JMIR Publications
The Leading eHealth Publisher

Virtual, augmented and mixed reality for motor neurorehabilitation: a systematic methodological review focused on the role of body representation

Massimo Magrini, Olivia Curzio, Cristina Dolciotti, Gabriele Donzelli, Maria Cristina Imiotti, Fabrizio Minichilli, Davide Moroni, Paolo Bongioanni

Submitted to: Journal of Medical Internet Research
on: June 21, 2024

Disclaimer: © The authors. All rights reserved. This is a privileged document currently under peer-review/community review. Authors have provided JMIR Publications with an exclusive license to publish this preprint on it's website for review purposes only. While the final peer-reviewed paper may be licensed under a CC BY license on publication, at this stage authors and publisher expressively prohibit redistribution of this draft paper other than for review purposes.

Table of Contents

Original Manuscript.. 5

Preprint JMIR Publications

Virtual, augmented and mixed reality for motor neurorehabilitation: a systematic methodological review focused on the role of body representation

Massimo Magrini[1*]; Olivia Curzio[2*]; Cristina Dolciotti[3]; Gabriele Donzelli[2]; Maria Cristina Imiotti[2]; Fabrizio Minichilli[2]; Davide Moroni[1]; Paolo Bongioanni[3]

[1]Institute of Information Science and Technologies, "Alessandro Faedo", National Research Council Pisa IT
[2]Institute of Clinical Physiology, National Research Council Pisa IT
[3]Spinal Cord Injuries Unit, Neuroscience Department, Pisa University Hospital Pisa IT
[*]these authors contributed equally

Corresponding Author:
Olivia Curzio
Institute of Clinical Physiology, National Research Council
Via Moruzzi 1
Pisa
IT

Abstract

Background: In neurorehabilitation, virtual reality (VR) applications cover a wide range of areas, including the rehabilitation of patients with various types of brain and spinal cord injuries. VR provides the subject multisensory feedback, enhancing neuronal plasticity within the sensorimotor cortex.

Objective: The systematic review critically analyses the existing literature on VR applications related to motor problems and somatic representation to propose new tools and experiments.

Methods: The Protocol was registered in the international database for systematic reviews PROSPERO (ID: 481092 - 22 November 2023). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Guidelines. To implement the search string, a broad overview of previous literature reviews in the field was developed. The databases PubMed, Embase, Scopus, and Web of Science (7 December 2023) were explored, and data regarding study design, methodology, participant characteristics, specific devices and instruments used and tested, body representation, and virtual somatic embodiment were collected. The Newcastle-Ottawa Scale was used to assess the methodological quality of the studies; for case report studies, a dedicated scale was used.

Results: The review included 26 studies, mainly clinical trials on neurological patients. Internationally, VR technologies in the period 2008-2023 have evolved significantly; the emergence of inexpensive devices such as Oculus Rift and HTC Vive has stimulated research in this area. The best results have been achieved for patients with sensorimotor deficits. In VR systems, users experience a first- or third-person view (where their avatar is present) of the synthetic world around them. All included studies used the first-person perspective, which was found to be most effective. Five studies incorporated EEG for recording brain responses during experiments, while two studies used transcranial stimulators to enhance the effect of the VR intervention. A couple of studies employed other kinds of devices, such as eye trackers. Regarding the 3D engine used, Unity 3D remains the preferred choice for the development of VR applications in research due to its ease of learning and seamless integration with devices.

Conclusions: The review of the selected studies shows that the use of VR devices enhances reinforcement learning, thereby improving motor and cognitive recovery. The emerging operational proposition supports the use of tailor-made techniques in the rehabilitation setting - aimed at improving and evaluating the outcomes of therapeutic interventions in the treatment of neurological patients. Clinical Trial: International database for systematic reviews PROSPERO, ID: 481092 - 22 November 2023.

(JMIR Preprints 21/06/2024:63487)
DOI: https://doi.org/10.2196/preprints.63487

Preprint Settings

1) Would you like to publish your submitted manuscript as preprint?

- ✓ **Please make my preprint PDF available to anyone at any time (recommended).**
- Please make my preprint PDF available only to logged-in users; I understand that my title and abstract will remain visible to all users.
- Only make the preprint title and abstract visible.
- No, I do not wish to publish my submitted manuscript as a preprint.

2) If accepted for publication in a JMIR journal, would you like the PDF to be visible to the public?

