Survey of Movement Reproduction in Immersive Virtual Rehabilitation

Liu Wang, Mengjie Huang, Rui Yang, Hai-Ning Liang, Ji Han, and Ying Sun

Abstract—Virtual reality (VR) has emerged as a powerful tool for rehabilitation. Many effective VR applications have been developed to support motor rehabilitation of people affected by motor issues. Movement reproduction, which transfers users' movements from the physical world to the virtual environment, is commonly used in VR rehabilitation applications. Three major components are required for movement reproduction in VR: (1) movement input, (2) movement representation, and (3) movement modulation. Until now, movement reproduction in virtual rehabilitation has not yet been systematically studied. This paper aims to provide a state-of-the-art review on this subject by focusing on existing literature on motor rehabilitation using immersive VR. In this review, we provided in-depth discussions on the rehabilitation goals and outcomes, technology issues behind virtual rehabilitation, and user experience regarding movement reproduction. Similarly, we present good practices and highlight challenges and opportunities that can form constructive suggestions for the design and development of fit-for-purpose VR rehabilitation applications and can help frame future research directions for this emerging area that combines VR and health.

Index Terms—Virtual Reality, Movement Reproduction, Rehabilitation, Movement Representation, User Experience

1 Introduction

Virtual reality (VR) is a powerful and promising platform to support tailored applications in various fields, such as education, military, and health care. Recent advancements in VR technology have led to a renewed interest in this technology in rehabilitation. VR has several advantages that can be leveraged for rehabilitation: increased engagement for repetitive tasks; low-cost and reduced clinical supervision; real-time and historical tracking of the patient's rehabilitation process; and controllable and easily-adjustable stimuli and interactions to enhance motor learning [1]. Virtual rehabilitation has been shown to be more effective and engaging than conventional programs for patients in learning motor skills. It has has been used for motor rehabilitation [2] that is often aimed at to achieve motor recovery for patients with stroke, cerebral palsy, Parkinson's disease, and acquired brain injury. Given the more unique affordances of VR (e.g., full-body interaction and high level of immersion), researchers are now exploring how to achieve improved motor learning outcomes and enhanced user experience by using immersive VR-based rehabilitation treatments. In contrast to many earlier non-immersive applications [3], immersive VR (iVR) systems have many advantages in generating more presence, embodiment, and engagement.

In VR, motion tracking and computer graphics technologies allow users to perform body movements and obtain visual feedback in real-time for rehabilitation purposes. Movement reproduction in this paper is defined as the process that (1) encompasses motion data acquisition, (2) virtual representations, and (3) intervention strategies in virtual rehabilitation, where users' movements are captured in the physical world and reproduced in the virtual environment. During a virtual rehabilitation treatment for learning motor skills, three major components are associated with movement reproduction: (1) movement input, (2) movement representation, and (3) movement modulation. *Movement input* is a technology-based approach that allows acquiring users' movement data to drive movements in the virtual environment. *Movement representation* refers to the virtual representation of the patients' movement in the virtual environment. *Movement modulation* is an intervention strategy that modulates the virtual representation with the goal of enhancing the process of motor learning.

To develop a virtual rehabilitation application, developers need to consider how to apply movement reproduction for the prescribed rehabilitation goals and to better meet rehabilitation outcomes. However, the movement reproduction for virtual rehabilitation and applications that use it have not yet been systematically analyzed and clearly categorized. Previous review papers [4–12] regarding virtual rehabilitation have been conducted mostly through the lenses of medicine and with focuses on clinical outcomes and efficacy of such programs. These reviews, for example, have examined rehabilitation applications for stroke [4, 9, 11, 12], Parkinson's disease [5], spinal cord injury [7], acquired brain injury [8] or a specified body region such as lower limbs [10]. In addition, some survey papers include iVR applications together with non-iVR ones in their analysis results [9–12].

We found it is scarce in the literature a survey paper of virtual rehabilitation applications structured from the perspective of human-computer interaction (HCI). Virtual rehabilitation applications have much overlap with inter-

- *L. Wang and M. Huang are with Design School, Xi'an Jiaotong-Liverpool University, Suzhou, China.*
- *R. Yang and H.-N. Liang are with School of Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou, China.*
- *L. Wang and J. Han are with Department of Civil Engineering and Industrial Design, University of Liverpool, Liverpool, United Kingdom.*
- *Y. Sun is with Occupational Therapy Department, Kunshan Rehabilitation Hospital, Suzhou, China.*
- *Corresponding author: M. Huang; E-mail: Mengjie.Huang@xjtlu.edu.cn*

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active systems and human factors. As such, an in-depth analysis and structure of the exiting literature from an HCI perspective can be valuable to understand how to developed more effective virtual rehabilitation systems that focus on user experience in addition to the treatment outcomes.

This paper aims to fill this gap and provides a review of state-of-the-art works that exploit iVR technologies and a comprehensive analysis particularly looking at the movement based virtual rehabilitation. In short, the novel contributions of this paper are:

(i) A new classification that particularly focuses on the movement reproduction process in iVR from a human-computer interaction perspective;
(ii) Comprehensive discussions on rehabilitation goals and outcomes, technologies, and user experience regarding movement reproduction in virtual rehabilitation;
(iii) Highlighted challenges and opportunities for the design and development of virtual rehabilitation applications and research gaps regarding movement reproduction in virtual rehabilitation.

To the best of the authors' knowledge, this is the first paper that reports the results of a systematic survey on movement-related interactions and technologies for motor rehabilitation using iVR systems. The three major aspects of movement reproduction and its in-depth analysis based on the available literature can provide researchers an overview of the landscape, possible trends, and gaps, which could serve to inspire the development of more, higher high-quality rehabilitation programs. We hope that the references to past and current work, the detailed discussions, and the identified challenges and opportunities are useful for both researchers and developers to design effective virtual rehabilitation applications and frame efficient assessment strategies.

This paper is structured as follows. The method used to conduct the review is provided next, in Section 2. The results of the reviewed publications are described in detail in Section 3. In section 4, the in-depth discussions about the virtual rehabilitation goals, outcomes, technology issues, and user experience are presented. Identified challenges and opportunities for movement reproduction in virtual rehabilitation are highlighted in Section 5. Finally, a conclusion is provided in Section 6.

2 Methodology

The literature search was conducted with the following databases: Web of Science, Engineering Village, IEEE Xplore, and Google Scholar. The literature was searched with the following keywords: "virtual reality", "rehabilitation", "movement or motion", and "movement reproduction". The first step of the literature search led to 1639 papers that were retrieved from these databases: Web of Science core collection, Engineering Village, and IEEE Xplore. Then, in the second step, all the publications were screened according to their title and abstract. Those deemed irrelevant to this review were excluded. Third, the screened papers (n=376) were further checked using their full-text with the following set of exclusion criteria:

- Applications and studies that are not conducted within an immersive virtual environment;
- Works which are not related to movement-based rehabilitation;
- Studies without a description of how movement reproduction is achieved; and
- Duplicated publications.

Afterwards, additional publications (n=4) from Google Scholar that matched our review criteria were added to the final cluster of publications. In the end, 47 publications were included in this survey for detailed analysis.

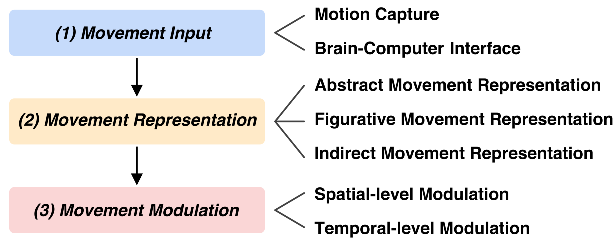

Fig. 1. Major components of movement reproduction

3 Results

From the literature obtained, three major aspects that contribute to movement reproduction in virtual rehabilitation are identified (as shown in Fig. 1). First, movement *input* refers to one technological component in virtual rehabilitation, with a focus on using motion capture systems to obtain users' movement, along with the promising approach of brain-computer interface (BCI) to identify users' movement intention. Second, movement *representation* in virtual rehabilitation applications is classified into three modes according to how movement is visually presented to users. Third, movement *modulation*, which refers to the manipulation of the user's movement in virtual rehabilitation, is described. Table 1 summarizes the final 47 publications reviewed in terms of movement reproduction, types of VR displays, rehabilitation goals for upper or lower limb, and rehabilitation goals for physical or occupational therapy.

3.1 Movement Input

Movement input is the process whereby the patient's real-time intended movement information is obtained from the physical world and transferred to the virtual environment to drive the movement representation. There are many devices and systems available to realize movement input for virtual motor rehabilitation. In the literature, the two typical methods to realize movement input are:

1) **Motion Capture**: users' body movements are tracked to be represented in VR.
2) **BCI**: brain signals of intended movements are analyzed to enable movements in VR.

3.1.1 *Motion Capture*

Motion capture is a method to achieve to capture people's real-time physical movement. With this method, users' movement data of joint positions and other body segments are transferred and then mapped to a representation of users in the virtual environment, typically in the form of an avatar. Motion captured data is to enable users to execute

TABLE 1
Summary of the literature search on movement reproduction in virtual rehabilitation.

