Mirror Therapy using Virtual Reality and Actuated Exoskeleton: Road to a Patient Care Device

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***Abstract*— We have developed a rehabilitation setup based on the mirror therapy protocol and leveraging cutting-edge technology. We posit that the lost hand functionalities can be recovered by producing a visual illusion of the impaired hand motion in virtual reality and inducing the same motion to the real hand through the actuation of a hand exoskeleton. Our tool has been tested with several healthy users and evaluated as well accepted and easy to use. However, research and technological efforts still need to be done to apply our technology to stroke patients. This abstract presents our plan and strategy to move our technology from our lab to real clinical environments leveraging electromyography sensing information.**

I. Introduction

In rehabilitation, Mirror Therapy (MT) is widely used for motor function recovery [1]–[3]. The standard scheme can be summarized as follows: patients move the healthy hand in front of a mirror, while the impaired one is hidden behind the mirror itself; the reflected motion of the healthy hand is perceived as a movement of the impaired one; such an illusion is assumed to stimulate neuroplasticity [1]. Virtual Reality (VR) enables immersive training environments stimulating motor learning and recovery, and neuroplasticity [4]. VR-assisted MT is well-tolerated by patients [5], and improves the functional abilities of impaired hands [6], [7]. Robotics-supported therapy is another viable complement to traditional methods [8]–[12]. These technologies have a lot of potential in rehabilitation; their extensive use could increase their acceptance among patients, thus enhancing the therapies' efficacy [13], [14]. The combined effect of VR and robotics is promising for clinical research in neuro-rehabilitation [15], also because it could increase the therapies' frequency and duration, resulting thus in better outcomes [16]. However, the use of these devices at home, and their consequent widespread implementation remains limited [17]. In the specific context of MT, to the best of our knowledge, wearable robotics and VR have been combined only in a recently approved clinical trial, whose results are not available yet [18].

Recently, we have proposed a feasibility study to verify the benefit of combining VR and wearable robotics in MT [19]. We posit that the perception of the impaired hand motion, visually reconstructed in VR and physically transmitted to the patient through an exoskeleton, increases the MT efficacy.

*This work was supported by Innosuisse - Swiss Innovation Agency, through the project "Virtual Reality and Hand Exoskeleton for Mirror Therapy: a Feasibility Study (VRHEM)" (100.533 IP-ICT).

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Fig. 1. Our rehabilitation tool for MT. The user wears the exoskeleton at the left hand and the VR headset. In the VR scene, shown in the white circle, the right hand is tracked and rendered, while the left hand is visually mirrored from the right one. The exoskeleton is actuated to move the left hand and match the posture of the right hand.

In this document, we describe our rehabilitation tool (Sec II) and discuss our strategy for future work to bring it into clinics (Sec. III). Section IV concludes our discussion, claiming that integrating an Electromyography (EMG) sensor within our setup is a reasonable way to pursue our objective.

II. VR and hand exoskeleton for MT

Our rehabilitation tool is shown in Fig. 1. The user wears on the left hand (pretended to be the impaired hand) the exoskeleton provided by Emovo Care [20]. This simple, portable, and lightweight hand orthosis is composed of two artificial exoskeletal fingers, worn coupling the wearer's index and middle finger, and the ring and pinkie fingers. One single motor actuates both exoskeletal fingers, resulting in the coordinated motion of the four wearers' fingers, to assist simple opening and closing motions. The user also wears a VR headset; in particular, we use the Meta Quest 2 [21]. We leverage the headset onboard hand tracking system to accurately visualize the user's right hand, pretended to be the healthy hand, in the VR scene. The right hand motion is also mirrored along the user's median plane to produce the visualization of the left hand. The user slowly closes and opens their right hand. The exoskeleton is used to induce such motion to the real left hand of the user, in sync with the movement rendered in VR. Thus, the visual perception of the left hand (i.e. the virtual left hand seen in VR) is coupled