- ✓ **Yes, please make my accepted manuscript PDF available to anyone at any time (Recommended).**
- Yes, but please make my accepted manuscript PDF available only to logged-in users; I understand that the title and abstract will remain v
- Yes, but only make the title and abstract visible (see Important note, above). I understand that if I later pay to participate in <a href="http

Preprint JMIR Publications

Original Manuscript

Preprint JMIR Publications

Virtual, augmented and mixed reality for motor neurorehabilitation: a systematic methodological review focused on the role of body representation

Massimo Magrini [1*§], PhD; Olivia Curzio [2*§], PhD; Cristina Dolciotti [3], MD; Gabriele Donzelli [2], PhD; Maria Cristina Imiotti [2], MH; Fabrizio Minichilli [2], PhD; Davide Moroni [1], PhD; Paolo Bongioanni [3], MD

[1] Institute of Information Science and Technologies, “Alessandro Faedo”, National Research Council, Via Moruzzi 1, 56124 Pisa, Italy; massimo.magrini@cnr.it; davide.moroni@cnr.it

[2] Institute of Clinical Physiology, National Research Council, 56124 Pisa, Italy; olivia.curzio@cnr.it; gabrieledonzelli@cnr.it; mariacristina.imiotti@cnr.it; fabrizio.minichilli@cnr.it

[3] Spinal Cord Injuries Unit, Neuroscience Department, Pisa University Hospital, Pisa, Italy; c.dolciotti@ao-pisa.toscana.it; p.bongioanni@ao-pisa.toscana.it

[*] Correspondence: olivia.curzio@cnr.it and massimo.magrini@cnr.it

[§] These authors contributed equally to this work.

Preprint JMIR Publications

Abstract

Background: In neurorehabilitation, virtual reality (VR) applications cover a wide range of areas, including the rehabilitation of patients with various types of brain and spinal cord injuries. VR provides the subject multisensory feedback, enhancing neuronal plasticity within the sensorimotor cortex.

Objectives: The systematic review critically analyses the existing literature on VR applications related to motor problems and somatic representation to propose new tools and experiments.

Methods: The Protocol was registered in the international database for systematic reviews PROSPERO (ID: 481092 - 22 November 2023). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Guidelines. To implement the search string, a broad overview of previous literature reviews in the field was developed. The databases PubMed, Embase, Scopus, and Web of Science (7 December 2023) were explored, and data regarding study design, methodology, participant characteristics, specific devices and instruments used and tested, body representation, and virtual somatic embodiment were collected. The Newcastle-Ottawa Scale was used to assess the methodological quality of the studies; for case report studies, a dedicated scale was used.

Results: The review included 26 studies, mainly clinical trials on neurological patients. Internationally, VR technologies in the period 2008-2023 have evolved significantly; the emergence of inexpensive devices such as Oculus Rift and HTC Vive has stimulated research in this area. The best results have been achieved for patients with sensorimotor deficits. In VR systems, users experience a first- or third-person view (where their avatar is present) of the synthetic world around them. All included studies used the first-person perspective, which was found to be most effective. Five studies incorporated EEG for recording brain responses during experiments, while two studies used transcranial stimulators to enhance the effect of the VR intervention. A couple of studies employed other kinds of devices, such as eye trackers. Regarding the 3D engine used, Unity 3D remains the preferred choice for the development of VR applications in research due to its ease of learning and seamless integration with devices.

Conclusions: The review of the selected studies shows that the use of VR devices enhances reinforcement learning, thereby improving motor and cognitive recovery. The emerging operational proposition supports the use of tailor-made techniques in the rehabilitation setting - aimed at improving and evaluating the outcomes of therapeutic interventions in the treatment of neurological patients.

Keywords: Body Representation; Embodiment Cognition; Virtual Reality; Augmented Reality; Neurorehabilitation

Introduction

Body Schema and Body Image: Two sides of the same coin?

In scientific terms, the body representation comprises two primary modes of expression, both of which are internal to the subject: the body schema and the body image, respectively. Although both modes are internal to the subject, the body schema can be defined as an objective representation because it is conditioned by multisensory perception, whereas the body image is a subjective representation resulting from cognitive processing and emotional response.

Representation of the body's spatial configuration and its relation to the external environment

Body representation, encompassing body schema and body image, profoundly influences motor control, movement coordination, and spatial awareness. While the body schema has been extensively studied in relation to motor and postural outcomes or adaptations following neurological diseases, body image, referring to the subjective mental representation of one's own body, has involved the study of complex neural pathways that create a synthesis between the objective and subjective representation of the body[1].

Preprint JMIR Publications

Body awareness, a complex concept involving perception, knowledge, and evaluation of one's own body and others, relies on the interplay between body schema and body image. Neuroimaging studies have identified specialized cortical areas for processing body shapes and actions, highlighting the significance of interoception alongside exteroception and proprioception for body awareness. There is evidence that the insular cortex processes interoceptive signals, thus playing a key role in determining body consciousness [2].
Despite extensive research on integrated representation of the body, precise brain structures remain elusive. However, the extra striate body area (EBA) has emerged as a neural substrate for body shape and size perception. Studies have shown correlations between EBA volume, functional connectivity with the posterior parietal cortex, and susceptibility to multisensory illusions, suggesting that EBA structure and connectivity encode body representations and alterations in body perception [3].