Author	Movement Input	Movement Representation	1PP or 3PP	Movement Modulation	VR Display	Upper Limb or Lower Limb	PT or OT
Achanccaray et al. 2018 [13]	BCI	FMR	1PP	/	HMD	Upper limb	PT
Almousa et al. 2020 [14]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Aoyagi et al. 2019 [15]	EMC	AMR	/	Spatial	HMD	Upper limb	PT
Avola et al. 2018 [16]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Baqai et al. 2019 [17]	EMC	FMR	1PP	/	HMD	Upper & lower limb	PT
Biffi et al. 2017 [18]	EMC	IMR	/	/	Powerwall	Lower limb	PT
Borrego et al. 2019 [19]	EMC	FMR	1PP+3PP	/	HMD	Lower limb	PT
Bourdin et al. 2019 [20]	EMC	FMR	1PP	Spatial	HMD	Upper limb	PT
Calabrò et al. 2020 [21]	BMC	IMR	/	/	Powerwall	Lower limb	PT
Camporesi and Kallmann 2015 [22]	EMC	FMR	3PP	/	Powerwall	Upper limb	PT
Charbonneau et al. 2017 [23]	EMC	FMR	1PP	/	HMD	Lower limb	PT
Choi et al. 2020 [24]	BCI	FMR	1PP	/	HMD	Upper limb	PT
Choi et al. 2020 [25]	BCI	FMR	1PP	/	HMD	Upper limb	PT
Cikajlo and Potisk 2019 [26]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Correa et al. 2019 [27]	EMC	FMR	1PP	/	HMD	Upper limb	PT
D'Antonio et al. 2020 [28]	EMC	IMR	/	Temporal	CAVE	Lower limb	PT
Dias et al. 2019 [29]	EMC	FMR	1PP	/	HMD	Upper limb	OT
Elor et al. 2019 [30]	EMC	AMR	/	/	HMD	Upper limb	PT
Elor et al. 2018 [31]	BMC	AMR	/	/	HMD	Upper limb	PT
Fern'andez-Vargas et al. 2017 [32]	BCI	FMR	1PP	/	HMD	Upper limb	PT
Ferreira et al. 2019 [33]	BMC	FMR	1PP	/	HMD	Upper limb	PT
Juliano and Liew 2020 [34]	EMC	AMR	/	/	HMD	Upper limb	OT
Keersmaecker et al. 2019 [35]	BMC	IMR	/	Temporal	HMD	Lower limb	PT
Kern et al. 2019 [36]	BMC	IMR	/	/	HMD	Lower limb	PT
Khan et al. 2020 [37]	EMC	FMR	3PP	Temporal	HMD	Lower limb	PT
Lee et al. 2019 [38]	BMC	FMR	1PP	/	HMD	Upper limb	OT
Lin et al. 2018 [39]	EMC	FMR	1PP	/	HMD	Upper limb	OT
Lin et al. 2020 [40]	BMC	FMR	1PP	/	HMD	Upper limb	OT
Liu et al. 2019 [41]	EMC	AMR	/	/	HMD	Upper limb	OT
Liu et al. 2020 [42]	EMC	FMR	3PP	/	Powerwall	Lower limb	PT
Liu et al. 2020 [43]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Luis et al. 2016 [44]	BMC	AMR	/	/	HMD	Lower limb	PT
Lupu et al. 2016 [45]	EMC	FMR	1PP	Spatial	HMD	Upper limb	PT
Naranjo et al. 2019 [46]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Nataraj et al. 2020 [47]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Nataraj et al. 2020 [48]	EMC	FMR	1PP	Temporal	HMD	Upper limb	PT
ÖGÜN et al. 2019 [49]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Oagaz et al. 2018 [50]	EMC	FMR	1PP+3PP	/	HMD	Lower limb	PT
Ona et al. 2019 [51]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Ozkul et al. 2020 [52]	EMC	IMR	/	/	HMD	Lower limb	PT
Perez-Marcos et al. 2012 [53]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Periara et al. 2020 [54]	EMC	FMR	1PP	/	HMD	Upper limb	PT
Shum et al. 2019 [55]	EMC	FMR	1PP	Spatial	HMD	Upper limb	PT
Trombetta et al. 2017 [56]	EMC	FMR	3PP	/	HMD	Upper & lower limb	PT
Veen et al. 2020 [57]	EMC	FMR	1PP+3PP	/	HMD	Upper & lower limb	PT
Vourvopoloulos et al. 2019 [58]	BCI	FMR	1PP	/	HMD	Upper limb	PT
Xiao et al. 2020 [59]	EMC	FMR	1PP	/	HMD	Upper limb	PT

EMC = external motion capture; BMC=built-in motion capture; BCI = brain-computer interface
FMR = figurative movement representation; AMR = abstract movement representation; IMR = indirect movement representation
1PP = first person perspective; 3PP = third person perspective; / = not applied to this study
HMD = head-mounted display; CAVE = cave automatic virtual environment; PT = physical therapy; OT = occupational therapy

purposeful movements and obtain visual feedback of these movements when the avatar reproduces them. There are various types of motion capture systems with different parameters and performances [60, 61]. In this paper, the motion capture systems used by researchers and developers are classified into two types according to the physical location of the sensors in the VR system:

- **Built-in motion capture system**
- **External motion capture system**

The built-in motion capture system tracks the user's hand movements via sensors placed or already comes with or in a VR system (e.g., HTV Vive). Virtual rehabilitation applications can be implemented by merely using the built-in tracking sensors and software packages that are usually made available without additional cost. For example, the head and hand movements can be easily obtained by the tracking units in commercial head-mounted display (HMD) VR packages, such as HTC Vive (as shown in Fig. 2 (a)) [31, 38], Oculus Rift [33, 35, 36], and Samsung Gear VR [44]. The built-in motion capture capabilities can be further enhanced by employing relatively inexpensive tracking accessories such as the Vive Tracker from HTC to support real-time tracking of specific body parts by attaching one such a tracker to the desired part of the body [36, 62].

The external motion capture system becomes the developer's choice when the built-in motion capture system does not meet the requirements of an application. There are many types of external motion capture systems based on their

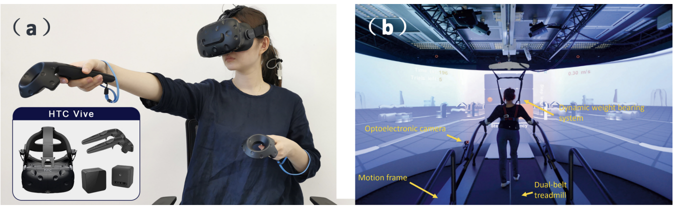

Fig. 2. Built-in motion capture system: HTC Vive (a) and external motion capture system: Vicon (b) [18]

performance, accuracy, area of coverage, and other features. For example, the Vicon motion capture system is marker-based to support full-body tracking for both upper and lower limb application [18, 22, 23, 42]. Fig. 2 (b) shows an external motion capture system based on Vicon. In a work by Camporesi and Kallmann [22], no less than ten infrared cameras were used in the Vicon motion capture system to allow very high precision tracking needed for their immersive environment. Another example of a marker-based optic motion capture solution is Natural Point's OptiTrack, which has also been applied in several virtual rehabilitation programs [15, 20, 53]. Both Vicon and OptiTrack based systems need markers to be placed on users' body and their accuracy can be improved further by adding infrared cameras. On the other hand, these systems may incur a relatively higher cost. The Leap Motion is another optical motion capture device that is low-cost and is favorable in upper limb rehabilitation programs to support natural interaction, where the users' gestures and hand movements can be tracked with high precision [26, 29]. Another low-cost motion capture device is Microsoft's Kinect, which contains depth cameras allowing marker-less and full-body tracking [19, 52, 63]. One other approach that is low-cost is the use of inertial measurement unit (IMU) that can track users' joint angle in wrist movements [41, 64] and can be attached to users' arms, suits or shoes when performing motor tasks [30, 50].

3.1.2 Brain-Computer Interface

BCI provides a new way for movement input by identifying the user's movement intention. It is an advanced technology that analyzes the brain signals obtained in real-time to enable the control of external systems, including VR. Also, it is used as a tool to determine whether the patient is correctly performing motor imagery (MI) training for rehabilitation [65]. MI is a type of cognitive training where patients imagine performing movements without any actual motor output. During the training via, similar activation patterns can be generated in the motor cortex when actual physical movements are performed. Two types of MI training can be adopted: *external*, with patients imagining scenes as an external observer; and *internal*, allowing patients to imagine movements in their own body. Fig. 3 shows a framework of BCI movement input in virtual rehabilitation. The brain signals of patients' movement intention are acquired from the measuring device and processed through three stages: pre-processing, feature extraction and classification. The pre-processing of brain signals is necessary in the initial, first stage to remove or minimize the influence of artifacts and noise in the data. The brain signals are classified based on the extracted features of the pre-processed data. They are finally transformed and interpreted to determine the intended meaning or intention of users to drive the motion of a virtual avatar body in the virtual environment.

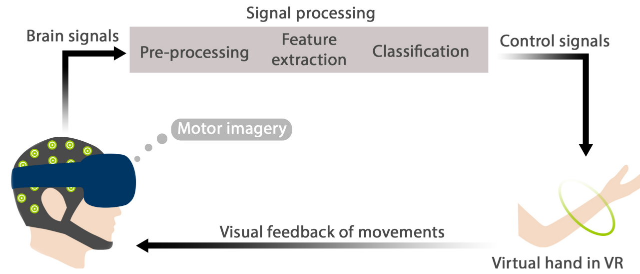

Fig. 3. Brain-computer interface (BCI) for virtual rehabilitation

In the field of motor rehabilitation, BCI has attracted considerable attention because this approach allows building a sensory-motor loop for patients with motor weakness or impediments [65]. As physical movement is often not possible in these patients for whom motion capture is not practical, BCI represents an suitable alternative because it can translate users' commands by identifying their intended movements from brain signals to drive movements and interactions in the virtual environment. In a paper by Vourvopoulos et al. [58], a platform that combined BCI and VR was developed for patients with stroke. The platform required electroencephalography (EEG) signals from patients that showed their movement intention. Then it would use the data to enable neurofeedback so that patients could observe their actions reflected in the virtual environment. Achanccaray et al. [13] developed another VR-BCI application for patients with stroke to allow them perform arm movements depending on the MI tasks. They showed that the application was effective for motor rehabilitation. A study by Fernández-Vargas et al. [32] using VR shows that the effect of using EEG signals only to reproduce movement is comparable with using a motion capture system.

3.2 Movement Representation

Movement representation is the visual feedback of the patient's motor behavior in VR and plays a significant role in learning motor skills [10]. In this paper, we have identified the following three modes of movement representation:

1) **Abstract movement representation (AMR)**: presented in the form of two-dimensional or three-dimensional abstract (non-humanoid) representation;
2) **Figurative movement representation (FMR)**: presented in the form of three-dimensional human or humanoid body (or body segment);
3) **Indirect movement representation (IMR)**: presented indirectly by changing the information context in VR, while not using FMR or AMR representation forms.

