAD model of the device with active and passive side.

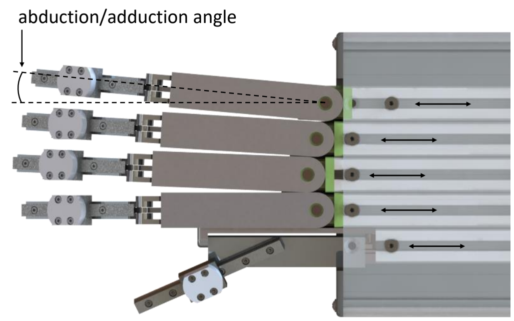


Fig. 2: Adjustable abduction/adduction angles of phalanges. The finger joints are displayed in a green color. The arrows on the right show the adjustable finger length.

Figure 2 shows that each finger support mechanism is adjustable in length to accommodate individual finger lengths, ensuring a personalized fit for each patient. In addition, each phalanx contains a joint in the back that makes it possible to adjust the finger abduction/adduction angles rather than keeping each finger completely straight. As shown in Figure 2, the mechanical design of the finger support of the thumb differs from the one of the other fingers because the thumb is intended to primarily execute abduction and adduction motions while the phalanges are responsible for flexion and extension movements. Therefore, two different finger support mechanisms, one for the thumb and another one for the phalanges, have been designed.

The device also incorporates a sliding mechanism on each finger support that can be seen in Figure 3. This mechanism facilitates movement when the fingers are positioned on the device and perform opening and closing motions. In addition, it allows for training across different finger sizes, accommodating both smaller and larger fingers. Inside the slider of each finger support mechanism, a vibration motor (FIT0774, DFRobot) is included to encourage the haptic sensitivity of the patient on the fingertips during training. Those sliders with the vibration motors are also used to fix the fingers of the patient on the device. Therefore, small magnets are attached to each finger of the patient that stick to the sliders. Furthermore, these magnets ensure that the fingers are not directly fixed to the device and can easily be removed at any time if the patient feels uncomfortable.

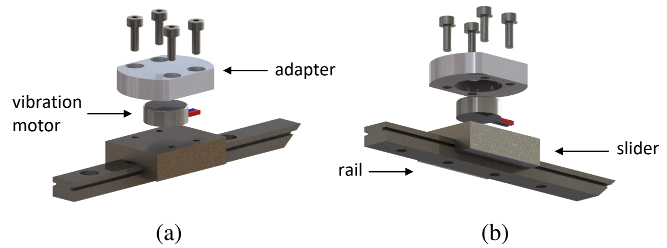


Fig. 3: Sliding mechanism with adapter and vibration motor; (a) top view isometric, (b) bottom view isometric.

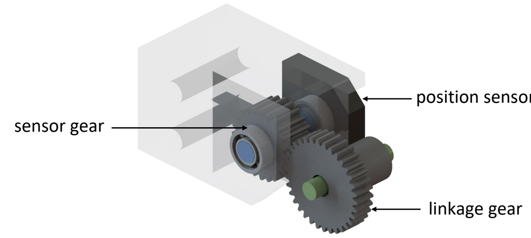


Fig. 5: CAD model of the gear box with the position sensor to create a more accurate measurement.

1) Active Side: The active side of the MIRAπ system moves the affected fingers of the patient during MT. As it can be seen in Figure 4 (a) and 4 (b), linear actuators drive the finger support mechanisms, facilitating flexion and extension motion for the phalanges and abduction and adduction movement for the thumb. To achieve movement with the finger support of the phalanges, a four-bar linkage mechanism was developed. This mechanism facilitates a natural finger movement and is the same for the phalanges of the active and passive side of the device. Because of this linkage mechanism, the shaft of the linear actuator requires connection to just one component of the mechanism, depicted in Figure 4 (a), to induce motion. On the other hand, the actuator shaft of the thumb needs to be connected to the wing of its finger support, see Figure 4 (b).

