The Metaverse for Stroke Motor Rehabilitation*

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***Abstract*—Stroke is a critical illness that causes disabilities and fatalities. The current standard motor rehabilitation usually requires some residual movement of stroke patients, limiting participation. Movement imagination, known as motor imagery (MI), potentially expedites motor rehabilitation by activating the motor brain areas, which may facilitate neuroplasticity. MI is, however, a difficult ability that may deteriorate over time. The Metaverse, a virtual reality (VR) social media platform, provides an immersive and interactive environment that allows stroke patients to experience the embodiment of their MI performance via their avatars. This paper provides a framework to design a Metaverse stroke motor rehabilitation program, outlining the essential elements required from the Metaverse and the challenges in implementing the Metaverse in stroke motor rehabilitation. Future research directions are identified that provide solutions and facilitate stroke recovery in motor functions through more advanced and innovative digital technologies suitable for vulnerable stroke patients.**

***Index Terms*—Metaverse, motor imagery, stroke, rehabilitation, neuroplasticity**

I. Introduction

A. Background

Stroke causes abnormalities of brain arteries that lead to adverse health risks such as disabilities and even death [1], [2]. Early stroke rehabilitation is crucial because the effectiveness of recovery depends on neuroplasticity, which is most active immediately when patients survive their stroke [2], [1]. Post-stroke recovery gradually slows down after the first six months post-stroke [2], [3], [4]. Motor impairments make stroke patients' independent living difficult [2], [5]. The current mainstream motor rehabilitation methods often rely on stroke patients' residual movement [2], [5]. Stroke patients in the early stage of recovery often suffer from severe motor disabilities, which limit their ability to participate in rehabilitation [5].

MI does not require any physical movement and is a promising way to trigger neuroplasticity by activating the brain areas related to motor processes via only imagination [2], [6]. Performing MI is not straightforward and usually requires training [7], [8], [6]. VR, such as Facebook's Metaverse, may provide an immersive environment to assist stroke patients in performing MI by inducing an illusion of actual physical movement via computer interfaces [9], [10], [6]. The American Guidelines for Adult Stroke Rehabilitation and Recovery currently only consider MI and VR as reasonable methods for upper limb stroke rehabilitation; thus, there is room for improvement for the integration of the Metaverse and MI-based stroke rehabilitation [11]

The Metaverse is a VR platform that may be applicable in stroke motor rehabilitation [9]. Metaverse users may experience presence via their avatars, which can interact with various virtual scenarios that simulate the real world [10]. Personalised computer simulations could accommodate the diverse needs of stroke patients with different severity of brain damage [9], [10]. The Metaverse potentially allows health professionals to remotely guide and assess stroke patients during rehabilitation [12]. There are challenges with the state-of-the-art technology for implementing the Metaverse in stroke rehabilitation; however, the literature has suggested possible solutions [9], [10], [12], [13].

B. Current Motor Rehabilitation

Stroke survivors may begin motor rehabilitation when released from emergency care, ideally within 24-48 hours post-stroke [2]. Standard motor rehabilitation often involves some residual movement, such as physiotherapy and occupational therapy, which teach stroke patients to regain control of their affected limbs and strategies to live independently [5]. On the other hand, MI does not require any physical movement and may activate the motor brain areas, thus triggering neuroplasticity for recovery [2], [7]. MI may expedite stroke patients' motor rehabilitation; however, the MI ability usually requires training and may deteriorate post-stroke, limiting rehabilitative options [7], [8].

C. Paper Contributions

In this paper, we propose and discuss a conceptual framework, typical state-of-the-art digital technologies, and future research opportunities for overcoming the obstacles in incorporating the Metaverse into stroke motor rehabilitation:

- An introduction of the Metaverse and its importance in stroke rehabilitation.
- A proposed framework outlining the essential features for implementing the Metaverse in stroke motor rehabilitation.

- Identification of the pros and cons of the state-of-the-art rehabilitative apparatus that could be incorporated with the Metaverse to enhance stroke motor rehabilitation.

- An explanation of a promising virtual healthcare system developed by Stanica et al. (2020) [14], outlining the associated advantages and challenges of implementing the Metaverse stroke motor rehabilitation.

- A discussion of future research opportunities based on the main challenges of the Metaverse in stroke motor rehabilitation regarding mainly the appropriate virtual stroke motor rehabilitation design, equipment compatibility, competence of stroke patients in rehabilitative Metaverse participation, and accessibility of Metaverse-related apparatus.