3.2.1 Abstract Movement Representation

AMR is usually displayed using simple graphics or three-dimensional (3D) objects (as shown in Fig. 4) that users can control. AMR is often used to represent the subtle movements of the human body. In this work by Juliano and Liew [34], a little black cursor was used to indicate the change in force of participants' fingers. When the force

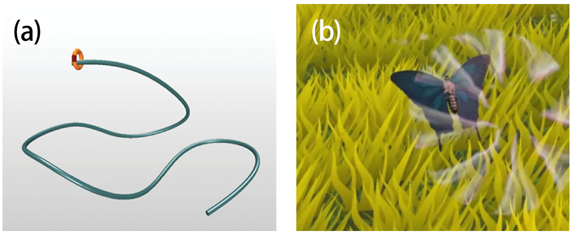

Fig. 4. AMR in forms of a 3D ring [41] (a) and a bubble [30] (b)

reduces or increases, the cursor would move towards the left or right, respectively. In an application by Liu et al. [41], a 3D circular ring (as shown in Fig. 4 (a)) was applied to assess the patients' wrists motor functions when they had to follow though a series of 3D curved lines. Similarly, Aoyagi et al. [15] proposed a rehabilitation system that used a virtual ball to represent participants' hand position in an upper limb virtual environment. Elor et al. [31] developed an upper limb rehabilitation application that relied on AMR mainly. The application was designed with a fictitious feature where patients would catch stars in the sky by manipulating a catcher the virtual environment. In this rehabilitation game, the patients were encouraged to use their weak arm more by rewarding them with more scores as more stars were caught by the weaker arm. Another application by Elor et al. [30] allows users to control a butterfly using a virtual bubble (as shown in Fig. 4 (b)) for the upper extremity rehabilitation.

Besides visualizing hand and arm movements, AMR can also represent movement of users' lower limbs. For example, an application by Luis et al. [44] was used for lower limb rehabilitation and represented the patients' movement in performing walking and balance tasks. In their program, a representation of a ball was used to show the balance of a teeterboard.

3.2.2 Figurative Movement Representation

FMR provides detailed and credible visual and kinematic information of patients' movements in VR. With rapid advancement in computer graphics and VR displays, FMR has been widely used rehabilitation applications in the publications reviewed. Data received from movement input devices are translated to FMR that shows movements and appearances that match closely those of the users.

The different perspectives given in the application reflect how much information the developers or clinicians want to provide to their patients, and can also largely depend on the rehabilitation type or outcomes. In terms of perspectives, FMR can be further classified into two categories according to what view users have when observing the representations in the virtual environments:

- **First-person perspective (1PP)**
- **Third-person perspective (3PP)**

In VR, 1PP is achieved by setting the camera view on the head of the avatar and simulates users' view in the physical world. In 1PP (as shown in Fig. 5 (a)), users can look at the hands, lower limbs, and other parts of their body, as they are accustomed to in the physical world and use them to pick objects up [66]. If the full-body motion is captured, the user can look down and around to check their embodied avatar. Many applications reviewed allow users to see their virtual

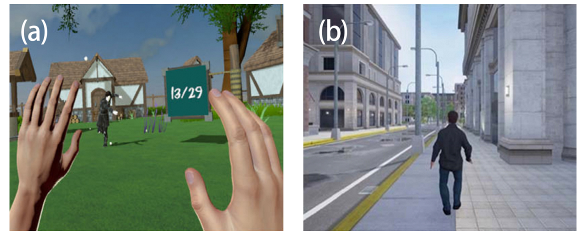

Fig. 5. FMR in 1PP [38] (a) and 3PP [42] (b)

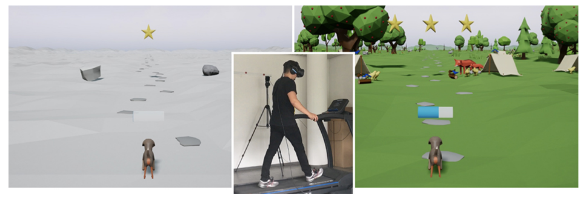

Fig. 6. IMR for lower limb rehabilitation [36]

avatars in 1PP when they perform tasks with their upper body (as shown in Table 1). Some of these applications provide non-human based avatars in 1PP to represent users' actions, such as using a robot and its hand for picking and placing objects [26]. In one application of rehabilitation by Naranjo et al. [46] both human-like and robotic hand avatars in 1PP are used. Additionally, FMR displayed in 1PP is also applicable to lower extremity tasks [23].

FMR in 3PP is usually displayed in an exocentric view (as shown in Fig. 5 (b)) or using other mechanisms like a virtual mirror [67] in front of the patient. FMR in 3PP is often used for lower limb rehabilitation, such as the training of gait [19, 42], where the full-body visual and kinematic information is provided to support body coordination. Trombetta et al. [56] developed a VR game, which included an FMR presented in 3PP and three rehabilitation tasks for lower limbs of post-stroke patients. Recently, Liu et al. [42] conducted a comprehensive study on FMR with three views for gait symmetry: the back view, the front view and the paretic side view and conluded that a paretic side view significantly improved gait performance. Furthermore, there is research using a full-body FMR presented in a mirror view [22] and 3PP [56] for upper limb rehabilitation.

There are also applications that allow users to have both 1PP and 3PP views. For example, in the application of mobility training for stroke patients by Oagaz et al. [50], the 1PP and 3PP can be toggled in between. Having access to both views could be beneficial as they could elicit different types of experiences and support achieving complementary outcomes [50, 68, 69].

3.2.3 Indirect Movement Representation

IMR does not directly present any user-related visual information but movements are displayed and be observed in the virtual environment with indirect representations. It is the change of optic flow in the environment that makes users believe as if they are moving or navigating. The optic flow speed provides users' information about the speed and the direction of their movements [70, 71]. In lower limb rehabilitation, the contextual environment changes with the optic flow to generate the sense of walking. The type of environment can use vivid contextual information, including the

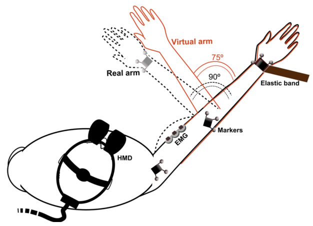

Fig. 7. An example of movement modulation in arm flexion [20]

background and visual objects, often with natural features, to enhance users' presence and engagement [18, 35, 36]. In a work by Biffi et al. [18], six rehabilitation tasks were developed via IMR for patients walking on a dual-belt treadmill (as shown in Fig. 2 (b)). A virtual rehabilitation application developed by Kern et al. [36] (as shown in Fig. 6) used IMR shown in an HMD plus an HTC Vive Tracker and a treadmill. The context information in their program provides a dynamic and changing world for the patients to explore and the experience increase their immersion and engagement in the rehabilitation process. Another application using IMR is by Keersmaecker et al. [35]. They conducted a research with a robot-assisted rehabilitation program for treadmill walking with two types of IMR. Ozkul et al. [52] also applied IMR in their lower limb rehabilitation for patients to train their balance without avatar representations.

3.3 Movement Modulation

Movement modulation refers to the intervention strategy of the captured movement information applied in movement representation. Prior to using any intervention in movement representation, establishing real-time normative movement information is important for all motor rehabilitation protocols. For motor rehabilitation aimed at achieving compensatory movements for patients, modulation of movements is effective and has been adopted widely in earlier non-VR rehabilitation treatments, such as for chronic stroke recovery [72]. VR gives the developers the ability to manipulate movement information easily and add additional details whenever necessary. This is where movement modulation is useful and allows applications to achieve rehabilitation goals, like using compensatory information to show movements. Movement representation can be modulated to be either augmented or reduced visual details [73, 74]. The strategy in movement modulation also varies according to the specific body parts involved, the perspective used, and rehabilitation goals. Our analysis of the literature show that there are two movement modulation strategies or levels in motor rehabilitation:

1) **Spatial-level**: position and angle
2) **Temporal-level**: indirect movement cues

3.3.1 *Spatial-level Modulation*

One type of movement modulation at the spatial level is to manipulate the position of the virtual body [15, 48, 55]. In an upper limb rehabilitation designed by Shum et al. [55], movement modulation at the spatial level is implemented in an iVR for the participants with hemiplegic cerebral palsy. In their hand-reaching task, the forward position in the more affected side was visually augmented to improve symmetry in bimanual tasks. Another virtual rehabilitation application proposed by Aoyagi et al. [15] also used spatial-level movement modulation. In their upper limb rehabilitation system, the participants were asked to trace a target ball in VR, while the position of the virtual hand was presented in the middle-point between the target ball and the actual hand.

Another type of movement modulation at the spatial level could be realized via changing the angle of flexion of movements of the joints. Two studies reviewed have applied this type of movement modulation. In works by Bourdin et al. [20] (as shown in Fig. 7) and Lupu et al. [45], the real arm movement was translated into a virtual arm avatar but the representation altered the flexion angle, either reducing or amplifying it.

3.3.2 *Temporal-level Modulation*

Temporal-level movement modulation is realized via indirect movement cues. For lower limb rehabilitation, movement modulation can be achieved by changing the speed of the optic flow. A study has shown that a lower optic flow speed increased participants' walking speed, while a faster flow speed increased their speed [75]. In a recent investigation of robot-assisted gait rehabilitation, the manipulation of optic flow only was found to have a limited effect on active participation in healthy participants. [35].

4 Discussion

The previous section has presented the main results of this literature review. In this section, the results are summarized and compared by discussing rehabilitation goals, rehabilitation outcomes, technology issues, and user experience from the frame of movement reproduction.

4.1 Rehabilitation Goals

Rehabilitation goals of virtual movement rehabilitation programs can be broadly classified into two: *physical* therapy and *occupational* therapy. Physical therapy focuses on improving the patients' overall physical functions and body movements, whereas occupational therapy focuses on helping a patient to (re)develop and relearn motor skills needed for activities in daily life. The next discussion is framed by these two categories. In addition, the following section is organized from the perspectives of body regions targeted for rehabilitation (i.e., upper limb and lower limb).

4.1.1 *Physical Therapy*

Physical therapy and occupational therapy are two major rehabilitation objectives of motor-impaired patients. In the literature we reviewed (as shown in Table 1), we can see that most applications (41 out of 47) in virtual rehabilitation focus on physical therapy, whereas only six publications deal with occupational therapy.