Contribution of the sensorimotor system, motor imagery, and cognitive domains to body representation

The sensory-motor system (SMS) significantly influences body representation, and consequently both motor and postural control, through various sensory modalities. Proprioception, a key SMS modality, enables individuals to perceive body position and movement independently of vision, contributing to body awareness and coordination. Additionally, discoveries of sensory neurons in frontal motor circuits challenge traditional views of motor control, suggesting SMS involvement in cognitive processes[4]. The visual perception of the body and its movement involves other considerations that refer to the so-called mirror neurons.
Mirror neurons, part of the SMS, activate during both action execution and observation, fostering a sense of embodiment [5]. Besides proprioception, the SMS integrates information from other senses like vision and touch, enhancing body representation accuracy [6–8].
The SMS is adaptable, undergoing changes in response to experience or injury, leading to corresponding adjustments in body representation. Motor skill learning alters body perception and control, influenced by top-down factors and task demands [9]. Experimental findings suggest that mediated sensory perception, like mirrored hand movements, can induce abnormal body representations [8]. When sensory or cognitive deficits limit body movement in space, the contribution of motor imagery becomes important.
Motor imagery (MI) is vital for cognitive body representation and is utilized in contexts such as rehabilitation to enhance motor skills and awareness[10]. Proprioceptive input significantly influences mental rotation, highlighting its role in motor control and spatial awareness [11].
Cognitive processes, including memory and attention, shape body representation and awareness. Brain regions like the parietal cortex integrate sensory inputs to create coherent body representations [12]. Subcortical structures like the limbic system regulate emotional responses and body memory, while brain plasticity modifies body image in response to experiences [13].
Peripersonal space (PPS) surrounding the body plays a crucial role in physical interactions and self-location. PPS adapts based on experiences, technology, and social interactions, supporting bodily self-consciousness and higher-level cognition [14].
Body image construction involves emotional regulation and cognitive processes. Stress can alter body perception, while self-esteem enhances it [15]. Body dissatisfaction is influenced by cognitive factors like visual memory and inhibition[16].

Body schema change and body image distortion

Changes in body schema and distortions in body image can result from various neurological and psychiatric conditions. Neurological disorders, such as spinal cord injuries (SCI), multiple sclerosis (MS), and strokes, can significantly impact both sensory and cognitive aspects of body perception. For instance, individuals with SCI or anaesthesia may continue to experience sensations related to body size, shape, and posture despite the absence of immediate sensory signals, suggesting the role of cognitive and emotional processing in body image [17]. Moreover, studies exploring body image experiences in people with spinal cord injuries reveal categories such as physical appearance concerns, negative functional features, and body disconnection [18]. Similarly, in MS patients, higher disability levels are associated with more negative body perceptions and lower self-esteem, highlighting the psychological impact of physical limitations [19].

In conditions like strokes, damage to brain areas involved in body perception and sensory processing can lead to neglect syndrome, where individuals may ignore or be unaware of one side of their body. Neglect syndrome often results from damage to the right parietal lobe and can affect an individual's ability to attend to stimuli on the affected side, including their own body parts [19,20]. Moreover, phenomena like phantom limb syndrome, observed in amputees, and alien limb syndrome, seen in conditions like Corticobasal Degeneration, illustrate how the brain's representation of the body can persist despite physical changes or dysfunction. Phantom limb syndrome involves sensations, including pain, in a missing limb, suggesting the persistence of the body schema [21]. Alien limb syndrome, on the other hand, involves a dysfunction in neural circuits controlling body ownership and limb movement, resulting in distorted perceptions of the limbs and sensations of foreignness[22].

These examples highlight the intricate relationship between neurological factors and body image perception, shedding light on how changes in body schema and distortions in body image can manifest across various conditions.

Applications of Virtual, Augmented and Mixed Reality in clinical rehabilitation

Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) have become important adjunctive technologies in supporting clinical neurorehabilitation. They not only provide new ways of conducting standardized, repetitive exercises and quantitative evaluations but also enable the development of novel therapeutic approaches encompassing adaptive and personalized pathways.

Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR) are technologies in which the boundary between reality and simulated reality is questioned. VR allows you to view a synthetic environment using a stereoscopic display mounted on the head, capable of consistently adapting the point of view with the head's position. This environment can support interaction in different ways and levels, providing a realistic feel suitable for games, training simulations, and virtual tours. AR, conversely, does not replace reality but modifies it by including virtual content. AR applications overlay graphics, audio, and/or haptic feedback onto real-world images, providing customers with additional context and interaction in numerous industries, such as retail, education, and navigation, to name just a few. It can be done using devices such as smartphones, tablet PCs, or even using smart glasses. The term XR is instead used as a general designation for VR, AR, and other types of mixed reality that rely on integrating reality with the digital environment. Such ICTs constitute this range of technologies advancing various fields such as healthcare, architecture, culture, and entertainment (games, etc.).