II. Metaverse Rehabilitation

The Metaverse is the epitome of VR technology, which enables sophisticated simulations of real-world scenarios with multisensory feedback, providing users with a virtual embodiment of their body parts on a social media platform [9], [10], [12], [13]. The Metaverse is, therefore, a promising technology to assist MI and encourage stroke patients without any voluntary movement to start motor rehabilitation once they are admitted to the rehabilitation centre with the assistance of online support groups, unrestricted by distance [9], [10], [12], [13].

Fig. 1 illustrates the essential elements of implementing the Metaverse in stroke motor rehabilitation. Online socialisation is an essential element of the Metaverse, which sets it apart from other VR platforms, allowing global long-distance interaction between health professionals, patients, and families in real time. Metaverse user profile personalises the Metaverse platform. It is necessary to identify the suitable equipment for visual display. Devices for multisensory feedback are ideal but may be optional depending on the user's and the professional's requirements. It is ideal to use a brain-computer interface (BCI) that allows real-time control of the Metaverse avatar in the first-person perspective, such as getting a virtual cup by performing MI [8], [13], [15]. The Metaverse rehabilitation program should be indistinguishable from games in the user's perspective to encourage participation.

Non-invasive and portable neuroimaging instruments such as electroencephalogram (EEG) and functional near-infrared spectroscopy (fNIRS) allow convenient and objective MI measurement [15]. Intensity variation scalp maps normalised between all conditions being compared are efficient in quantitatively illustrating active brain areas associated with certain rehabilitative tasks [2], [6]. An active brain area is directly proportional to a high-intensity signal [2], [6]. A straightforward yet robust way to quantify EEG signals is via analyses of the motor-related frequency band in the range of 8-30 Hz compared across the different brain areas [2], [6]. fNIRS, with a higher spatial resolution than EEG, detects the concentration changes in haemoglobin around the brain to indicate brain activation. A higher oxygenated haemoglobin concentration corresponds to a more active brain region because more oxygen molecules are needed for the active brain area. Furthermore, the rehabilitation program should record specific event markers for convenient data analysis.

Finally, physical assessments such as the Fugl-Meyer Assessment (FMA) should be performed by certified professionals before and after each therapy to verify the neuroimaging results [16], [17]. FMA consists of assessment items corresponding to a total of 100 points concerning the upper extremity (66 points), lower extremity (34 points), balance (14 points) and sensation (48 points) [16]. Each FMA item scores from 0 to 2 for severe to no impairment, respectively. The following after-session surveys are recommended for MI evaluation: the NASA Task Load Index (NASA-TLX), movement imagery questionnaire 3 (MIQ-3), and vividness movement imagery questionnaire 2 (VMIQ-2) [18], [19], [20].

A. *State-of-the-Art Rehabilitative Digital Apparatus*

Fig. 2 is a conceptual illustration of the state-of-the-art equipment typical for application in VR and augmented reality (AR) as outlined by the following:

- Fig. 2(a) shows the head-mounted display (HMD) Oculus Rift CV1 (Oculus, USA) (resolution 1,080 × 1,200 per eye, 90 Hz refresh rate, 110○ field of view) is designed for video games compatible with the wireless and lightweight EEG system Neuroelectrics Enobio 32 for MI-BCI [21]. 28 EEG AgCl NG Geltrodes positioned around the motor and frontal cortices, connected to the wireless amplifier at the back, are sufficient [21]. Pretraining acquired EEG signals are for calibration [21]. Unity and Openvibe are applications operating on the same computer to simultaneously run the BCI scenario and classify the real-time EEG signals, eliciting a sense of embodiment by controlling BCI via MI [21]. The HMD is simple to operate, but its bulkiness and software time lags can cause cybersickness for vulnerable stroke patients [22].

- Fig. 2(b) depicts the Microsoft HoloLens Version 1 AR Headset (Microsoft Corporation, USA) (1280×720 display resolution per eye) displays digital information 1 m in front of the headset when the user has looked at a target for more than two seconds [18]. Microsoft HoloLens displays an AR environment with digital elements in the user's surroundings via the lens, allowing users to see the real world, which evokes a sense of security for the user [18]. HoloLens, however, may require some users greater mental demand than VR [18].