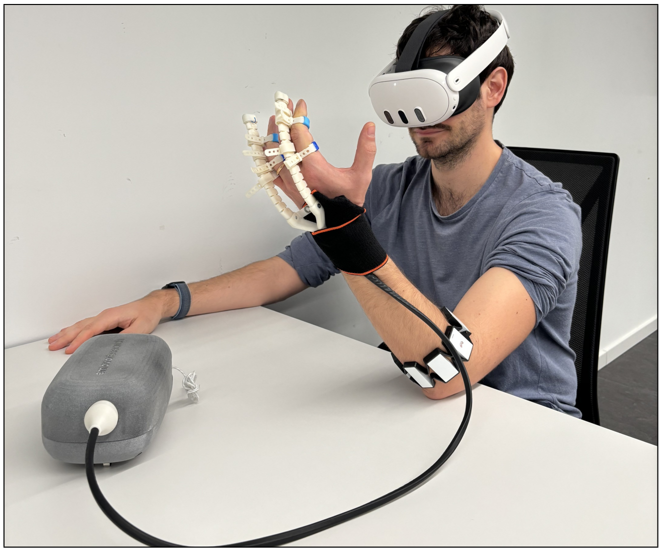

Fig. 2. Enhanced configuration of our setup: an EMG sensor can augment the tool perception skill and open it to interesting rehabilitation applications.

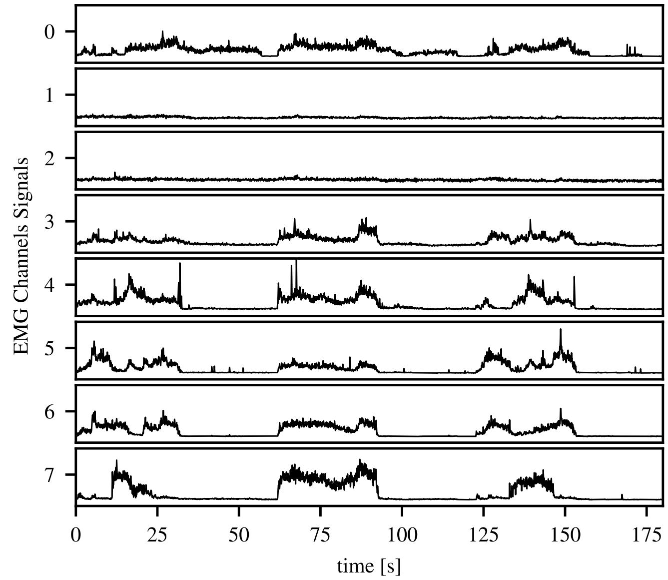

Fig. 3. Myo EMG signals recorded during a rehabilitation experiment where the user executes simple opening and closing hand motions.

with the physical perception resulting from its motion (as induced by the exoskeleton on the wearer's left hand).

Our rehabilitation setup aims at improving MT by augmenting the brain illusion of impaired hand motion, by coupling visual and physical perceptions. As a first step of our development, we made sure that our tool well integrates the involved technologies and that it could be positively used and perceived by potential users (e.g. patients). To this end, we carried out a user study involving 21 healthy people [19], to measure the impact of our design choices on the system's usability, acceptability, and sense of embodiment. Results show that the system is well accepted by the users, and we have obtained positive feedback about its usability and sense of embodiment. Furthermore, our tool has the potential to go beyond the efficacy of the MT. In particular, the portable nature of our platform could allow motor-impaired patients to take the therapy independently at home, facilitating the delivery of higher dosages and repetitions, factors that are typically linked to better therapeutic outcomes. We believe that this aspect would positively affect the quality of life of both patients and therapists. The same line of developments opens up new perspectives in the field of telemedicine, where a therapist could wear their own VR headset to remotely assist patients. However, such potential has one single, crucial starting step to be made: the validation within real clinical environment. This aspect of our work sets important research challenges that we discuss in the next section.

III. Road to clinical tests

This section explores different directions to move our current rehabilitation device towards clinical testing. We plan our future activities around three pillars: the first relates to the hardware and software components of our tool, according to which we will investigate how to modify and augment our setup; the second concerns innovative validation tools that will be used to assess the therapy in an online fashion; lastly, a line of development is related to the tests with patients.

A. Enhancement of the sensory equipment

Our tool is portable, easy to use, and relatively inexpensive. These features favor the democratization of rehabilitation devices and their large domestic use, improving the life quality of patients and therapists. However, these positive aspects, brought by the devices' lightness, are paid at the cost of little sensory capabilities that limit the tool's potential.

Current investigations are devoted to equipping our setup with additional sensors that (i) do not affect the portability of the whole device and (ii) provide complementary information for rehabilitation therapy. To this end, we have built a new preliminary setup that includes an EMG sensor, see Fig. 2. We are currently investigating the use of the Myo armband, widely employed in combination with arm prostheses [22], to measure the muscular activity of the hand. In the future, we plan to test other state-of-the-art EMG sensors, such as the ones provided by Vulcan[1], MindRove[2], Cometa[3] or Delsys[4]. This information can be integrated into our setup to enable additional features. Indeed, an online perception of the patient's muscular activity would allow adaptive closed-loop exoskeleton control, and a consequent positive impact on the therapy [23], [24].