Applications span disparate areas with different objectives and purposes. In relation to VR, these areas include stroke [23,24], Parkinson's [25], Alzheimer's [26], brain injury [27,28], unilateral spatial neglect [29], and pain management [30]. VR is also utilized in psychiatric disorders like specific phobias [31] and eating disorders [32,33].

Technological solutions in VR include head-mounted displays (HMDs), Powerwall screens, and CAVE environments. HMDs, the most common, provide immersive experiences with head and hand movement tracking. Powerwall screens offer partially immersive experiences, while CAVE environments create immersive experiences with rear-projected screens and head and hand tracking [34].

Reviews suggest the efficacy of VR therapy for motor symptoms, although the degree of effectiveness remains undefined [28,35]. Challenges such as system latency and distance perception affect VR technology. Future advancements should focus on improving user presence and distance perception accuracy [36]. The same principles also pertain to AR/MR applications, where the technology involves see-through glasses and gesture tracking mechanisms. The same principles also pertain to AR/MR applications, where the technology involves see-through glasses and gesture-tracking mechanisms. These devices, whether wearable or contactless, enable the integration of digital content into the physical world, allowing for various degrees of fusion between digital and physical elements within the environment, resulting in exergame that can be catalogued as AR or MR based on the level of interplay between physical and synthetic world.

Scope of the review and paper organization

Neurological disorders are a leading cause of disability and death worldwide. Motivated by this, our interdisciplinary group, which includes competencies ranging from neurology to psychology, from computer science and engineering to physiatry, is designing and developing a new VR-based system for addressing body image disorders in post-stroke individuals. To this end, our research objectives include systematically reviewing the literature on body representation and VR applications in neurologic patients and focusing on technical aspects to propose innovative VR and eXtended Reality (XR) headset models. An analysis of the literature has shown that in the last decades, several reviews concerning such new technologies in neurorehabilitation have been produced, often focusing on specific aspects, such as clinical utility [37], studying effects on multiple cognitive domains [38] or addressing particular conditions, such as the post-stoke one [39]. Still, to date, the interaction between VR/AR/MR-based approaches to neurorehabilitation and body image representation appears to be understudied. The relevance of the body image concept and its potential to bring about significant changes in therapy by better understanding the mechanics underlying body image and neurological disorders has not yet been comprehensively reviewed on a global scale. This introduces a gap in understanding the state of research pertaining to the use of novel adjunctive technology for beneficial intervention in the neuro-motor domain and body image representation. To address this gap, we have conducted a systematic review aimed at providing current knowledge on VR/AR/MR solutions for neurorehabilitation centred on the body image concept.

The objective is to systematically compare current approaches to address a range of research questions related to the most promising works, taking into account different rationales, strategies, technologies, clinical settings, and desired outcomes.

The paper is organized as follows. The next section outlines the methods used, including the search strategy and the formal steps taken to select and retrieve relevant literature. Subsequently, the outcomes of these steps are presented, along with an analysis of various aspects of the works selected and retrieved. This is followed by a comprehensive discussion that reports the principal findings of the study based on the results analysis. Lastly, in the conclusion, we provide a summary of the work's content, its relevance, and offer perspectives for future studies and insights.

Methods

Search strategy

For the present systematic review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was adopted [40]. The research protocol was registered by G.D. before data extraction in the PROSPERO public registry (ID: 481092 - November 22nd, 2023).

This review was performed by searching four different electronic databases: PubMed, Embase, Scopus, and Web of Science. The search of the four databases was conducted without any time

limitations on December 7th, 2023, by O.C. and M.M.
Based on the analysis of all the literature reviews on the topic, we created a new search string - adding "Spinal Cord Injury" at clinical team instruction - and reasoning as follows:
1) Target population: (Neurologic* OR Poststroke OR Post-stroke OR Post Stroke OR Stroke OR Brain Surgery OR Cerebral Palsy OR Paresis OR Spinal Cord Injury)
2) Body image and associated concepts:
(Body Scheme* OR Body Imag* OR Body perception OR Dismorphism OR Bodily Self OR Bodily Self Consciousness OR Body Illusion* OR Body Matrix OR Body Model Theory OR Body Representation OR Body Swapping OR Embodiment OR Embodiment Cognition OR Ownership Illusion*)
3) Expositions, computer science concepts:
(Virtual Reality OR Augmented Reality OR Mixed Reality OR 3D OR Tridimensional OR Avatar OR Virtual Embodiment OR Virtual Reality Reflection Therapy)
4) Experimental intervention outcome:
(Neurorehabilitation OR Motor Recovery OR Motor Rehabilitation OR Action Understanding).
From these four groups of concepts, therefore, we developed an updated query:
(Neurologic OR Poststroke OR Post-stroke OR Post Stroke OR Stroke OR Brain Surgery OR Cerebral Palsy OR Paresis OR Spinal Cord Injury) AND (Body Scheme* OR Body Imag* OR Body perception OR Dismorphism OR Bodily Self OR Bodily Self Consciousness OR Body Illusion* OR Body Matrix OR Body Model Theory OR Body Repre-sentation OR Body Swapping OR Embodiment OR Embodiment Cognition OR Owner-ship Illusion*) AND (Virtual Reality OR Augmented Reality OR Mixed Reality OR 3D OR Tridimensional OR Avatar OR Virtual Embodiment OR Virtual Reality Reflection Therapy) AND (Neurorehabilitation OR Motor Recovery OR Motor Rehabilitation OR Action Understanding).*
At this point, the four databases, PubMed, Embase, Scopus, and Web of Science, were searched (December 7th, 2023). In the PubMed search, the filter was applied by requesting only those articles with keywords in the title and abstract. Querying the Scopus search and putting the filter "title and abstract," we did not get any record. We then repeated the search by putting "article" and "computer science" as filters.