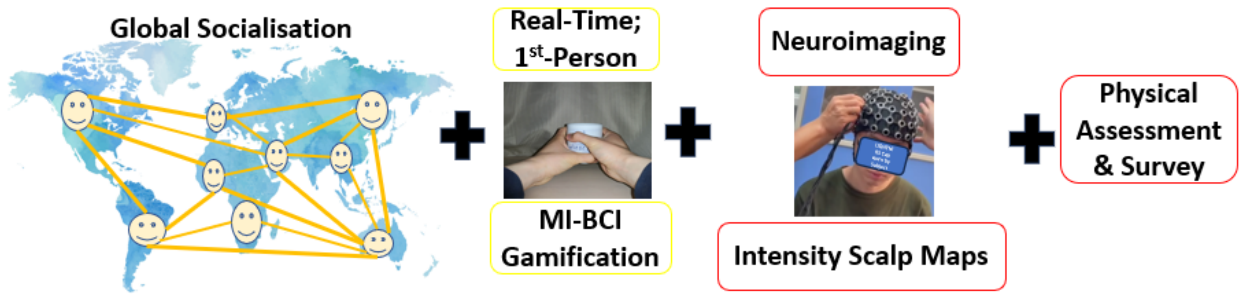

Fig. 1. General schematic showing the essential features of implementing Metaverse in stroke motor rehabilitation.

- Fig. 2(c) illustrates the Cave Automatic Virtual Environment (CAVE) (University of Illinois, Chicago) provides a three-dimensional (3D) virtual environment generated by 4 or 6 back-projected screens with a dedicated glass [13]. It also possesses a head tracking device and speakers around the CAVE for real-time visual and audio feedback [13]. CAVE is free of wearable hardware, preventing discomfort from using bulky equipment; nevertheless, CAVE is not widely accessible as it is costly and occupies a large space [13].

- Fig. 2(d) is the RecoveriX PRO Hand Therapy (g.tec medical engineering GmbH Austria) is a BCI stroke rehabilitation system for the hands [23]. Fig. 2 shows a stroke patient wearing the g.NautilusPRO headset for EEG measurement with two g.Estim pads attached to the arms for functional electrical stimulation while sitting on a chair in front of a computer screen showing a pair of virtual hands. A laptop connects all hardware of the Recoverix system such that real-time electrical feedback corresponding to the hand movement of the virtual hands controlled by the patient's EEG signals can be established. The RecoveriX system requires a training session to calibrate the EEG signals and determine an appropriate level of electrical stimulation only when the patient needs assistance to raise the hand. Although the RecoveriX system requires health professionals to set up and guide the patient, the RecoveriX system could consolidate the rehabilitative aspect of the Metaverse.

B. Healthcare via VR

Fig. 3 is a schematic of the Immersive Neurorehabilitation Exercises Using Virtual Reality (INEREX-VR) (University Politehnica of Bucharest, Romania) system for virtual healthcare interaction between health professionals and patients using relatively accessible biosensors consisting of 3 main users: the medical trainee, the patient and the therapist [14]. Once they log into the online INERX-VR system they can track the rehabilitation progress and refine the training protocol accordingly, reducing the costs and difficulties in arranging ongoing in-person therapies with scarce medical professionals [14]. Virtual therapists recorded by real-life physicians teach the patient how to use the INEREX-VR system, and the medical trainee evaluates the patient's emotional state monitored by the RAGE Project Facial Expressions Recognition software and the Mi Fit 3 bracelet (Xiaomi Corporation, China) for heart rate [14]. The patient plays the rehabilitation games via the HTC Vive (HTC, USA) headset operated by Unity3D for avatar animation [14]. The HTC Vive system connects to a high-end VR compatible PC (Intel Core™ i7-9700K 12 M Cache, up to 4.90 GHz processor, ASUS GeForce RTX 2070 ROG STRIX GAMING O8G 8 GB GDDR6 256-bit graphics card, 16 Gb DDR4 3200 MHz RAM and GIGABYTE Z390 GAMING X motherboard) for complex data processing [14]. Finally, artificial intelligence (AI) in collaboration with the therapist can facilitate the evaluation of the movements, accuracy, and the electromyogram (EMG) data of the patient measured by the Myo Armband (Thalmic Labs, Canada) [9], [14]. Moreover, the INEREX-VR focuses on the spastic stage of stroke rehabilitation, approximately three weeks of stroke onset for patients with a minor increase in muscle tone [14]. The framework of INEREX-VR and AI can be incorporated into the Metaverse to enhance the effectiveness of stroke rehabilitation. It is, however, a dilemma to resolve the technical difficulty of accessing and using EEG equipment by the public [12].

There are drawbacks to existing apparatuses; nevertheless, future innovation is expected to deliver more user-friendly and accessible digital technologies suitable for MI training in stroke motor rehabilitation [2], [5], [12], [21].