The research challenge is represented by the need to keep the processing of EMG signals light and fast, handle its noise signal (e.g. see the plots of Fig. 3 showing the EMG signal for a simple hand opening/closing motion), and extract useful information for online adaptive control (such as the compliance of the hand). In this regard, AI and Machine

[1] wearevulcan.com/en/emg-sensor
[2] mindrove.com/product/armband_8_ch/
[3] cometasystems.com
[4] delsys.com/trigno/

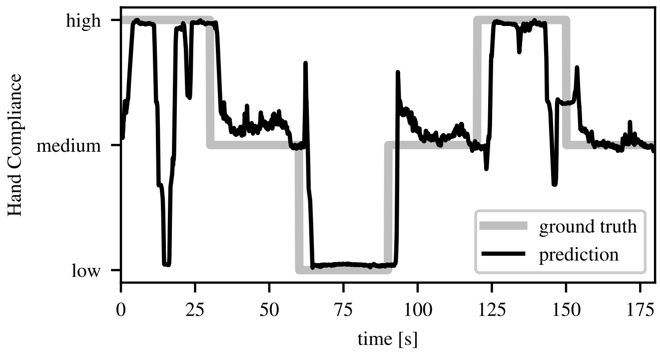

Fig. 4. Hand compliance estimated by a ML method that fuses information about the exoskeleton motion and the EMG sensor. In the experiment, the user changes hand compliance level every 30 s.

Learning (ML) methods can provide the required technology to compute reliable feedback for the exoskeleton controller. In preliminary work, we start developing a ML tool to predict the hand compliance of a healthy user wearing the exoskeleton and the EMG sensor. Figure 4 shows the estimate of the user's hand compliance for the same experiment of Fig. 3.

B. *Online assessment of the therapy*

Normally, therapy assessment is performed by clinicians and lacks high reliability and standardization [25]. A tool capable of delivering therapy and objectively assessing its outcome would bring obvious benefits. Robotics offers possibilities to accurately and objectively assess motor impairment [26], [27], e.g. through proprioception and haptic perception [24] or evaluating the fingers' range of motion [28], [29], an indicator of rehabilitation outcomes [30].

We aim to expand our rehabilitation tool to include therapy assessment capabilities. One challenge is to reach this goal with simple and lightweight devices, without affecting the portability and ease of use of the tool. This could be achieved by using wearable sensors to be seamlessly integrated with the exoskeleton. Also in this case, a valuable solution is represented by EMG sensors, but tactile, force sensors or their combination can be also considered. As in the task described in Sec. III-A, we could leverage AI techniques to fuse information from different sensors to measure the therapy outcome. To this end, we plan to exploit our expertise in ML that we have developed for other relevant perception tasks in robotics, see e.g. [31], [32].

C. *Validation and testing with patients*

The current version of our device has been tested only with healthy users, while validations with actual patients are paramount for a rehabilitation tool. We plan to evaluate our technology with patients in a two-step procedure. Firstly we will select a small sample of patients and, in a later stage, we will handle real clinical trials involving a larger pool. This approach will allow us to tackle the complex task of coping with patients addressing the corresponding technical, logistic, and regulatory challenges step-by-step.

Considering a small user study involving few patients, we could directly extend the validation study proposed with healthy users [19] and easily verify whether our tool remains valid regarding usability, acceptability, and safety. Indeed, very importantly, what is already deemed good with healthy users may not be the case for patients with hand impairments. Obtaining feedback from a small number of patients (and avoiding the logistics duties otherwise required for big pools of testers) should be enough to modify the tool from an engineering point of view, and elaborate a set of instructions for use and wearing procedures tailored to patients.

A full-fledged clinical trial, performed over a long period, is required to validate the proposed framework as a rehabilitation setup. We could measure whether it achieves different results concerning traditional treatments. We could also test whether the tool is usable at home by patients. If so, we could measure how this impacts the frequency of use and, consequently, the therapy outcome. Preparing a clinical trial requires complicated work and specialized people, to follow strictly regulated procedures and ethical guidelines. Also, patient recruitment is a big challenge to be addressed.