Eligibility and exclusion criteria, study selection, data extraction

After removing duplicates, two researchers who are among the authors of the paper (O.C., M.M.) independently evaluated titles and abstracts (n = 95) based on the eligibility criteria.
Articles were included if they were VR, AR o XR interventions explicitly described as being for the neurorehabilitation; reported data on user uptake; reported implementation data; published in the peer-reviewed literature.
The articles selected by the two reviewers were screened in the next phase, and the full text was read. All the authors thoroughly read the articles specified in the first phase in equal proportion, deciding to accept or reject the papers. In case of conflicts, the two authors discussed together, and if the agreement was not reached, other authors (G.D. and D.M.) expressed the final judgment. The exclusion criteria were the following: Generic studies; editorials; studies without original findings; reviews; studies where there were no VR tools; were not available in English.
The entire selection process is shown in Figure 1, which utilizes the flow chart provided by the PRISMA 2020 guidelines.

Quality of the studies and their features

Relevant features were extracted, and, specifically, the following information was considered: the methodology, the characteristics of the participants involved in the study, whether specific devices were tested, and which tools were used.

These relevant data were included in table form (Table 1) to obtain a synthetic framework of all articles read in full by authors. This table format enabled the authors to complete a cursory overview of the materials selected in the first phase.
The main methodological issue in analysing the VR application is the extent of the concept of virtual body ownership and embodiment. The VR instruments linked to body and movement representation are intended to gather information about the structure of the tools and their clinical experimentation.
To assess the quality of each study, the Newcastle-Ottawa Scale (NOS) was used. A score of a maximum of 9 stars – except for cross-sectional studies that can reach a maximum of 8 stars - was assigned to each study and reported in Table 1, where the characteristics of the studies are described. For case report studies, we used a dedicated scale published by Murad et al., 2017 which assigns a maximum of 8 points for each study [41].

Results

Search results and study characteristics

The four databases, PubMed, Embase, Scopus, and Web of Science, were searched (December 7th, 2023). From PubMed, 87 results were initially obtained. Then, the filter was applied by requesting only those articles that had the keywords in the title and abstract; thus, eight articles were obtained. Instead, from the Embase search engine, we got 14 articles. Querying the Scopus search engine with the search string, we initially got 581 records ("all field" search). By using the filter "title and abstract," we did not get any records. We then repeated the search by putting "article" and "computer science" as filters. At this point, we obtained 59 articles from Scopus that we analysed. Using the Clarivate Web of Science archive and querying it with our search strip, we obtained 29 records.
Out of the total 110 records we obtained from the four search engines, we removed duplicates (n=12) and arrived at a new total of 98 records. Three records were discharged because they were proceedings, and the remaining ones were scientific papers, either experimental or based on systematic or narrative literature reviews (Figure 1). The number of included studies was reduced to 26 after screening the full text and applying the exclusion criteria. By the end of the identification process, we removed 80% of the articles from the initial set we had identified using the four search engines.