2) Passive Side: In contrast to the active side, the passive side of the MIRAπ system measures the movement of the healthy fingers of the patient during training with the device. Therefore, position sensors are included in the finger support mechanisms which can be seen in Figure 4 (c) and Figure 4 (d). Those sensors are connected to only one part of the mechanisms via a shaft and are turned when the position of the mechanisms changes. As Figure 4 (c) shows, a gearbox was developed for the finger support of the phalanges to increase the value range of the sensor which creates a more accurate measurement. It consists of two gears with a gear ratio of 1:1.42 and a module of 0.388. The sensor gear has 24 teeth and an outer diameter of 10 mm while the likage gear includes 34 teeth with an outer diameter of 13.2 mm. Via the green shaft in Figure 5, the linkage gear is connected to the mechanism of the phalanx which rotates the gear. Subsequently, the sensor gear is turned by the linkage gear and is connected to the position sensor via the blue shaft, as depicted in Figure 5.

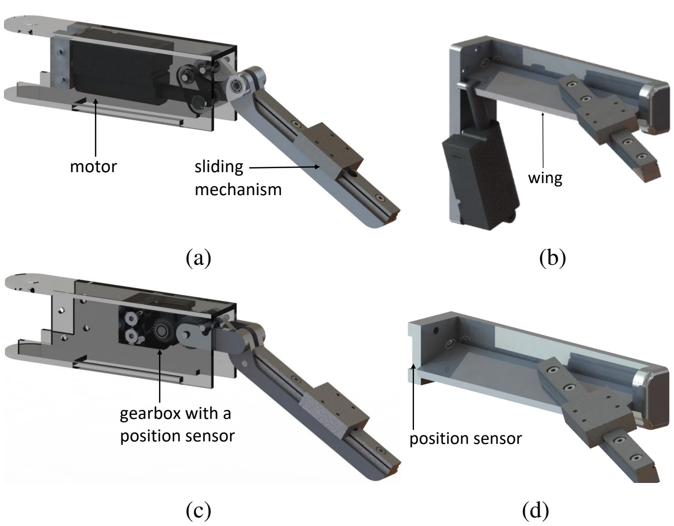


Fig. 4: Finger support mechanisms of the device; (a) motor mechanism of the phalanges, (b) motor mechanism of the thumb, (c) sensor mechanism of the phalanges, (d) sensor mechanism of the thumb.

B. Electronics Development

The device is controlled with a custom-made printed circuit board (PCB) which was specifically developed for this purpose. The PCB includes a programmable microchip (Atmega2560-16-AU, Microchip Technologies) used as a processing unit. This microchip enables communication with external components like sensors, actuators, and also the VR environment. The supply voltage for the microchip and therefore for the PCB is 5 V. This voltage is provided by the motor drivers (MDD3A, Cytron) that are powered with an external power supply of 12 V. In addition, 5 linear actuators (PQ12-63-12-P, Actuonix), 5 rotary position sensors (3382G-2-104G, Bourns), 10 vibration motors (FIT0774, DFRobot), and a microcontroller with a Bluetooth and a Wi-Fi module (ESP32, Espressif) are needed. This additional ESP32 is necessary for the wireless data exchange between the MIRAπ device and the VR environment. The linear actuators are equipped with internal potentiometers used as position feedback of the actuators. This feedback is needed to accurately control the movement of the actuators. As this potentiometer needs an input voltage of 3.3 V, there is also a voltage regulator included on the PCB. This electronic part regulates the input voltage of 5 V down to an output voltage of 3.3 V.

To offer a comprehensive view of the schematic of the device, a simplified wiring diagram was created and is presented in Figure 6. There, the vibration motors are omitted for simplicity. Those of the affected side are connected to the main PCP while the ones from the passive side are linked to PCB 2. For programming the microchip, In-Circuit Serial Programming (ICSP) with an external programmer is used.

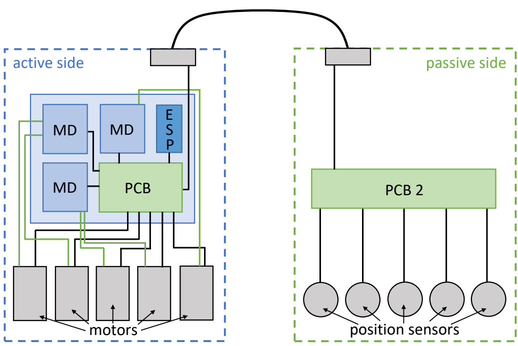


Fig. 6: Simplified wiring of the electronic components of the MIRAπ device.