The tests with patients will allow us to verify the soundness of the solutions proposed in Sec. III-A and Sec. III-B. In particular, we will verify whether the use of EMG sensing will have a positive impact on our rehabilitation procedure.

IV. Conclusions

We have developed a mirror therapy setup for the rehabilitation of hand impairments. The tool has been validated with healthy users and is well-accepted, usable, and safe. It is thus promising for its deployment in real clinical environments. However, much technical work and research investigation still need to be done. We discussed these challenges and outlined three pillars for our future developments: hardware and software, validation, and clinical trials. We believe that integrating EMG sensing would add value to our current framework as it allows our system to remain light and simple, and would enable more advanced exoskeleton control, and online quantitative assessment of the therapy. Finally, the testing phase with patients will allow us to verify the soundness of the EMG sensing integration in our framework.

References

[1] H. Thieme, J. Mehrholz, M. Pohl, J. Behrens, and C. Dohle, "Mirror therapy for improving motor function after stroke," *Cochrane database of systematic reviews (Online)*, vol. 3, p. CD008449, 12 2012.

[2] D. Gandhi, A. Sterba, H. Khatter, and J. Pandian, "Mirror therapy in stroke rehabilitation: Current perspectives," *Therapeutics and Clinical Risk Management*, vol. Volume 16, pp. 75–85, 02 2020.

[3] M. Yavuzer, R. Selles, N. Sezer, S. Tomruk Sütbeyaz, J. Bussmann, F. Köseoğlu, M. Atay, and H. Stam, "Mirror therapy improves hand function in subacute stroke: A randomized controlled trial," *Archives of physical medicine and rehabilitation*, vol. 89, pp. 393–8, 03 2008.

[4] M. F. Levin, P. L. Weiss, and E. A. Keshner, "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles," *Physical Therapy*, vol. 95, no. 3, pp. 415–425, 03 2015.

[5] L. M. Weber, D. M. Nilsen, G. Gillen, J. Yoon, and J. Stein, "Immersive virtual reality mirror therapy for upper limb recovery after stroke: A pilot study," *Am J Phys Med Rehabil*, vol. 98, no. 9, pp. 783–788, Sep. 2019.

[6] C.-W. Lin, L.-C. Kuo, Y.-C. Lin, F.-C. Su, Y.-A. Lin, and H.-Y. Hsu, "Development and testing of a virtual reality mirror therapy system for the sensorimotor performance of upper extremity: A pilot randomized controlled trial," *IEEE Access*, vol. 9, pp. 14 725–14 734, 2021.

[7] C. Heinrich, N. Morkisch, T. Langlotz, H. Regenbrecht, and C. Dohle, "Feasibility and psychophysical effects of immersive virtual reality-based mirror therapy," *J Neuroeng Rehabil*, vol. 19, no. 1, p. 107, 2022.

[8] J. Mehrholz, M. Pohl, T. Platz, J. Kugler, and B. Elsner, "Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke," *Cochrane database of systematic reviews (Online)*, vol. 11, 11 2015.

[9] J. M. Veerbeek, A. C. Langbroek-Amersfoort, E. E. H. van Wegen, C. G. M. Meskers, and G. Kwakkel, "Effects of robot-assisted therapy for the upper limb after stroke: A systematic review and meta-analysis," *Neurorehabilitation and Neural Repair*, vol. 31, no. 2, pp. 107–121, 2017.

[10] A. Pollock, S. E. Farmer, M. C. Brady, P. Langhorne, G. E. Mead, J. Mehrholz, and F. van Wijck, "Interventions for improving upper limb function after stroke," *The Cochrane database of systematic reviews*, no. 11, p. CD010820, November 2014.

[11] N. Norouzi-Gheidari, P. S. Archambault, and J. Fung, "Effects of robot-assisted therapy on stroke rehabilitation in upper limbs: systematic review and meta-analysis of the literature," *Journal of rehabilitation research and development*, vol. 49, no. 4, p. 479—496, 2012.

[12] G. Prange, M. Jannink, C. Groothuis-Oudshoorn, H. Hermens, and M. IJzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *Journal of rehabilitation research and development*, vol. 43, pp. 171–84, 03 2006.

[13] J. W. Krakauer, "Motor learning: its relevance to stroke recovery and neurorehabilitation," *Current opinion in neurology*, vol. 19, no. 1, p. 84—90, February 2006.

[14] B. H. Dobkin, "Strategies for stroke rehabilitation," *The Lancet. Neurology*, vol. 9, no. 3, p. 528–536, 2004.