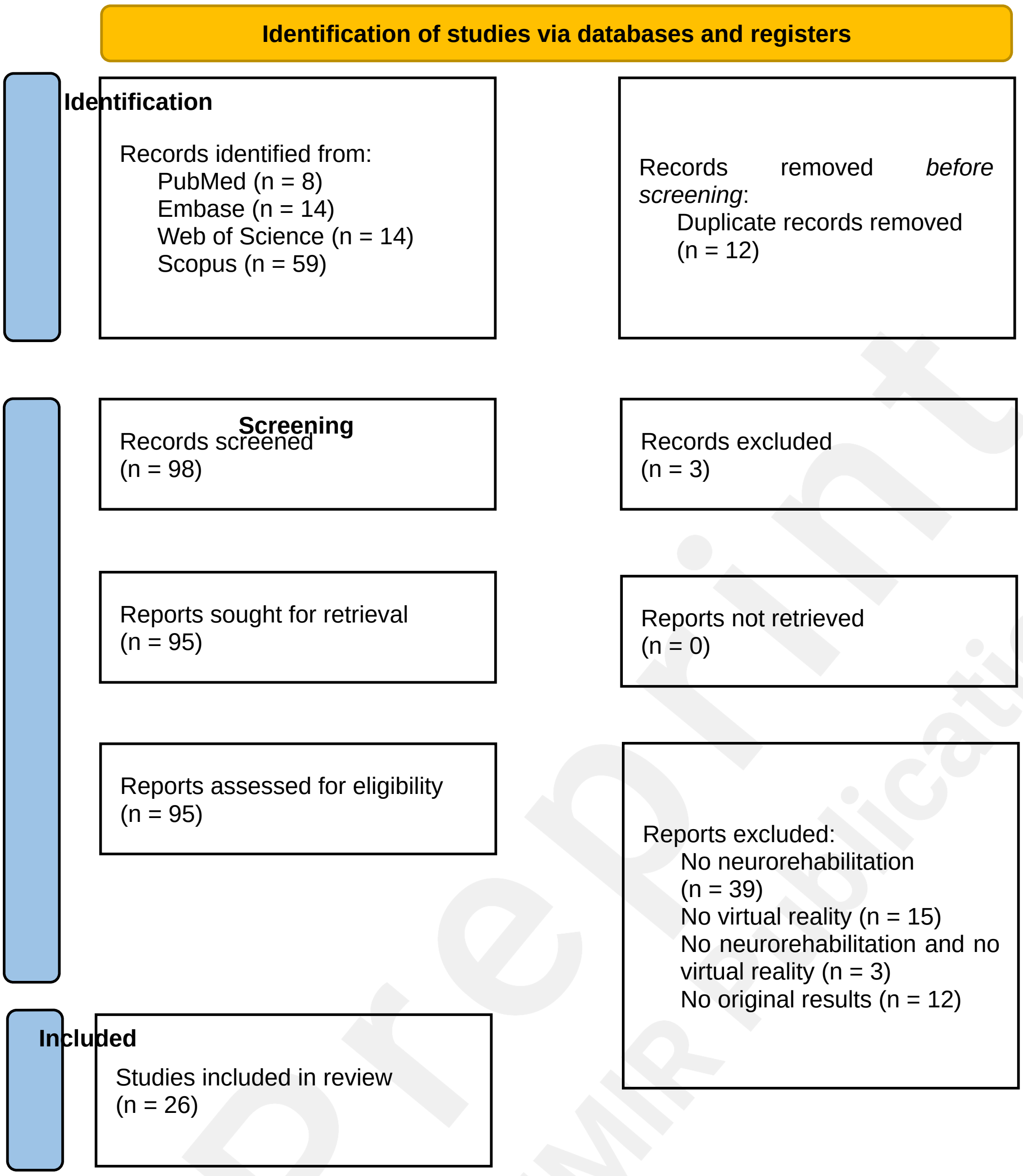
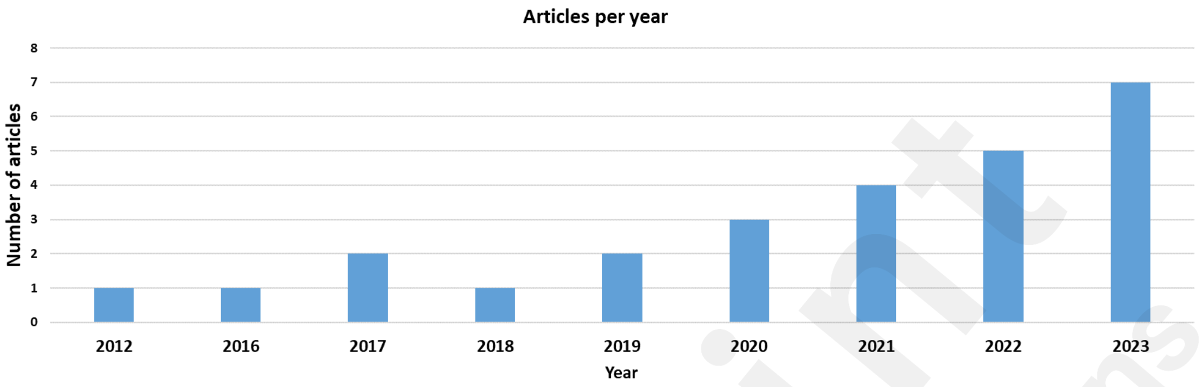


Figure 1. PRISMA 2020 flow diagram of article selection.