(a) (b)

Fig. 8: Device setup of VR application; (a) active and passive side of the device with the screen, (b) virtual hands displayed on the screen.

C. Software Development

The motor control of the device is based on a closed-loop system that uses the position sensors (target position) and the internal potentiometers (actual positions) in combination with a PID controller. To design the PID controller and determine the parameters K_p, K_i, and K_d, a system model of the linear actuator is required. Therefore, the actuator was used to record data while it is in motion, applying an input voltage of 12 V. The recorded output data was mapped to the corresponding angle values for both the thumb and the phalanges, considering their distinct minimum and maximum angles. With the system identification toolbox in MATLAB, this mapped output data was used to generate the system models. With the estimated transfer functions, the second Ziegler-Nichols method was used to calculate the parameters for the PID controller. Therefore, the critical gains (K_{cr}) and the critical periods (P_{cr}) needed for the calculation were evaluated via a simulation in Simulink. After obtaining K_{cr} and P_{cr} of each transfer function, the parameters needed for the PID controller were calculated. As those parameters are based on an estimated transfer function, also fine-tuning was performed to further improve the systems. A simulation of the closed-loop system with a sine-wave representing the target position is shown in Figure 7.

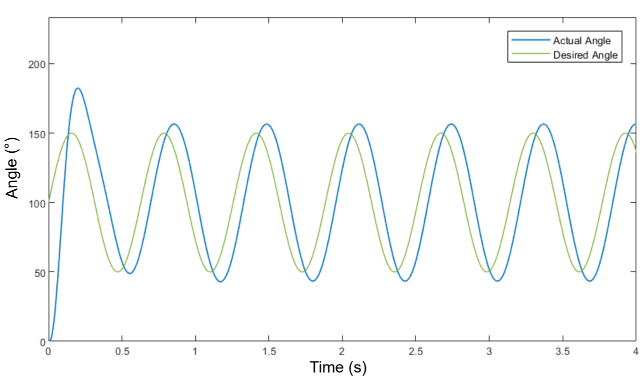
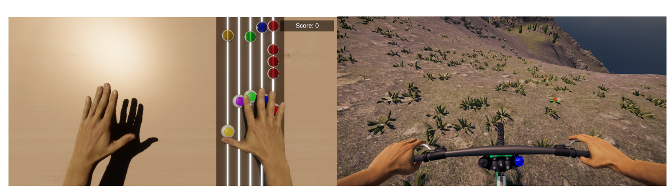


Fig. 7: Step response of the PID controller used for the motor control of the device. The normalized raw data is shown in green.

Virtual Reality Games: To enhance patient engagement with the device, a VR application with games was created. This application uses gamification and visualizes both hands on a screen that is positioned above the hands of the patient. The device setup with the default VR application displayed on the screen is shown in Figure 8. Developed using Unity, the VR games include high-definition human models designed to simulate realistic movements and interactions within the virtual environment. By establishing a connection via Serial, TCP socket (Wi-Fi), or Bluetooth, the device is connected to the VR environment. The connection can be selected through a menu displayed on the screen at the beginning. Once connected, the VR application retrieves finger angles transmitted by the device as lines of comma-separated values. Those values are applied to the hands of the human model within the selected VR game.

The default application focuses on hand visualization where the two virtual hands on the display mirror the movements of the hands of the patient during MT. Instead of solely performing MT through finger movements, a reaction-based game was implemented. Musical notes appear, and patients have to press virtual buttons with the device at the right time. Pressing these virtual buttons triggers vibration on the corresponding finger. The third game involves controlling the speed of a mountain bike using virtual brakes. Therefore, patients navigate down a predetermined track, halting the bike by closing the fingers of the healthy hand. That simulates the action of braking on a real bike. At the same time, the affected fingers get closed by the device and the bike stops. The two VR games can be seen in Figure 9.



(a) (b)

Fig. 9: Screenshots of the games included in the VR application; (a) piano game, (b) bike game.

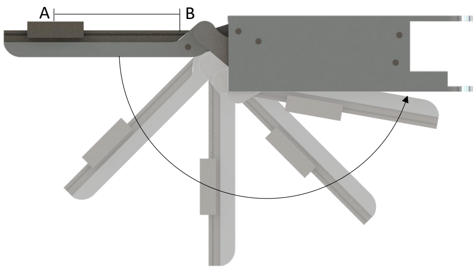


Fig. 10: Motion analysis of the phalanx's finger support. Finger support displayed in different positions where the distance between A and B is used for the travel distance evaluation.