Physical therapy aims to restore motor functions by using physical interventions or therapeutic exercises through repetitive, intensive, and long-term training. By improving the range of motion and strengthening the muscle of the body, physical therapy is usually taken in the early stage of the rehabilitation process, in which therapeutic exercise is an important component. For virtual rehabilitation targeting therapeutic exercise in a physical therapy regime, the type of movement feedback provided is highly dependent on the motion(s) captured, to provide feedback via movements represented in the virtual world. In the physical therapy programs we identified, 30 employed external motion capture systems, 6 used built-in motion capture systems, and 5 relied on BCI to capture movement input information. All the BCI-based programs aimed at the recovery of motor functions in a specific limb. In the current literature, movement representation (FMR, AMR and IMR) varies in these programs. As there are no rigid requirements of the environment in which movement is performed, movement representation in physical therapy largely depends on the predefined gameplay strategies and themes. It is worth noting that the body ownership elicited by FMR would be beneficial for motor rehabilitation. However, movement representation with AMR and IMR has the potential to extend the forms of the games, scenarios, and themes. This flexiility can bring more freedom in the development of physical therapy programs, and generate more diverse and creative modes of therapeutic exercises for users. From this literature review, all the programs that applied movement modulation are for physical therapy. Movement modulation in physical therapy based on virtual rehabilitation can be introduced as an effective strategy for improving the range of motions in the body [20, 55] and for enhancing the sense of agency [15]. Technically speaking, movement modulation is also feasible for customization (e.g., the difficulty level) via reduction or enhancement modes in a specific movement types such as arm reaching [55] and arm flexion [20, 45]. The customized difficulty level via tailored movement modulation in motion tasks offers users adjustable, personalized goals that can meet their actual needs. Additionally, with modulation of movement, a physical therapist can try to find an optimum training pattern and regime that is based on specific motor functions and types of therapy.

In the rehabilitation process, patient dropout is one major issue that frequently arises, either with a virtual environment or a standard non-VR approach. Conventional physical therapy can be tedious and boring due to intensive and repetitive tasks. The lack of positive feedback, along with the negative effect on their mental state after suffering an accident or motor disease, may result in a decrease level of adherence or compliance rate of patients, which could lead to dropouts halfway during the rehabilitation process. Virtual rehabilitation applications can be designed and used to decrease the dropout rate. On the one hand, movement reproduction activates the real-time feedback of users' actions. Using auditory, visual and tactile stimuli, the feedback given can be more enriching, immersive, and motivating to not only serve to guide but also to encourage further practices (e.g., by incorporating gamification elements [63, 76] or including aspects that can connect patients to the VR environment to make it more personalised). Feedback that is interesting and given in real-time is often not possible in conventional physical therapy. However, iVR systems can afford this easily and, when design well, can be quite engaging and motivating to users and can potentially reduce dropouts [31]. On the other hand, movement input facilitates physical therapy by monitoring the rehabilitation progress using real-time data captured by trackers [31, 46, 56]. The acquired spatial-temporal data can be used to also track therapy process and help locate areas in the process that can be improved for the rehabilitation of other patients. This iterative, longer-term data driving process can make the therapy more suitable, effective, and enjoyable for patients, which could also decrease the dropouts.

4.1.2 Occupational Therapy

Occupational therapy is oriented to support learning (and sometimes re-learning) of complex motor skills to carry out activities in users' daily life. The ultimate goal of occupational therapy is to help patients regain independence in their daily activities and to return to normal life disrupted by the lose of motor functions of parts of their body. Occupational therapy is often introduced later in the rehabilitation progress than physical therapy. The incorporation of occupational therapy with virtual rehabilitation is less visible in papers in our review (6 out of 47 papers, as shown in Table 1) compared to physical therapy.

External motion capture systems (4 out of 6) were more frequently used in occupational therapy than built-in motion capture systems (2 out of 6). Theses sensors include the pinch force sensor [34], IMU [41], and leap motion trackers [29, 40] that were used to track precise and complex limb movements required in training tasks in occupational therapy. Based on this observation, one can suspect that built-in motion capture systems may not be that suitable for occupational therapy using virtual rehabilitation to some extent. First, built-in sensors require patients to grasp controllers, which contains the motion sensors, with their hands. Holding them continuously can be challenging for patients who have motor issues. Second, in the same way, if patients need to use their hands to hold the trackers, their hands are no longer available for other tasks (e.g., holding a cup or a hammer) that they need to do during occupational therapy.

Our review shows that movement representation in occupational therapy based virtual rehabilitation relied mostly on FMR. As occupational therapy is developed for simulating a wide range of real-life activities, a higher degree of realism representation is required in the virtual scenarios. For example, FMR can support various activities with their hands, such as dish washing [29], using a hammer, pouring tea or water into a cup [38], as well as functional training with their arms [39]. Besides, AMR is also helpful in the occupational therapy targeted at fine motor skill training with users' fingers and wrists [34, 41]. Our review also points to a gap in the literature in the use of movement modulation in occupational therapy with virtual rehabilitation systems. This is probably because occupational therapy is focused more on movements that are more technically complex and challenging to apply modulation strategy.

Overall, there is a relatively limited number of studies on occupational therapy with virtual rehabilitation. A couple of reasons might explain this. In general, occupational therapy is tailored for training of skills through simulated real-life, daily experiences. Thus, it is difficult for developers to provide the degree of fidelity and realism required in a virtual environment. One approach to provide realistic visuals and feedback is in the form games but it is difficult to ensure that they could provide the learning experience that aligns with real life activities, especially to meet occupational therapy requirements. From another point of view, the necessity and significance of using VR in occupation therapy may be questioned. Since its main focus is for patients to regain abilities to do daily-life activities, the therapy outcome may be more direct and better achieved with rehabilitation performed in the real, physical world than in a virtual one.

4.1.3 Upper Limb Rehabilitation

In the literature, movement based virtual rehabilitation can fall into two major applications according to the targeted body region: upper limb and lower limb. Both applications shared the same goal to improve the quality of life of patients via motor learning. Movement reproduction in those applications is necessary for and supportive of motor learning to achieve their rehabilitation goal. The main focus in upper limb rehabilitation is to train patients to relearn specific motor skills and activities in daily life through movement tasks tailored for the recovery of motor functions in the upper limb [77]. Upper limb dysfunction can be found in many patients with stroke, Parkinson's disease, cerebral palsy, or acquired brain injury. The resulting neurological problems include a series of upper motor dysfunctions such as motor control impairments, weakened muscle strength, changes in muscle tension, and joint laxity [77]. The recovery of upper limb motor function is critical for those patients because these impairments negatively impact their quality of life. The upper limb is attached to the trunk and the body areas which extend from shoulder joints to fingers [78]. According to the specific regions in the upper limb, the movement tasks in upper limb rehabilitation include a wide range of motion in the shoulder, elbow, arm, wrist, hand and fingers. As shown in Table 1, 35 publications in total related to upper limb virtual rehabilitation are identified in this review.

In upper limb virtual rehabilitation, there is a focus on using external motion capture systems to track users' upper limb movements. Although built-in motion capture systems can track a range of movements and are used in several applications (4 out of 35), the most applications used external motion capture systems because they help realize a more natural interaction that originates from users' upper limb. 11 publications have been identified using Leap Motion, which is the most frequently used external motion capture device for movement input. A small number of studies (5 out of 35) used BCI to realize movement input in upper limb rehabilitation.

With regard to movement representation, the majority of the upper limb rehabilitation applications have relied on FMR (30 out of 35). Only a small number of studies (5 out of 35) utilized AMR in their applications. There are possibly several reasons behind it. First, FMR, which presents more realistic representations of the upper limbs, may offer a natural experience for users. Second, some upper limb motor tasks that require subtle movements need FMR to represent precise hand movements. Last, some frequently used motion capture device like Leap Motion already provide figurative hand models, which can be easily applied in rehabilitation programs.

A few studies (5 out of 35) applied movement modulation in the upper limb to investigate its impact on motor performance and user experience. Three of these studies modulated virtual hand movements in position [15, 48, 55], and the other two modulated virtual arm rotation angle [20, 45].

4.1.4 Lower Limb Rehabilitation

Lower limb rehabilitation aims to restore motor functions related to the lower limb for patients with neurological issues. Patients with Parkinson's disease, spinal cord injury, traumatic brain injury, and multiple sclerosis can adopt lower limb rehabilitation treatments to regain their lower limb motor functions by improving their walking and balance abilities. Balance and gait are two major types of training in lower limb rehabilitation. The regions in lower limb rehabilitation covers from the gluteal region to the foot [78]. As such, the movements in lower limb rehabilitation include activities in the hip, legs, knee, ankle and feet. As shown in Table 1, in total 15 articles related to lower limb rehabilitation are found in our review. Among the 15 articles, three articles applied both upper and lower limb rehabilitation [17, 56, 57].

Around one-fourth of the publications (4 out of 15) in lower limb rehabilitation took advantage of built-in motion capture systems. However, most applications (11 out of 15) utilized external motion capture systems. When developing lower limb rehabilitation programs, it is essential to represent lower body movements, whereas the head tracking unit in the built-in motion capture system alone lacks the capability or precision to track lower limb movements. We found no publications reporting using BCI for movement input.

Several applications (8 out of 15) used FMR to represent full-body movements for lower limb rehabilitation. Only one study reviewed represented users' movements via AMR [44]. Besides, IMR is more suitable for lower limb rehabilitation than upper limb rehabilitation, with less than half of the studies (6 out of 15) relying on IMR. Lower limb rehabilitation for gait training could be tedious for patients and a virtual environment that contains changing scenes could increase users' motivations to use such an environment [36]. IMR in lower limb rehabilitation, when facilitated with a treadmill, can be a promising and innovative platform for patients in practice and improve their walking ability.