Geographical and Timeline Distribution

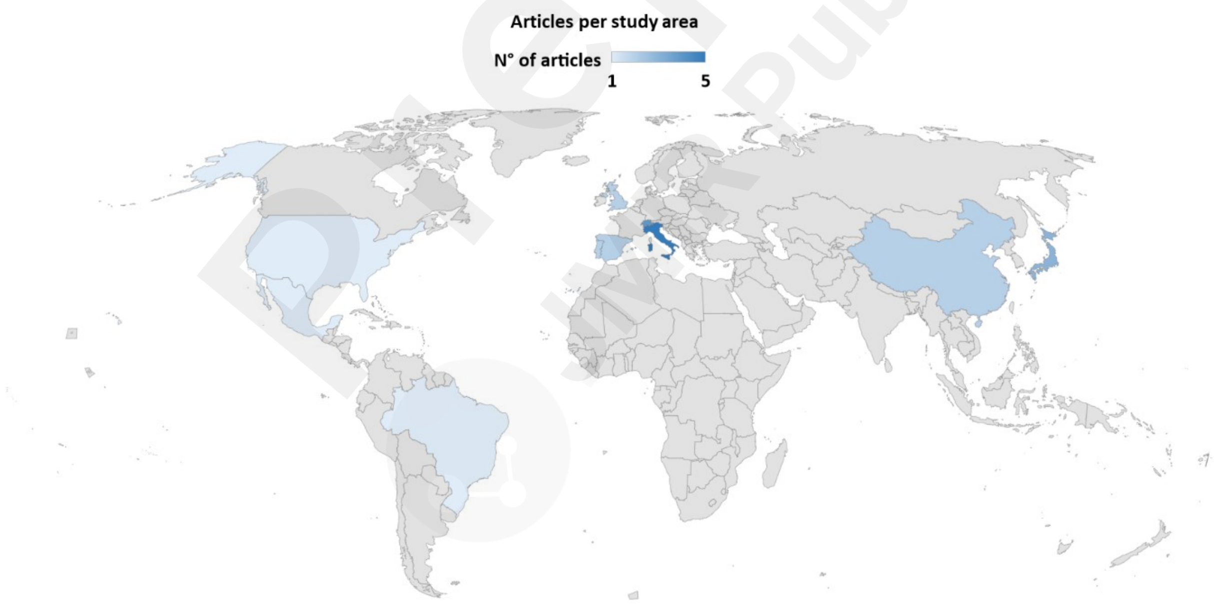
Looking at the timeline distribution of the articles, Figure 2 shows that research has increased over the last five years, during which time over 80% of the studies were published.

Figure 2. Timeline distribution of the articles included in the systematic review.



The articles included in this systematic review concern studies carried out in Italy (n = 5), Swiss (n = 4), Japan (n = 3), China (n = 2), Portugal (n = 2), United Kingdom (n = 2), Spain (n = 2), United States (n = 1), Mexico (n = 1), New Zealand (n = 1), Korea (n = 1), and Brazil (n = 1). Figure 3 shows the geographical distribution of surveyed countries.

Figure 3. Geographical distribution of the studies included in the systematic review.



Study design and population

Amongst the twenty-six selected studies, variability is observed in the sample size of the subjects studied and in the type of subjects involved in the analysis. One study was implemented on a single patient [42], and another study was based on an analysis of one patient and five healthy male control participants [43]. The largest samples concern Dong's 2023 study involving 113 healthy subjects and 16 post-stroke patients [44]. The body parts most studied were the upper limbs and hands, while three studies evaluated the application of virtual reality to the entire body. Two studies involved children: In Phelan et al. (2023), three boys and five girls with upper limb motor impairment (mean age 13 years) [45] and in Garcia-Hernandez et al. (2021), 19 children with cerebral palsy (mean age of 8 years) [46]. Studies involving only healthy subjects were twelve; studies involving only patients were eleven; mixed studies, i.e., with patients and healthy subjects compared, were three. Only two articles report a study that can be defined as a case-control design. The main pathological conditions found were post-stroke (n=6), spinal trauma (n=2), cerebral palsy (n=1), left hemisphere damage and chronic motor deficits (n=1), severe upper limb palsy (n=1), paraplegia (n=1), fixed dystonia (n=1).

Intervention evaluation studies and outcome measures

Among the selected works, 16 explicitly declare that they work on body perception, which we talked about in the introduction. Most works investigate the embodiment of virtual representations of the limbs. In particular, six works focus on the sense of agency toward virtual limbs.
Matsumiya et al. (2021) explicitly considers motor control, therefore also investigating the aspect of Motor imagery (MI) [47].
The questionnaire seems to be the most used method for evaluating the effectiveness of the proposed systems (18 out of 26). Three studies indicate the use of standard assessment systems (or those derived from standards), such as the Box and Block test. A certain number of studies indicate the extraction of indices from physiological data such as EEG (12 studies), EMG (2), MRI, GSR, EDA, and motor-evoked potentials (1 each). The manual controllers provided with virtual reality systems can easily be used to detect movement characteristics: 4 studies use indices derived from their data. Gaze analysis is not widely used among the selected articles, appearing in only two studies. The selected studies are quite heterogeneous, so it is normal to see this dispersion in the types of evaluation tools. However, given the evident extensive use of tools that are not perfectly objective, such as questionnaires (risk of self-report bias) [48], it emerges that there is still no total clarity in the objective and standardized evaluation of the effectiveness of VR use.