III. Evaluation

A. Range Of Motion Analysis

A ROM analysis was performed using the CAD models of the finger support mechanisms of the thumb and the phalanges to determine their flexion and extension angles. To simplify the analysis, the finger supports were evaluated without the vibration motors on the sliding fingertips. As the movement trajectory of the finger supports is the same for the active and passive side, only the CAD models of the active side were analyzed. For the motion analysis of the thumb, the front view of the thumb's finger support was analyzed. In contrast, Figure 10 presents the side view of the motion analysis of the finger support developed for the phalanges.

B. Travel Distance Evaluation

To verify the efficacy of the sliding mechanism, the travel distance of the slider along the rail during finger movements, was measured. Therefore, two different finger lengths, one representing shorter fingers and another one reflecting longer fingers, were used. The finger length of the longer finger equals 90 mm, while the shorter finger has a length of 70 mm. Afterward, the finger was placed on the finger support of the device where it was secured onto the slider using a magnet attached to the fingertip. Then, finger flexion and extension movements were executed, see Figure 11. To evaluate the travel distance, the position of the slider during both extension and flexion was measured. This is the distance between position A and B in Figure 10. In addition, the x and y position of the fingertip were measured based on the drawing in Figure 11 (b).

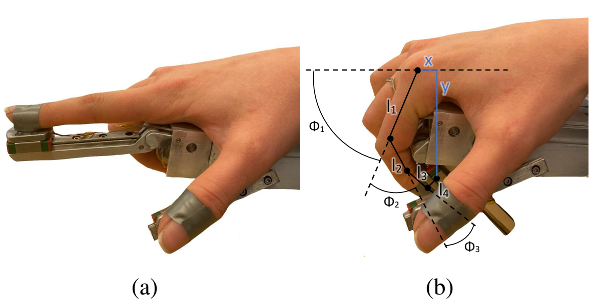


Fig. 11: Measurement positions for the travel distance evaluation; (a) extension of the finger, (b) flexion of the finger.

C. Delay Time Measurement

The effectiveness of MT depends on how fast the device responds to the movements of the healthy fingers. Therefore, the delay time of the actuator was evaluated where the signal of the microcontroller and the signal of the internal potentiometer of the actuator were measured with a digital oscilloscope (TBS 2000 Series, Tektronix). Afterward, the measurement graph of the oscilloscope was analyzed in MATLAB where a time delay arises between the initiation of the input signal and the moment when the actuator begins to move. Also, the time difference between the signal of the healthy hand and the one of the affected hand was measured. Therefore, the potentiometer value of the actuator was used as the signal of the affected hand and the signal of the healthy hand came from the corresponding position sensor. The measurement graph is shown in Figure 12.

D. Preference User Study

The user study assessed the subjective experiences of healthy people undergoing both conventional and physical MT sessions. Therefore, four tests were executed. For these tests, 12 voluntary participants with an average age of 21.08 ± 2.92 years participated in the experiments. They consisted of 5 females and 7 males. The inclusion of female and male participants aims to capture potential gender variations in response to the device, while the specified age range ensures a degree of homogeneity. The exclusion criteria encompassed individuals with neurological or psychiatric disorders, musculoskeletal injuries, or any condition that may affect their ability to participate in the tests. For all training sessions during the tests, participants followed the same pre-determined training program, moving their hands as directed by the instructor. In addition, the healthy participants were instructed to move only the right hand, mimicking their healthy hand, while keeping the other hand still to simulate the weakness when using the device.