A few research papers (3 out of 15) studied movement modulation in the temporal level in lower limb rehabilitation. One study modulated the optic flow speed during robot-assisted treadmill walking exercises for healthy participants in VR [35], and found that a slower optic flow speed in the virtual environment of a hallway increased users' muscle activity. A study modulated the optic flow speed in a CAVE rehabilitation system for balance training, but no correlation was found between the sway amplitude and the modulated speed [28]. Another study modulated the avatar step cycles with temporal and auditory cues to help users coordinate their steps within a walking task [37]. It found that movement modulation in temporal levels of the avatar could change the user's movements.

4.2 Rehabilitation Outcomes

The process of motor learning reveals the gradual progress of movement rehabilitation. An effective virtual rehabilitation outcome can be achieved by incorporating motor learning principles and assessed by the motor learning assessment approaches. In this section, we discuss the motor learning principles that determine the general design guidelines of rehabilitation applications. At the same time, in the discussion of motor learning assessment, some necessary and standardized assessments of rehabilitation outcomes are presented. In the discussion of motor learning results, the relationship between the movement reproduction methods and rehabilitation results is illustrated.

4.2.1 Motor Learning Principles

The primary goal of either upper or lower limb rehabilitation is for users to relearn or reacquire some lost motor skill or function, so that they regain independence in their daily-life activities in the long run. Virtual rehabilitation applications should be goal-directed, with movement reproduction incorporating motor learning principles to help achieve their intended outcomes effectively. According to motor learning principles [79], movement reproduction optimizes the relearning of motor skills mainly via repetitive tasks, appropriate sensory feedback, and motivation reinforcement. Next, we provide a discussion on how movement reproduction is incorporated with motor learning principles in virtual rehabilitation.

Movement reproduction facilitates motor learning by enabling performance of tasks in a progressive manner within the virtual programs. The motion capture applied in these systems can support various activities that integrate multiple or separate body movements in virtual tasks [48, 56]. Through repetitions of various movements, motion capture devices track can their successful completion in the virtual environment and deliver feedback of the tasks to patients in a way that can motivate them to go to the next task [31]. Also, motion capture devices record the movement performance by using spatial and temporal data to enable progressive rehabilitation. The progressive difficulty in rehabilitation tasks can be adjusted using the data recorded.

Movement reproduction provides necessary sensory feedback, especially visual feedback for motor learning. FMR and AMR represent the patient's movement directly through virtual avatars and serve as the visual feedback for motor learning. Some motor tasks in virtual rehabilitation, such as grasping of objects by hand and flexion of an arm [16, 45], require the coordination of several body parts. Avatars presented in the form of FMR are especially suitable for these kinds of tasks because of the affordability of visual feedback to present movements with multiple joint changes is significant for motor learning. In some rehabilitation tasks, such as pinch force training [34], very little visual information is required to present the subtle movement in the body. Moreover, the redundancy of movement information in the visual feedback might distract patients from the tasks. In those tasks, a much simpler visual pattern, such as AMR, may help patients to be more concentrated on motor learning. Another kind of visual feedback in the form of IMR, which does not use avatar representations, provides patients with visual feedback in a more contextualised manner. This kind of visual feedback is currently used in tasks for lower limb rehabilitation. Specifically, in lower limb tasks dealing with gait, the walking of the patient is limited by the space of the training room and by size of the effective tracking area. The optic flow in virtual environments is necessary to allow patients to sense their walking speed and direction, often with the help of a treadmill to facilitate the generation of realistic sensory feedback [35].

Movement reproduction in virtual rehabilitation reinforces patients' motivation in motor learning by implementing movement modulation. Movement modulation motivates patients to perform movements in rehabilitation tasks by either reduction or augmentation the movement representation of the position or angle of a virtual limb. Paper in our review show that the use of modulation is effective by reducing the rotation angle, or by increasing the presented distance between the real and targeted positions to increase the range of motion, as well as muscle activity in the arm, which can be very effective in the rehabilitation of patients with ischemic issues and motor challenges [20, 45, 48, 55]. Movement modulation can motivate faster walking speed by manipulating the optic flow speed with more contextual information [35, 75].

4.2.2 Motor Learning Assessments

Effective assessment methods are required to monitor the learning outcomes of the virtual rehabilitation applications. Motor learning can be assessed by qualitative, semi-quantitative and quantitative assessment methods. In virtual rehabilitation, the standardized assessment (semi-quantitative) and quantitative assessment have been used to monitor the motor learning outcomes. The majority of the publications reviewed (36 out of 47) assessed the motor learning outcomes in virtual rehabilitation. As shown in Fig. 8 (a), quantitative assessments are more frequently used (31 out of 36) to assess motor learning outcomes, compared to the standardized assessment method (12 out of 36). In the 36 publications, seven studies adopted both of these two assessment methods.

The standardized functional assessments are used frequently for upper limb rehabilitation with high reliability. These include the Action Research Arm Test (ARAT), Box Block Test (BBT), and Fugl-Meyer Upper Extremity (FUE) [80]. The ARAT and BBT assessments has been shown to have high efficacy for upper extremity rehabilitation for patients with stroke supported by built-in motion capture using FMR [38]. BBT tests can also be conducted in virtual rehabilitation for patients with Parkinson's disease to assess manual dexterity [26, 51]. For many patients with stroke, ischemic side rehabilitation is vital for carrying out daily life movements. The motor learning outcomes assessed in one study have shown that the ischemic side rehabilitation in VR was effective for upper extremity functions measured by FUE, ARAT, Functional Independence Measure and Performance Assessment of Self-Care Skills [49]. However, results did not show improvements in functional independence. For lower limb rehabilitation assessments, Berg Balance Scale [19, 21, 28, 44, 52] is a frequently used method for balance analysis. The Time Up and Go Test [21, 44, 52] has also been used to assess mobility and balance.

One of the advantages of standardized assessment methods is that they are easy to use, follow a standard process, and provide specific ways to measure patients' functional impairments. They are most frequently used to help the therapist to determine the types and levels of impairments and make rehabilitation plans accordingly. Still, there are limitations using these standardized assessments as reported in the literature. One limitation is that they require on-site administration and subjective ratings by occupational therapists [81]. Another limitation is the "ceiling effect" that may occur in the later period of rehabilitation [82]. For instance, the scores of FUE become less sensitive when the individual is learning fine motor skills, such as wrist motor function [41].

In addition to standardized assessments, quantitative movement data can be obtained from motion capture devices to provide accurate and objective information for revealing the rehabilitation results. The analysis of the spatial-temporal data, such as range of motion [17], movement speed [16], level of muscle activity [17, 20], task completion time [26, 41] and movement trajectory [15, 22], can quantify the degree of motor impairments. This type of analysis can help overcome the limitations of standardized assessments, and support more effective therapeutic plans and outcomes.

4.2.3 Motor Learning Results

Motor learning results can be assessed using both quantitative and standardized assessment methods mentioned in the preceding section to show the actual effectiveness and outcome of the rehabilitation process.

Virtual rehabilitation programs that utilized external motion capture devices have been shown to improve motor functions, such as walking ability in patients with acquired brain injury [18], fine motor skills in individuals with Parkinson's disease [26], and upper limb symmetry in patients with Cerebral Palsy [55]. In rehabilitation programs with built-in motion capture systems, effective, positive rehabilitation results were also found, particularly in the improvement of walking speed and stability of patients with Parkinson's disease and stroke [21, 44], and the upper limb mobility of patients with stroke [38]. However, the effect of movement input on rehabilitation results has yet to be explored. we did any paper in our review that has reported comparative rehabilitation results using different motion capture systems. Only one study reviewed has compared two types of external motion capture devices (Kinect and OptiTrack) [53]. The authors gave a better preference for OpticTrack but did not present any rehabilitation results . Further research can be conducted to fill this gap. BCI-based movement input is a suitable approach to bring positive rehabilitation outcomes to patients with severe movement disorders. As revealed by a pilot study [58], the virtual rehabilitation intervention leveraged by the BCI approach potentially has the most positive effect on patients with the worst level of motor impairments [58], as they typically have very limited body movement.

A virtual rehabilitation program that represented wrist movement with AMR showed positive rehabilitation results for individuals with upper neuron lesions using quantitative assessments of virtual guiding tasks [43]. Two virtual rehabilitation programs, which utilized FMR and IMR respectively, led to improvements of lower limb motor function for patients with stroke [28, 83]. One aspect that our review cannot conclude is whether differences in movement representation impact rehabilitation results, because there are a limited number of studies. On the other hand, there are indications from one study that that the use of movement representation in virtual environment showed better quality of upper-limb reaching motions than without movement representation [22]. Besides, a study of bimanual virtual rehabilitation tasks performed by healthy participants showed that FMR led to higher learning outcomes for coordination skills than AMR [59]. This might be because the increased realism of movement representation elicited a higher sense of agency and consequently influenced their participants' performance. The results from a lower limb virtual rehabilitation program showed shorter stride length and smaller knee flexion during crushing objects using non-human (monster-like) movement representation than human-like movement representation [23]. Studies using full-body motion-based VR games have shown that augmenting players with non-human abilities (e.g., [84]) had shown to have a positive effect on game experience and energy exertion. However, given the limited available literature in rehabilitation, it is still unclear whether adding such non-human powers and using monster-like avatars can have a positive effect on patients going through rehabilitation. Further research is needed to validate this approach.

The influence of movement modulation on motor learning outcomes is relatively clear. A study showed that the implementation of movement modulation was found to have improved bimanual symmetry in a virtual rehabilitation program targeting individuals with hemiplegic cerebral palsy [55]. Another study conducted among healthy individuals found that their arm rotation resulted in larger ranges of motion, driven in part by movement modulation, which also showed its promising effect for improvement in virtual rehabilitation outcomes [20]. A study of robot-assisted gait rehabilitation showed that slow optic flow had only a small effect on hip interaction torques during walking tasks in a virtual environment [35]. As suggested by this study, the influence of optic flow speed on rehabilitation results needs to be further explored for patients with gait impairments trained via a robot-assisted treadmill.

As many virtual rehabilitation applications in this review were still at a preliminary stage of research and development. Only half of the studies (24 out of 47) had included patients to assess the effectiveness of their program. In the future, more studies literature to validate their results with their intended motor-impaired patients.

4.3 Technology issues

For an effective virtual rehabilitation application, several movement reproduction technologies are required and play significant roles. VR, motion capture, BCI, movement representation, model generation and movement modulation are the technologies involved behind the movement reproduction, which will be discussed in the following section.