[15] E. Wade and C. J. Winstein, "Virtual reality and robotics for stroke rehabilitation: where do we go from here?" *Top Stroke Rehabil*, vol. 18, no. 6, pp. 685–700, Nov. 2011.

[16] W. E. Clark, M. Sivan, and R. J. O'Connor, "Evaluating the use of robotic and virtual reality rehabilitation technologies to improve function in stroke survivors: A narrative review," *J Rehabil Assist Technol Eng*, vol. 6, Nov. 2019.

[17] G. Turchetti, N. Vitiello, L. Trieste, S. Romiti, E. Geisler, and S. Micera, "Why effectiveness of robot-mediated neurorehabilitation does not necessarily influence its adoption," *IEEE Reviews in Biomedical Engineering*, vol. 7, pp. 143–153, 2014.

[18] D. Wei, X.-Y. Hua, M.-X. Zheng, J.-J. Wu, and J.-G. Xu, "Effectiveness of robot-assisted virtual reality mirror therapy for upper limb motor dysfunction after stroke: study protocol for a single-center randomized controlled clinical trial," *BMC Neurology*, vol. 22, no. 1, p. 307, Aug. 2022. [Online]. Available: https://doi.org/10.1186/s12883-022-02836-6

[19] G. Abbate, A. Giusti, L. Randazzo, and A. Paolillo, "A mirror therapy system using virtual reality and an actuated exoskeleton for the recovery of hand motor impairments: a study of acceptability, usability, and embodiment," *Scientific Reports*, vol. 13, no. 1, p. 22881, 2023.

[20] "Emovocare," https://emovocare.com/, Accessed: 2023.

[21] "Meta Quest 2," https://www.meta.com/ch/en/quest/products/quest-2/, Accessed: 2023.

[22] P. Visconti, F. Gaetani, G. Zappatore, and P. Primiceri, "Technical features and functionalities of myo armband: An overview on related literature and advanced applications of myoelectric armbands mainly focused on arm prostheses," *International Journal on Smart Sensing and Intelligent Systems*, vol. 11, pp. 1–25, 06 2018.

[23] J. G. Younggeun Choi, Feng Qi and N. Schweighofer, "Performance-based adaptive schedules enhance motor learning," *Journal of Motor Behavior*, vol. 40, no. 4, pp. 273–280, 2008.

[24] J.-C. Metzger, O. Lambercy, A. Califfi, D. Dinacci, C. Petrillo, P. Rossi, F. M. Conti, and R. Gassert, "Assessment-driven selection and adaptation of exercise difficulty in robot-assisted therapy: a pilot study with a hand rehabilitation robot," *J. Neuroeng. Rehabilitat.*, vol. 11, no. 1, p. 154, 2014.

[25] J. Gordon *et al.*, "Assumptions underlying physical therapy intervention: Theoretical and historical perspectives," 1987.

[26] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *J. Neuroeng. Rehabilitat.*, vol. 11, no. 1, p. 3, 2014.

[27] O. Lambercy, L. Lünenburger, R. Gassert, and M. Bolliger, *Robots for Measurement/Clinical Assessment*. London: Springer London, 2012, pp. 443–456.

[28] Y. Su, G. Li, Y. Deng, I. Sarakoglou, N. G. Tsagarakis, and J. Chen, "The joint-space reconstruction of human fingers by using a highly under-actuated exoskeleton," 2024, pp. –.

[29] H. Wang, P. Chen, Y. Li, B. Sun, Z. Liao, B. Niu, and J. Niu, "New Rehabilitation Assessment Method of the End-Effector Finger Rehabilitation Robot Based on Multi-Sensor Source," *Healthcare*, vol. 9, no. 10, p. 1251, 2021.

[30] K. Marek, J. Redlicka, E. Miller, and I. Zubrycki, "Objectivizing Measures of Post-Stroke Hand Rehabilitation through Multi-Disciplinary Scales," *Journal of Clinical Medicine*, vol. 12, no. 23, p. 7497, 2023.

[31] M. Nava, A. Paolillo, J. Guzzi, L. M. Gambardella, and A. Giusti, "Learning visual localization of a quadrotor using its noise as self-supervision," vol. 7, no. 2, pp. 2218–2225, 2022.

[32] G. Abbate, A. Giusti, V. Schmuck, O. Celiktutan, and A. Paolillo, "Self-supervised prediction of the intention to interact with a service robot," vol. 171, p. 104568, 2024.