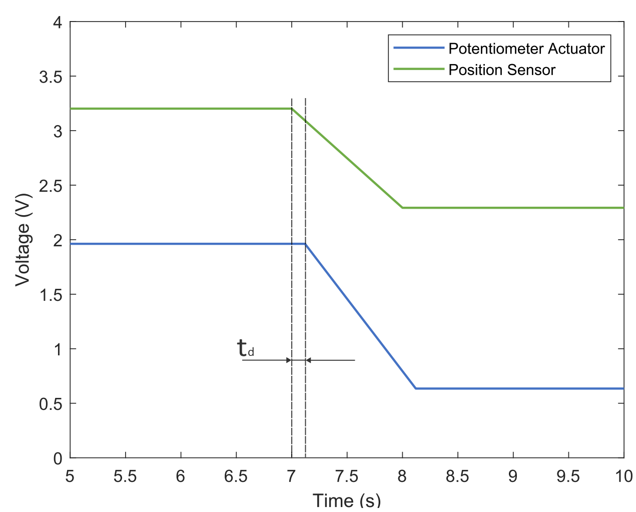


Fig. 12: Graphic of measuring the delay time t_d between moving the passive side and the actuation of the active side.

The first test was a comparative test to evaluate the MT effect of the device without using an actual mirror and to compare it to conventional MT. For this test, the participants were randomly assigned to two different groups: Group A who did conventional MT first, and Group B who first trained with the device. Participants of group A were sitting in front of a mirror and performed conventional MT for 5 minutes. In contrast, group B performed physical MT with the device without vibration and VR for 5 minutes. After that, the groups were switched to ensure that all participants experienced both conventional and physical MT. Another test was done to rate the influence of the additional haptic feedback of the device on the MT effect to address the second hypothesis. During this test, all participants used the device with its additional haptic feedback that stimulated their fingertips during physical MT. Training was again done for 5 minutes. A similar test was executed to rate the effect of the device's MT with its additional VR application. Therefore, all participants used the device with the VR hands displayed on a screen for 5 minutes. During the last test, vibration and VR were combined and training was executed for another 5 minutes. After each test, participants rated the effect of MT of each training setting on a scale from 1 to 7.

E. Clinical Study

As the device received full approval from the Yale University IRB, it was possible to conduct a clinical study (2000037049). The IRB enabled patients from the Yale inpatient rehabilitation unit at Milford Hospital to participate in the clinical trial. Adult patients with paralysis or impaired motor function of only one hand were accepted. Patients that were not cleared physically or medically to participate in standard acute inpatient rehabilitation therapies or suffer from spasticity of the affected hand, were excluded form the study. Eligible patients were approached for enrollment and informed consent was obtained. Although patient data cannot be published due to confidentiality reasons, it can be noted that the patients were aged between 55 and 70 years. The procedure consisted of conventional MT and physical MT with the device. Therefore, all patients received 5 conventional MT sessions as planned by their rehabilitation team. Each therapy session took 10 minutes. In addition, each patient received physical MT from the MIRAπ device, again 5 training sessions with 10 minutes each. They performed physical MT alone and in combination with the VR application. During all sessions, patients were monitored throughout by a research coordinator.

After completing five conventional MT sessions and five MIRAπ sessions, patients completed a short post-survey about the usability and comfort of the device. The survey contained three validated device implementation outcome measures: Acceptability of Intervention Measure (AIM), Feasibility of Intervention Measure (FIM), and the System Usability Scale (SUS). This questionnaire of the clinical study contained 22 questions that the patients had to answer on a scale with 5 options (completely disagree, disagree, neutral, agree, and completely agree).

IV. Results

One of the key features of the device is that the finger support mechanisms are adjustable in length, allowing for comfortable and ergonomic positioning of the fingers during therapy sessions. By visualizing both hands on a screen, the VR environment encourages active participation in therapy exercises while the vibration feedback enhances the haptic sensitivity of the patient.

Resulting from the ROM measurement, the maximum angle for abduction of the thumb is 90 °, representing the furthest distance achievable from the resting position of the thumb with 0 ° used as reference. For the phalanges, full extension is denoted as an angle of 0 °, while the maximum flexion angle evaluated reaches 170 °.

The travel distance of the slider on the rail was measured and equals 50 mm for the longer finger and 30 mm for the shorter finger. The distance between the fingertip on the sliding mechanism and the MCP joint of the finger displayed in Figure 11 (b) was also evaluated and equals 12.6 mm in x-direction and 66.5 mm in y-direction.

To ensure that patients feel the MT effect, the delay time of the device should be as short as possible. Therefore, the delay time measurement was carried out 10 times to calculate the average delay time. Arising from this measurement, the calculated average delay time of the device is 118.6 ms while the delay time of the actuator equals 118.5 ms.