4.3.1 Virtual Reality

VR is a technology that simulates and mimics real-life environments via immersive displays and is experienced by users through a human-computer interface. Various types of software and hardware need to be integrated to generate a virtual environment with varying degrees of realism. The interface is the main component that links users to the environment and can typically involve users' visual, auditory, and tactile senses during interaction [85]. In virtual rehabilitation, VR technology enables the patients to be immersed in the computer-generated virtual environments and interact in real-time with the virtual objects in a naturalistic way, for example using body, arm, and hand motions [3]. VR has several advantages that can be leveraged for motor rehabilitation: natural interaction, multi-sensory, and real-time feedback [85]. In their earlier years, VR applications in motor rehabilitation focused on using desktop displays with joysticks as their primary input mechanism. While they were not as immersive as current VR HMDs. Since 2016, immersive VR HMDs has grown significantly and become more affordable with the release of Oculus Rift and HTC Vive. Accordingly, most of the publications identified are based on HMD devices (42 out of 47) in the recent four years. In these studies based on HMD devices: 4 studies used HTC Vive; 30 studies used Occulus Rift; one study used Occulus Quest; 2 studies used NVIS; 2 studies used Samsung Gear VR; one study used Occulus Goggle; and two studies did not mention the types of HMD devicse used. Besides HMDs, there were still a small number of studies using another other types of VR displays, such as powerwall screen (4 out of 47). One study used CAVE [28].

The most frequently used HMD devices are Oculus Rift and HTC Vive because they provide several advantages to researchers. First, they allow 360-degree view of the virtual environment, providing a high level of immersion and increased level of presence and embodiment. Second, these HMD devices are inexpensive and lightweight, which are suitable for home-based rehabilitation. Another solution to visualize movements is via a powerwall screen, which shows 3D images with high-saturation on a big screen, and users are provided with stereo glasses. This kind of VR display is usually furnished with optical motion capture systems such as Vicon, allowing a wide range of movements in virtual environments [18, 22, 42]. Simular to CAVEs, Powerwall screen setups are expensive and not very flexible, features that HMD devices have helped overcome. This trend will likely continue with HMD devices being the preferred choice of VR displays for virtual rehabilitation studies.

4.3.2 Motion Capture

Motion capture is the most frequently used method to realize movement input in virtual rehabilitation. Proper choice of motion capture systems can help accelerate patients' rehabilitation [60].

As shown in Fig. 8 (b), eight papers used built-in motion capture systems for upper and lower limb virtual rehabilitation. The advantages of using a built-in motion system are fairly straightforward. First, the setup is quite simple as it is often built into the VR package. Second, the handheld controllers provided to track hand movements are particularly suitable for many upper limb rehabilitation routines. On the other hand, the main limitation of the built-in motion capture systems is that the full-body kinematic data and fine body movements can be challenging to track. To achieve full-body tracking, external tracking devices are required.

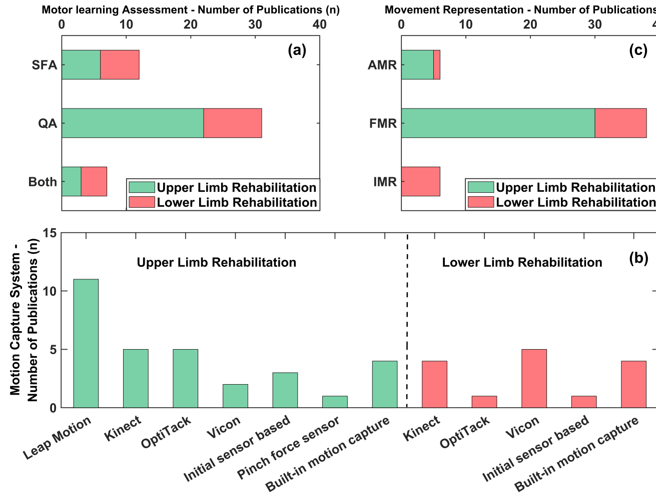

Fig. 8. Number of publications: (a) motor learning assessment (SFA = Standardized Functional Assessment; QA = Qualitative Assessment ;Both = using both two methods); (b) motion capture system; (c) movement representation

Compared with built-in motion capture systems, external motion capture systems can achieve more natural interaction and highly accurate performance, especially for full-body interaction. An advantage these systems is that they enable users to interact more naturally with the virtual environment, for example without the need for their hands to hold controllers or tracking device. Another benefit is that they allow tracking of the full-body quite accurately even for fine movements of specific body segments. As such, they are suitable for both upper and lower limb rehabilitation. As shown in Fig. 8 (b), the majority of the upper limb rehabilitation studies utilize external motion capture systems, which Leap Motion being the most popular choice. For lower limb rehabilitation, the majority of the applications took advantage of full-body motion capture systems, with Vicon and Kinect as the most frequently used systems, as shown in Fig. 8 (b). In one study we reviewed, the authors compared two motion capture systems (Kinect and OptiTrack) and concluded that the marker-based OptiTrack is preferred because of its higher saturation and reliability [53]. Such comparison, while useful, needs to be placed in a larger context, as the OptiTrack, just like the Vicon, is expensive and require a large space to set up.

4.3.3 Brain-Computer Interface

For motor rehabilitation, the advantage of BCI is that it can be incorporated with MI training to realize motor recovery at all stages [13, 32], especially in the earlier on during rehabilitation that requires no physical movements executed by patients who do not have ability to move or are in pain to do so. MI training is effective in conventional physical rehabilitation for both upper limb and lower limb movements, including a range of ADL and motor skill tasks. Action observation (AO) is another type of training where patients get trained by observation of movements of other people to help activate brain areas that are used for performing movements [86]. MI and AO training are both effective when used separately and can be integrated together into a training program for rehabilitation of individuals with neurological disorders [87]. The combination of BCI and VR provides a suitable platform for MI and AO training [88]. This BCI-VR combination is considered a promising platform for motor rehabilitation and there are already some applications in the literature [13, 24, 25, 32, 58].

4.3.4 Movement Representation

In the earlier rehabilitation programs based on the two-dimensional virtual environment [89], movement representation was mainly in the form of AMR due to its low cost and applicability. It has also been applied in recent years in immersive VR-based rehabilitation programs. The advantage of AMR is its low production cost and low requirements on rendering compared with FMR. Existing applications that use AMR have important implications for developing rehabilitation programs that deal with subtle movements such as finger movements and wrist motor functions.

In recent years, the use of FMR has become an important way to represent movement in applications dealing with motor rehabilitation. Fig. 8 (c) shows an overview of movement representation in upper and lower limb rehabilitation. The use of FMR has two significant advantages in motor rehabilitation: the sense of embodiment [3] and full-body interaction. FMR provides more detailed and credible visual and kinematic information in the virtual environments based on patients' movements. The visual and kinematic information can help build up the patients' sense of embodiment over their impaired limbs, making them perceive their movements in the virtual environments as their own [90]. Eventually, the sensorimotor mechanisms can be (re)activated in their brain to help regain motor function in these patients [91].

Unlike AMR and FMR, both of which are suitable for upper limb rehabilitation, IMR provides a suitable way of representing users' locomotion in lower limb rehabilitation. Besides the visual flow of the virtual environment, other types of sensory information may also be utilized for applications with IMR. For example, the footstep sound is often matched to the walking movements to generate a higher sense of the presence and immersion.

4.3.5 Model Generation

Virtual model of movement representation shows users' partial or full body and is commonly referred to as avatars. The generation of an avatar in the virtual environment could be a challenging task. There are typically two ways to acquire an avatar model for rehabilitation. One is to acquire the model from online resources, while the other is to construct the 3D model manually using a modeling software. The first choice has the advantage that it is fast and does not cost much due to rich online resources, often provided free of charge. Some commercial motion capture systems also provide avatar models for developers, For example, Leap Motion offers hand models for avatars used in upper limb rehabilitation [46, 49]. Modeling avatars manually is a suitable choice if researchers want to develop a customized application that is tailored to their specific user needs [13, 92]. Avatars could be designed in many shapes to fit the parameters of of movement representation in the virtual environment. However, this process usually requires a longer time and necessary modeling skills.

Avatar reshaping is the process whereby the avatar models are customized according to users' preferences. Advances in computer graphics technologies can now allow fully customizable avatars as part of a virtual rehabilitation program. A customized avatar could be used in an application to resemble the users' body or match their biological or preferred gender to provide a sense of affinity and closeness [56, 93]. Furthermore, researchers have investigated the effect of customization factors, such as degree of realism, on users' perceptual and psychological experience. It has been identified in the literature that the degree of realism in the avatars vary from a very simple form of a human figure to a very realistic one (e.g., from a simple humanoid or human-like figure to a replica of a person). Inamura et al. [94] compared the effect of avatar arms with either a human or humanoid appearance on the sense of ownership in a virtual rehabilitation application. Their results showed a stronger perceived sense of ownership with the human avatar than the humanoid avatar. Charbonneau et al. [23] studied two avatars in different realism levels in their lower limb rehabilitation application, and found that using a novel monster-like avatar would be more enjoyable than a human avatar and patients spent less time in completing rehabilitation tasks.

In addition to the avatars, other visuals used in virtual environments can be contextualized and customized. Contextualization is often important in lower limb rehabilitation, as gait training is repetitive and can become tedious when training for a long time. With realistic, enriched visual context and optic flow in the contextualized information, it is possible to increase patients' motivation and immersive experience, which in turn can make repetitive tasks less tedious. The ADL training is another facet that requires context generation in virtual environments. Activities that happen in daily life can be simulated to allow patients to experience and regain lost motor functions. Various scenarios can be developed to fit the context of the tasks to provide immersive and realistic interaction and experience for ADL training. Users can either practice the activities that are necessary for basic living or essential activities, such as making phone calls, cooking, and taking a bus.