III. Challenges & Research Opportunities

Table I outlines the typical challenges influencing the feasibility of implementing the Metaverse in stroke motor rehabilitation. Stroke patients have suffered brain damage, which often impairs their cognitive functions [15]. MI is difficult, especially for stroke patients with poor brain health [15], [19]. Stroke patients may easily lose focus during MI even with the assistance of the Metaverse; furthermore, the equipment, such as HMD, may cause discomfort and insecurity, reducing the effectiveness of the Metaverse [12], [22].

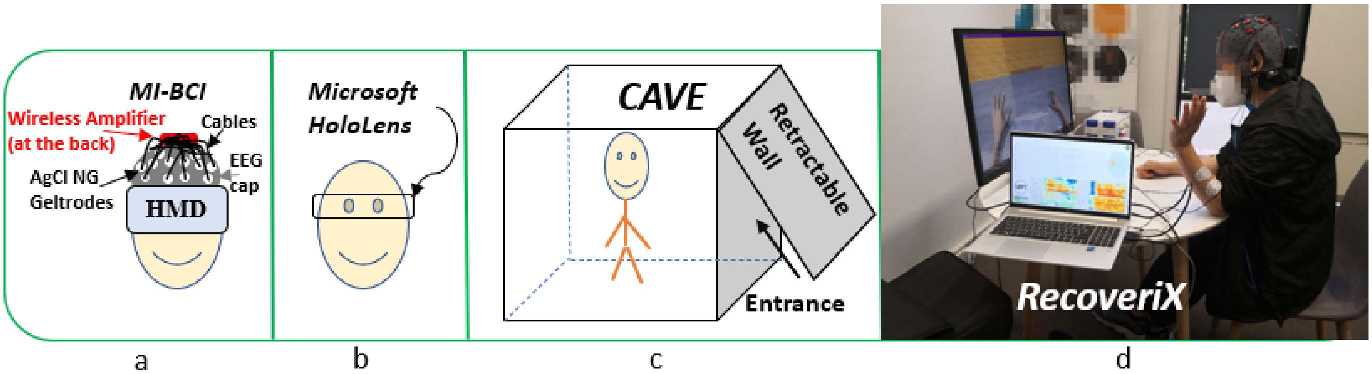

Fig. 2. Conceptual illustration of digital technologies (left to right): Rift HMD with EEG, Microsoft HoloLens, CAVE, RecoveriX.

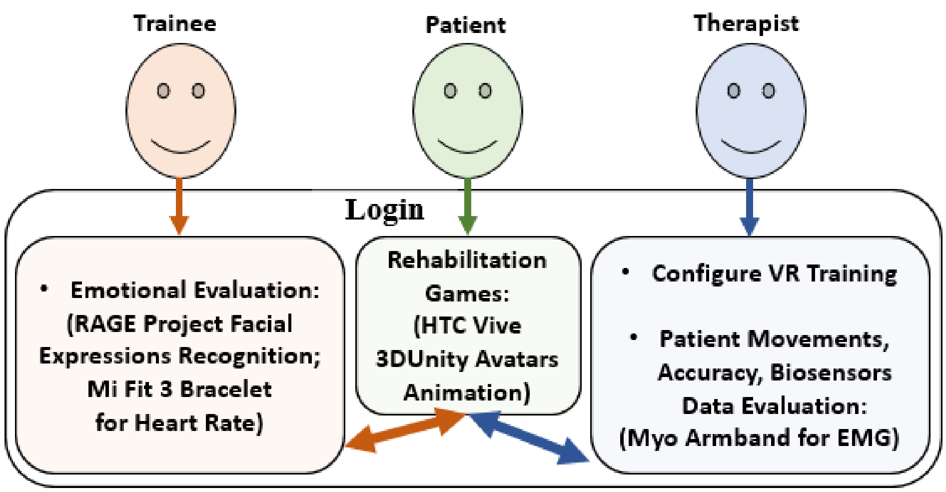

Fig. 3. A schematic of the interaction between patients and health professionals via the INREX-VR system.

Further research in the topics suggested in Table I could remediate the challenges facing the Metaverse in stroke motor rehabilitation:

- Although the Metaverse appears to be a practical option for stroke motor rehabilitation, a certain level of cognitive function is required of its users, which threshold is not well-defined and further research is necessary [13], [15].
- Unnecessary information displayed in the Metaverse may only increase the mental workload of users [18], [24]. VR is an immersive environment separated from the real world, usually via a HMD [9], [18]. AR is having digital elements in the real environment through the lens of devices [18]. VR requires less effort and mental demand than AR; however, the associated reason for the difference in workload between AR and VR is unknown [18]. The optimal dosage of AR and VR assisted MI rehabilitation should be further investigated [8], [18]. Future research is recommended to study the minimal features in a virtual environment required to induce presence, the sensation of spatially existing in a remote mediated environment which could be constructed by computers [10], [24]. The effects of group therapy sessions on social media concerning motivation and attention should be further studied [9], [10].
- MI quantification is a challenge as MI capability varies between individuals, and the underlying neural correlates of MI are not fully understood and require future research to elucidate the neural nature of MI [15].
- There are technical difficulties in controlling the Metaverse by only imagination. Some people are incapable of controlling BCI by MI, rendering MI-BCI ineffective for MI training; however, the underlying cause of BCI illiteracy can arise from improper MI-BCI training design in lieu of physiological nature [21]. The pretraining design for MI-BCI calibration can be improved by straightforward feedback via first-person VR avatar and a gamified scoring system with progressive difficulty for motivation and increasing information transfer rate [21].

TABLE I
METAVERSE CHALLENGES & RESEARCH OPPORTUNITIES IN STROKE MOTOR REHABILITATION.

Challenges	**Research Opportunities**
Cognitive Function Deficit	Cognitive Function Threshold
Attention Deficit	Minimal Features; (Group) Therapy Dosage
Lack of Motivation	Therapy on Social Media
Differences in MI Ability	MI Quantification
BCI Illiteracy	MI-BCI Calibration
Motor & Sensory Impairment	MI-BCI Feedback
Cybersickness Lack of Clinical Expertise	6G network & Reducing Latency; Wearable Hardware & Collaborative AI
Lack of Access	Cost Minimisation; Legal Framework

- The types of feedback are also crucial for the usability of MI-BCI. The feedback should make the user feel like a real physical movement has been performed, even if the user has only thought about the movement. Multisensory feedback can be achieved by using equipment such as visuotactile gloves and visuomotor stimulation in addition to visuals, requiring customised design to achieve full presence for stroke patients with a variety of motor and sensory impairments [8], [13].

- The plausibility of the display is less important than head tracking, frame rate, sound, and interaction methods [10]. To prevent cybersickness and lack of clinical expertise, research should focus on minimising latency and refining the interoperability between computer interfaces and users by human-AI collaboration such as fuzzy deep learning via expert inputs and supercomputers [2], [9]. The Metaverse requires vast networks on a global scale to ensure ubiquitous access with ultra-reliability, low latency, and large bandwidth [25]. 1G to 4G wireless systems mainly handle communications between people, while 5G enables mobile connections among machines and people [25]. The 6G network is expected to be capable of enormous data exchange for the integration of the virtual and real worlds, with a peak data rate of $>$100 Gbit/s and $<$1 ms latency in the air required of the Metaverse [25]. Future research is still needed for improving the 6G network because the sensing accuracy of 6G mobile technology is at the centimetre level, but Metverse requires a millimetre-level accuracy [25].

- The weight and the tightness of skin-contact biosensors lead to user irritation. Reducing the dependence on wearable hardware is crucial to provide a user-friendly and safe Metaverse apparatus, especially for vulnerable stroke patients in clinical settings [12], [22].

- Finally, optimisation of the legal framework concerning the implementation and affordability of the Metaverse is an important research topic for multidisciplinary professionals and policy makers [12]. To facilitate the implementation of the Metaverse in stroke motor rehabilitation, there needs to be a framework that ensures legality. Song et al. (2023) suggested the ″Rule of Lawful Governance″ for the safety features of the Metaverse [26]. The Metaverse in healthcare has to protect its users' privacy and intellectual property rights in accordance with relevant laws and regulations [26]. In the case of ambiguous legal or ethical matters, the Metaverse should commit to negotiations with all parties involved for resolutions [26]. The Sandbox Metaverse VR platform uses blockchain and AI technologies, which guarantees ownership of virtual assets and ensures security in transactions for goods and services in the digital world, providing a safe environment for health professionals and patients [26]. Digital currency enhances the immersiveness of the Metaverse, but necessary financial transactions for the Metaverse may only be secure with well-formulated regulations.

IV. CONCLUSIONS

The Metaverse is a promising VR social media platform for stroke motor rehabilitation. A pipeline to design a suitable Metaverse motor rehabilitation program is proposed for future multidisciplinary research. Apparatuses such as EEG-controlled BCI, INEREX-VR, AI, and 6G networks are suggested to facilitate the development of the Metaverse rehabilitation. The main difficulties in incorporating the Metaverse into stroke motor rehabilitation are determining an optimal

VR design for stroke patients, and the feasibility of using MI-BCI, calling for future solutions to implement the Metaverse stroke motor rehabilitation.

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