The results of the first user study test showed that the participants could feel the MT effect with the device even without an actual mirror. Furthermore, the test highlighted that participants reported an even more intense MT effect when using the physical MT device instead of only performing conventional MT. Figure 13 illustrates the results of this comparative test. As it can be seen in this figure, 91.67 % rated the effect of MT created with the device higher than with only using a mirror during conventional MT. Although, one person thought it felt the same. Resulting from the second test, only 25 % felt the MT effect more intense with the additional haptic feedback compared to the first test with only physical MT. The other participants thought it felt the same. In comparison,

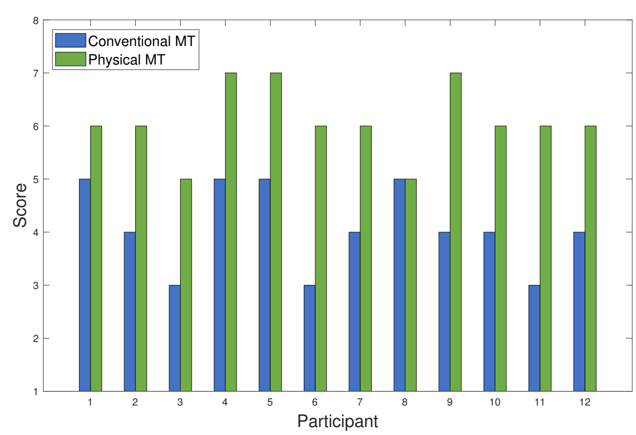


Fig. 13: Scores of conventional MT compared to the scores physical MT with the device. 1 refers to the least/lowest and 7 is the most/highest. 4 is thus neutral.

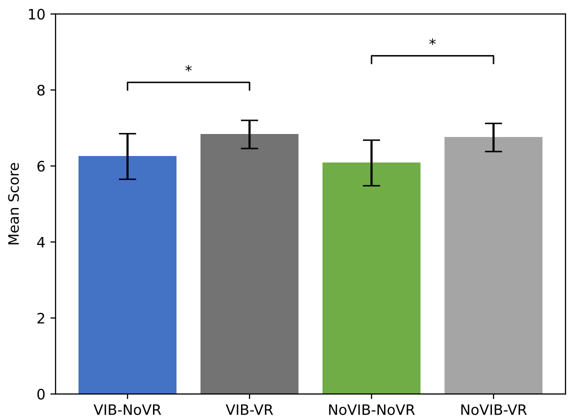


Fig. 14: Significance graph of the user study tests. Significant differences of p = 0.014 between VIB-NoVR and VIB-VR and p = 0.018 between NoVIB-NoVR and NoVIB-VR.

the third test showed that 66.67 % of the participants had a greater MT effect with the VR hands displayed on the screen than without the VR application. Figure 14 shows the results of all four tests. Therefore, the mean score and the standard deviation were calculated based on the ratings of the questionnaires. A statistical analysis done in SPSS indicates significant differences in the distributions between the different testing conditions (NoVR-NoVIB, VIB-NoVR, NoVIB-VR, VIB-VR). This is underlined by Friedman's Two-Way Analysis of Variance by Ranks which led to $\chi^2_{(3)} = 14.5$. The pairwise comparison suggests that there is only a significant difference between physical MT and physical MT with VR and without vibration (p = 0.018). However, the results showed no significant difference between physical MT and physical MT with vibration and without VR (p = 0.580). That indicates that vibration does not significantly change the overall MT effect while VR does. That indicates that vibration does not significantly change the overall MT effect while VR does. These results support our hypotheses, suggesting that vibration enhances the MT effect to some extent, while the most effective approach involves the use of VR.

The results of the acceptability questions of the clinical study showed that the device was appealing to the patients and that 100 % of the patients welcomed and liked the device. Regarding feasibility, 75 % of the patients found the device easy to use while all patients thought that using the device is doable, possible and implementable. In terms of system usability, 100 % of the patients felt very confident using the device and would like to use the device frequently. Although all patients thought that the device is easy to use, 50 % of them would need the help of a technical person and some extra knowledge to use the device. Overall, patients reported feeling comfortable and competent when using the device. Also, 100 % of the patients thought that the device helped them and made their hands move without experiencing any pain or discomfort during training. This was evaluated via 4 additional questions that had to be answered with yes or no.