4.3.6 Movement Modulation

Movement modulation has been previously applied in many non-VR motor rehabilitation treatments. The term "error augmentation" is used to refer to the application of movement modulation in rehabilitation protocols for enhancing motor learning in non-VR applications [95]. The upper limb rehabilitation program designed by Shum et al. [55] was the first to investigate movement modulation in immersive VR for the participants with hemiplegic cerebral palsy. In their hand-reaching task, the remained forward distance in the affected arm was augmented to improve symmetry in this bimanual task. This movement modulation strategy was found to produce a change in the sense of agency while compensating for motor performance. In the literature we reviewed, movement modulation was referred in only five publications, although it was an effective strategy in many other rehabilitation treatments. For instance, Roosink et al.

[73] adopted this kind of movement modulation strategy by using a "virtual mirror" in a virtual environment for pain rehabilitation. It used a powerwall screen and was designed for trunk flexion movements. During the the treatment, the full-body movement was captured in real-time and projected with both augmented and reduced movement modulation of the flexion angles. Their results showed that participants were able to differentiate modulation levels consistently, indicating that the movement modulation strategy might be helpful for pain rehabilitation by promoting or preventing specific movement patterns (like erroneous motions).

4.4 User Experience

As discussed above, virtual rehabilitation is a combination of multiple technologies integrated into one system. Whether the users accept or interact well with such systems eventually affects the effectiveness of rehabilitation. An optimal user experience in rehabilitation can reduce dropouts and improve its results. User experience is complex and takes into account both human and environmental factors when probing into the anticipated use and acceptance of a product, system, or service. It encompasses a variety of aspects resulting from users' perceptions, expectations, and prior experiences (or lack of thereof). This paper focuses on three aspects of user experience, which are discussed next. *Usability* of a rehabilitation application serves to ensure that the overall system is efficient, effective and easy to use for the targeted users. *Sense of presence* ensures that the patients feel that they are active participants in the VR environment and that they are part of it. *Sense of embodiment* assesses the embodied experience resulting from movement reproduction in the virtual environment.

4.4.1 Usability

Usability helps to determine how usable a virtual rehabilitation system is. Many users with motor-impairments also have cognitive and perceptual challenges, such as impaired memories and unclear vision, which can add additional stress to their interaction with a interactive system. As such, virtual rehabilitation systems need to take usability to a higher level. A simple usability scale can check the usability of systems designed to improve learnability, efficiency, memorability, error avoidance, and satisfaction [96]. In total, we idenfied nine studies in our review that evaluated the usability of their developed virtual rehabilitation applications (as shown in Table 1 of supplemental material).

The established System Usability Scale (SUS) is frequently adopted in previous studies. As summarized by Avola et al. [16], the main features that contribute to a VR system with good usability are minimalistic interface, simple customization of training tasks, and consistency. The other three studies also used SUS in their usability evaluations to assess the whole system [33, 54, 55]. Camporesi and Kallman [22] compared the usability of having movement representation as visual feedback against a condition without movement representation. They found that using the movement representation in their rehabilitation application led to improved usability because the users felt that the movement representation helped them observe and understand their movements.

Likewise the usability scale can also be modified and adapted to suit the needs specific to virtual rehabilitation applications. Naranjo et al. [46] tested the usability of the interface of their rehabilitation system using the VRUSE method. This method is based on conducting a questionnaire with multiple key usability factors particularly designed for evaluating and diagnosing the usability of a VR system according to the perception and attitudes of its users [97]. Lee et al. [38] also used a self-report questionnaire with eight items to assess their upper limb virtual rehabilitation program. Besides usability scales, other evaluation methods based on observations, interviews, focus groups, logging data, and user feedback, can also be adopted to gather supplementary usablity data [14]. In a study conducted by Elor et al. [30], the feasibility, ease of use, and comfort of their upper limb rehabilitation application was investigated via observations, interviews, and questionnaires.

Overall, a usability study can provide the researchers and developers with a user-oriented view of the virtual rehabilitation. Patients in virtual rehabilitation may have cognitive impairments and may lack previous experience with VR. Accordingly, the learnability and satisfaction of these VR applications should be addressed as key attributes with a focus on the usability and practicality of the systems for those individuals who are most vulnerable. For example, the training sessions should be included for the users to get them familiar with the (new) virtual environment, with the difficulty level easily adjustable and the interface simple and easy to learn and use, especially for those individuals with motor and visual impairments. With the appropriate movement reproduction approaches and optimized usability, effective motor rehabilitation outcomes could then be achieved.

4.4.2 Sense of Presence

Presence is a fundamental user experience in VR systems. It typically refers to participants' perceived "sense of being there", being in the simulated virtual environment. Presence is related to the users' involvement with as well as the immersion in the VR system [98]. A higher level of presence is often predicted by or co-related to a higher level of immersion and involvement. In the reviewed literature, several groups of researchers (as shown in Table 2 of supplemental material) investigated the sense of presence as one focus in their studies [19, 23, 24, 34].

According to Choi et al. [24], the feeling of presence is positively related to control performance in rehabilitation that took advantage of BCI as movement input in the virtual environment. Previous works [19, 34] have evaluated presence in non-VR and VR rehabilitation applications. Borrego et al. [19] found that the sense of presence was significantly higher for FMR presented in 1PP (first-person perspective) than the 3PP (third-person perspective) in virtual environment rendered in a non-VR display. The findings suggest that the sense of presence could provide a vivid experience and, consequently, support virtual rehabilitation more effectively. Another study by Juliano and Liew [34] found no significance in presence between the non-VR and immersive VR rehabilitation environments but suggested that presence is associated with motor skill acquisition. The sense of presence may be enhanced by the increasing realism of visual elements in the virtual environment. However, in another study, two different types of FMRs (a human and a monster) in 1PP were reported to generate a similar levels of presence in their virtual gait rehabilitation program [23].

4.4.3 Sense of Embodiment

The sense of embodiment is related to the movement reproduction process because it shows how the virtual body or movement responds to the user's actions in the virtual environment. The sense of embodiment is recognized as a psychological state where the virtual self is experienced as if it is the actual self. Three dimensions constitute the sense of embodiment: the sense of *self-location*, the sense of *agency*, and the sense of *ownership* [90]. The sense of self-location is a psychological state and refers to the feeling of being inside a body. The sense of agency refers to having a "global motor control", including the subjective experience of action, control, intention, motor selection and the conscious experience of will and is highly related to action awareness [83]. The sense of ownership is considered as one's self-attribution of a body, which implies that the body is the source of the sensations [90]. Creating a sense of ownership and sense of agency in individuals with motor impairments is vital in virtual rehabilitation [99]. In the literature reviewed, a small number of studies (as shown Table 2 in supplemental material) evaluated the sense of embodiment in virtual rehabilitation.

The sense of ownership is generated from movement representation and is influenced by the perspective(s) given to patients. In a study by Choi et al. [24], the provided movement representation of users' hands was found to have increased the sense of ownership and increased their MI performance in their BCI-based virtual rehabilitation. In a study by Borrego et al. [19], the assessed sense of body ownership was higher in 1PP displayed in a VR HMD than 3PP displayed in a standard screen. The sense of ownership is correlated with the closeness of the visual representation to the user's own body. However, no difference in the sense of ownership was found for human and non-human FMR in a study by Charbonneau et al. [23]. For the relationship between movement modulation and sense of ownership, there is insufficient evidence in the reviewed literature to draw a a more definite conclusion. A study by Bourdin et al. [20] revealed that differences in amplified arm movements did not induce significant changes in ownership.

The improvement in the sense of agency is a key consideration for rehabilitation of motor-impaired patients, as they usually experience a weaker sense of agency than healthy individuals. A couple of papers in our review highlighted agency as an important driving factor for improving motor learning results. Studies by Nataraj et al. [47, 48] revealed that the increase in the sense of agency positively correlates with better motor performance in virtual hand reaching tasks in terms of movement smoothness, movement speed and path length. Movement input using motion capture has been found to engender a sense of agency over the virtual body in the virtual environment [20]. Research by Borrego et al. [19] showed that there was no difference in the agency in either 3PP or 1PP conditions. There is evidence in the literature that shows that the sense agency may be modified by movement modulation to accelerate motor learning. On the other hand, in the work by Bourdin et al. [20], the sense of agency was not affected by the movement modulation. However, one study by Aoyagi et al. [15] indicated that movement modulation increased the sense of agency in a goal-directed task. A recent study by Wang et al. [74] showed that sense of agency was significantly influenced by five movement modulation modes in hand reaching tasks. Hence, more in-depth research is needed to investigate the impact and role of movement reproduction to enhance the sense of agency in virtual rehabilitation.

5 Challenges and Opportunities

This section draws together the challenges and opportunities of movement reproduction in virtual rehabilitation by providing constructive suggestions for research, design, and application development. The recommendations regarding the development of movement input methods, the design of movement representation modes, the implementation of modulation strategies, the application of assessment approaches, and the enhancement of user experience are intended to help the development of virtual rehabilitation in the future and inspire further research in this area.

5.1 Development of Movement Input Methods

In the reviewed literature, external motion capture systems are frequently used for movement input. Currently, the alternatives to external motion capture systems used in the virtual rehabilitation program are limited, especially in those applications designed for lower limb rehabilitation. The alternative low-cost solution from Microsoft (i.e., the Kinect) has been officially halted several years ago. In the meantime, the other marker-based solutions, such as Vicon, are expensive, posing difficulties for its widespread use. Recently, Microsoft Azure Kinect DK and Intel RealSense have been introduced to the market with similar and improved capabilities like the old generation of Kinect, opening up opportunities for applications in virtual rehabilitation. To a certain extent, the limited choices of cost-effective products for motion capture systems restrict the applications of lower limb virtual rehabilitation. It is expected that the new generation of motion capture devices represent suitable solutions that can save developers' efforts to create efficient VR rehabilitation systems. Also, it would be helpful that motion capture accessories to be designed to be lightweight, easy-to-wear and easy-to-integrate into VR systems, and inexpensive. Additionally, it would be interesting to have a combination of motion capture systems and existing rehabilitation equipment to enable more efficient and tailored feedback to patients in both the virtual environment and real world.

Besides, BCI is considered a novel method to be combined with VR to obtain users' intention of movement in MI training. The brain signals are complex and highly subjective to various individual differences, which represent the two main difficulties in the analysis of brain signals: individual differences and insufficient information [100]. These difficulties need to be solved in order to further improve the recognition and classification of brain signals. In short, more effective virtual rehabilitation based on BCI could be realized in the future.

5.2 Design of Movement Representation Modes

Movement representation provides users with visual feedback of their motions in the virtual environment. Our review shows that FMR is most frequently used in virtual rehabilitation because of its advantages in a wide range of applications, induced body ownership, and the afforded detailed movement information. A challenge in exploiting FMR is that an appropriate rigging in skeleton or a customized movement representation may require longer development time and need collaboration across a multidisciplinary team of developers. The future development of FMR can be reinforced by 3D-scanning technology to enable more realistic and self-like appearances to improve further user customization. However, the increase of realism in FMR may result in a well-known effect: the "Uncanny Valley" [101]. Such an effect implies that an inappropriate level of realism used in the avatars could induce negative emotions in users, which may eventually affect their acceptance of the virtual rehabilitation programs. What is noteworthy is that the developers and researchers should be mindful of the Uncanny Valley effect to avoid any negative consequences in user experiences.

AMR and IMR are less frequently used, but the advantages of AMR in presenting precise movement and movement control and IMR in presenting locomotion should not overlooked. The application of AMR and IMR can allow more freedom and creative designs in the virtual programs, extend the ranges of interaction mechanics, and potentially provide users with more interesting and novel interactions in virtual rehabilitation. As stated in Section 4.4.3, movement representation modes have a close relationship with the sense of ownership and agency, which are two important considerations in virtual rehabilitation. However, a firm conclusion cannot be made from the limited number of studies available. More research could be undertaken to explore the impact of different uses of AMR, IMR and FMR on user experiences, such as sense of ownership and agency, and to study the potential impact on the overall rehabilitation effectiveness.

5.3 Implementation of Modulation Strategies

Movement modulation is a promising intervention strategy that can be employed in virtual rehabilitation applications. the existing results in the literature are encouraging for rehabilitation purposes. Previously, studies in non-VR rehabilitation had shown its effectiveness in motivating motor learning via amplification or reduction of movement action possibilities in the virtual environment. To date, only a small number of studies have applied or explored movement modulation in virtual rehabilitation. As VR is still an emerging technology for rehabilitation, more research in movement modulation can be conducted in the future to verify its positive effect on motor learning. Furthermore, it is still an open question whether other types of such modulation strategies, besides those mentioned in the literature, could be created. Most importantly, to what extent should the modulation strategy or strategies be adopted to enhance user experience and motor learning is an interesting and meaningful research direction.

5.4 Application of Assessment Approaches

As stated in the discussion section, a large number of papers have assessed motor learning outcomes through quantitative assessments. Quantitative measures, as complementary to standardized assessment methods, are usually used to obtain data from devices such as motion capture trackers to assess motor learning results. These kinds of objective data offer accurate information on motion behavior, such as range of motion, movement speed, and trajectory, and are very helpful to demonstrate more specified and progressive rehabilitation outcomes in patients. Hence, the challenges and opportunities are to focus on the analysis of the collected raw data and the interpretation of results. First, machine learning methods can be integrated with conventional analysis methods to help identify the particular level of a patient's motor learning results more accurately and efficiently. Second, the visualization of rehabilitation results using information visualization techniques can help provide patterns of patients' behavior and reaction to facilitate understanding their progress and to identify potential problems and the resulting outcomes, positive or otherwise. Third, a professional real-time analysis platform can be established for online data processing to help understand the results by across various virtual rehabilitation systems across research groups. Furthermore, an adaptive rehabilitation system can be introduced with the ability to make adjustments of the following training task according to the motor performance revealed by the patient's movement data.

5.5 Enhancement of User Experience

An optimized user experience from virtual rehabilitation programs can be beneficial to reduce the dropouts. Stopping midway through the rehabilitation process is one major issue that affects the effectiveness of VR based systems. In addition to technological issues, dropouts could be due to psychological issues that have been explored to a lesser extent within many virtual rehabilitation programs. It is recommended to enhance the user experience of a virtual rehabilitation program, which can be measured via usability tests to ensure that the application is easy to use, easy to learn, pleasing to be immersive in, and effective supporting users' rehabilitation needs. At the same time, users' perceived sense of presence, which is fundamental to a positive experience in VR, can be evaluated to see if users are well immersed in the virtual environment. Besides those essential qualities that VR programs should embrace, the measurements of embodied experience also opens up opportunities for maximizing user experience regarding movement reproduction from the perspectives of human-computer interaction and experience design. The results of this evaluation processes can potentially contribute to making more efficient virtual rehabilitation applications. Notably, the sense of agency, which is a crucial consideration for motor-impaired individuals, can be modified and enhanced by manipulating the different parameters in movement reproduction. Further research is still needed to find more effective ways to strengthen the outcome of motor learning using virtual environments.

6 Conclusion

This paper has reviewed the state-of-the-art research and publications of movement reproduction in virtual motor rehabilitation. After a research and filtering process, 47 publications are included and discussed within the scope of movement reproduction. This review shows a clear focus on using the external motion capture system to facilitate motor learning in virtual rehabilitation. Moreover, BCI-based movement input is also considered a novel intervention in virtual rehabilitation. Results in the analysis of the movement representation showed a focus on using figurative movement representation (FMR) to help patients visualize their upper and lower limb movements in virtual reality (VR) systems. However, the use of movement representation has to meet the specific rehabilitation goal and its impact on users' experience should be taken into consideration. In the identified studies, a small number investigated movement modulation, which is considered a promising and effective approach to improve motor learning outcomes. Many publications reviewed are still at the preliminary stage of their study; they presented their preliminary design and rehabilitation results in limited ways.

This paper contributes a new classification method in virtual rehabilitation through the lenses of movement reproduction and its three subcomponents (movement input, movement representation, and movement modulation). It provides a comprehensive analysis of these aspects rooted from the literature. The extensive list of practical examples cited in this paper could provide researchers and designers with references when developing movement-based virtual rehabilitation applications. Furthermore, the challenges and opportunities practices in this paper can be beneficial for developers to design virtual rehabilitation and help researchers establish meaningful investigations in the field of virtual rehabilitation to improve the quality of life of motor-impaired patients.

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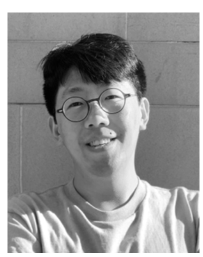
Liu Wang received her M.Eng. degree in Industrial Design from Beijing Institute of Technology, Beijing, China in 2019. She is currently working toward her Ph.D. at the University of Liverpool, Liverpool, United Kingdom. Her research interests include human-computer interaction and embodied experience in virtual reality.

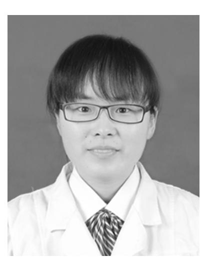
Mengjie Huang is an Assistant Professor in Design School, Xi'an Jiaotong-Liverpool University, China, and an Honorary Lecturer in the Department of Civil Engineering and Industrial Design, the University of Liverpool, United Kingdom. She received her Ph.D. degree from National University of Singapore, Singapore. Dr. Huang's current research interests include human-computer interaction and human factors.

Rui Yang is an Assistant Professor in the School of Advanced Technology, Xi'an Jiaotong-Liverpool University, China, and an Honorary Lecturer in the Department of Computer Science, the University of Liverpool, United Kingdom. He received his B.Eng. degree in Computer Engineering and Ph.D. degree in Electrical and Computer Engineering from National University of Singapore. His research interests include machine learning based data analysis.

Hai-Ning Liang is a Professor in the Department of Computing at Xi'an Jiaotong-Liverpool University, China. He obtained his PhD in Computer Science from The University of Western Ontario, Canada. His research interests fall in the broad area of human-computer interaction and are focused on developing novel interactive techniques and applications for virtual/augmented, gaming, visualization, and learning systems.



Ji Han is an Assistant Professor in Industrial Design at the University of Liverpool. His research addresses various topics relating to design and creativity and places a strong emphasis on exploring new design theory and developing advanced design support tools. His general interests include design creativity, data-driven design, AI in design, and virtual reality.



Ying Sun is the Chief of the Occupational Therapy Department, Kunshan Rehabilitation Hospital, Suzhou, China. Dr. Sun's current research interests are the evaluation of functional assessment scales and functional rehabilitation methods.

Supplemental Material

1 Tables

Table 1: Summary of the literature that includes presence and embodiment evaluation in virtual rehabilitation applications.

	Evaluation	Number of Participants
Aoyagi et al. [1]	Sense of agency in condition with and without movement modulation.	14
Borrego et al. [2]	Presence and embodiment under 1PP in VR and 3PP in non-VR condition.	78
Bourdin et al. [3]	Embodiment under different movement modulation modes.	27
Charbonneau et al. [4]	Presence and embodiment in embodying two different FMR (a human and a monster) in 1PP.	10
Choi et al. [5]	Presence and embodiment evaluation in BCI-VR rehabilitation.	14
Juliano et al. [6]	Presence in VR and non-VR environment.	70
Nataraj et al. [7]	Sense of agency in negative and positive feedback in virtual reaching tasks.	24
Nataraj et al. [8]	Sense of agency in different movement modulation modes.	16

Table 2: Summary of the literature that included usability evaluation.

	Evaluation	Number of Participants
Almousa et al. [9]	Usability evaluation regarding the overall virtual rehabilitation application.	5
Avola et al. [10]	The usability of the rehabilitation system tested by System Usability Scale.	10
Camporesi and Kallman [11]	The effect of use of movement representation on usability.	50
Elor et al. [12]	Usability study of the system with items: ease of use, feasibility, and comfort.	9
Ferreira et al. [13]	Usability test was carried out using System Usability Scale to evaluate the system.	8
Lee et al. [14]	Usability evaluation on seven items regarding the virtual rehabilitation system.	12
Naranjo et al. [15]	The usability of the whole system tested by VRUSE method with ten items.	30
Pereira et al. [16]	Usability of hardware and software was carried out to evaluate the virtual rehabilitation system.	7
Shum et al. [17]	Whole system evaluation regarding both the hardware and the virtual environment.	17

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