V. Discussion

This paper shows the development and evaluation of a robotic mirror therapy device for individuals with hand impairments. The device can be used for physical MT alone or in combination with VR games and haptic feedback. Through different measurements, the device characteristics were evaluated.

Results of the evaluation revealed that the phalanges exhibit a ROM of 170 ° during flexion and extension, while the thumb can perform 90 ° abduction and adduction. This means that the patient can execute finger curling movements with the index, middle, ring, and pinkie fingers, along with upward and downward movements with the thumb to train activities of daily living. This closely resembles the results of the ROM analysis of a hand exoskeleton device described in [8]. However, the developed device has a higher ROM than the wearable finger exoskeleton of Hernandez et al. [6] (26 ° of the MCP joint and 43 ° of the PIP joint).

Further measurements showed that the device has a delay time of only 118.6 ms. As the actuator itself has a delay of 118.5 ms, the device adds only minimal additional latency which indicates its potential effectiveness in therapeutic applications. This is particularly significant as a short delay time is important for achieving the MT effect. A perception test was done by Ismail et al. [14] to evaluate the effect of different delay times on the MT effect. Their test showed that the best results for the MT effect occur with a delay time less than 190 ms. Significant weaker effects were observed for delay times between 290 ms and 490 ms. Shimada et al. [15] also underline these results with their study. Compared to the results of this paper, the delay times in [14] and [15] are significantly greater. Therefore, anticipated is that the device can induce the MT effect.

An equation to calculate the position of the fingertip according to the finger bone lengths and the angles of each joint was developed by Rätz et al. [16]. With this equation, the fingertip position was calculated based on Figure 11 (b). The calculated values equal 12.45 mm in the x-direction and 66.64 mm in the y-direction. These values agree with those measured and demonstrate the accuracy of the formula developed in [16]. The findings from the user study revealed that participants experienced the MT effect even without a physical mirror, suggesting the potential efficacy of the device. Moreover, participants reported an even stronger MT effect, when using the device for training. However, adding haptic feedback didn't significantly enhance the experience for most participants. But they could imagine that it helps to increase the haptic sensitivity in the fingers. Conversely, integrating VR hands led to a notable increase in the MT effect for most of the participants. This concludes with a greater MT effect with visual feedback instead of haptic feedback. It also aligns with the principles of MT as it is based on visual feedback.

The post-survey of the clinical study showed positive feedback from all patients regarding their experience with the device. In terms of acceptability, the device was well-received, with patients expressing enthusiasm and willingness to incorporate it into their regular therapy plan. Furthermore, they anticipated that other patients would express interest in familiarizing themselves with the device and incorporating it into their therapy. Importantly, all patients attested to the beneficial effects of training with the device, noting improvements of their hand function without experiencing any pain or discomfort during its use.

Compared to prior research, the developed device combines MT, movement of the affected hand, haptic feedback, and also VR games. Also, the findings from the user study and the clinical study underscores the device's potential as a valuable tool in rehabilitation. While this indicates promise of the functionality, future efforts should prioritize further evaluation of the device through a comparative clinical study to evaluate the performance of the device compared to conventional MT. It would also be beneficial to assess the effectiveness of the device in improving hand impairments and enhancing overall rehabilitation outcomes. The results of the evaluation of the device are promising that it can be used for further research purposes and studies in the future.

VI. Conclusion

This paper introduces a robotic mirror therapy device for hand impairments, offering flexibility with physical therapy, VR games, and haptic feedback. The evaluation showed significant finger ROM and only a minimal delay time. Healthy participant tests further support the efficacy of the device, with visual feedback proving more impact than haptic feedback in enhancing the MT effect. Feedback from patients in the clinical study underscores the device's acceptability and usability. In addition, its therapeutic benefits are highlighting its potential as a valuable tool in rehabilitation. Moreover, the device's integration of multiple therapeutic modalities distinguishes it from prior research efforts. This is provided by the different therapy options possible with the device. While promising, future research should focus on comparative clinical studies to validate the effectiveness of the device compared to conventional therapy. Overall, the device shows potential for further research and clinical applications in hand and finger rehabilitation.

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