Quality assessment

The quality assessment showed that all the studies analysed reached a quality at least as sufficient except for one study in which the results were not adequately reported [49]. More specifically, 13 studies obtained the maximum score, while all the other studies scored well, just slightly below the maximum score. The main reason for not obtaining the maximum score was related to the limited sample size and inadequate reporting of the results. However, it is important to emphasize that a large proportion of the studies considered are feasibility and/or usability studies.

The VR technologies and technical details on the hardware/software

In the last two decades, VR technologies have undergone significant advancements. There has been a shift from complex and bulky systems that require high-performance computers to more affordable and agile alternatives. The emergence of budget-friendly VR devices such as Oculus Rift and HTC Vive has undeniably propelled research utilizing virtual reality technologies. Among the studies we examined, 7 employed the Oculus Rift (Dk1 and Dk2), three utilized the more recent and portable Oculus Quest 1 & 2, 6 employed the HTC Vive, one utilized other devices (typically older and more expensive), only one used Valve Index, and six did not specify the system used. Two studies used standard, large monitors instead of HMDs; even though they are not immersive, the modality of the experiment shares many similarities with the others, so we decided to include them in the list.
In general, these devices utilize hand trackers for navigation within the virtual space. However, only five of them explicitly mentioned the use of hand trackers. Fregna et al. (2022) chose to utilize the optical-based hand tracking system embedded in the Oculus Quest 2 [50]. In three works, the authors reported using Microsoft Kinect for interaction with the Virtual Scene. This confirms that this device,

originally created for video games, even though it had very little success in its domain, found new life in dozens of research works worldwide. Langlotz et al. (2020), instead, reports the use of the Kinect's little brother, the Leap Motion [51]. Llobera et al. (2013) opted for an Intersense 6-degree wand device [43].

In virtual reality systems, users can experience either a first-person or third-person view of the synthetic world around them (where they see their avatar). Most of the studies we gathered exclusively employed the first-person perspective (FPP), also referred to as the first-person view (FPV). Two studies, Tambone et al. (2021) [52] and Borrego et al. (2019) [53] conducted a comparison between FPP and FPV, noting a higher level of embodiment in the first mode.

To provide feedback crucial for creating the illusion in several studies, Pais-Vieira et al. (2022) [42] utilized a custom-developed thermal tactile sleeve. Shokur et al. (2016) [54] employed a similar solution, a tactile t-shirt equipped with eccentric mass vibrators. Matsumiya et al. [47] used a Phantom Force feedback device, while the remaining studies did not specify the use of special feedback devices.

Five studies incorporated EEG for recording brain responses during experiments: Pais-Vieira et al. (2022) [42] and Batista et al. (2023) [55] used a Brain Product GmbH EEG; Lim et al. (2020) [56] utilized Wearable Sensing, Llobera et al. (2013) [43] and Sanford et al. (2022)[57] employed a gUSBAmp for recording both EEG and EMG. Two studies used transcranial stimulators for different purposes: Buetleret al. (2022) [58] for detecting motor responses and Lim et al. (2020) [56] for enhancing the virtual hand illusion. A couple of studies employed other kinds of devices for these experiments: Wenk et al. (2022) [59] and Matsumiya et al. [47] employed an eye tracker, and Tambone (2021) [52] utilized an additional OLED display.

Most studies did not specify the 3D engine used, but eight research articles explicitly claimed to have utilized Unity 3D, while only one cited Unreal Engine. Unity 3D remains the preferred choice for developing VR applications in research projects due to its ease of learning, seamless integration with devices, and generally lower resource requirements compared to other engines like Unreal Engine 5. As for other additional software, MakeHuman, cited by Wenk (2023) [60] and Odermatt (2021) [61] is confirmed to be widely used for avatar creation in VR applications.

Table 1 summarizes the main characteristics of the studies and the VR tools included in this review in the order of year of publication, from the most recent in the first line to the oldest in the 26th line.

Table 1: Relevant literature in Virtual, Augmented, and Mixed reality applications for motor neurorehabilitation focused on body representation.

	First author, institution, title, journal	Year	Objective	Method and population	Body part, representation, cognition, action	VR, hardware, and software (HW/SW), tools, and View	Experimentation details	Results	Assessment /Evaluation methods	Quality score*
1	Dong, Y. [44] Beihang Univ, Beijing Adv Innovat Ctr Biomed Engn, Sch Biol Sci & Med Engn, Key Lab Biomech & Mechanobiol, Minist Educ, Beijing *A haptic-feedback virtual reality system to improve the Box and Block Test (BBT) for upper extremity motor function assessment* Virtual Reality	2023	To test a haptic-feedback, virtual reality-based version of the Box and Block Test.	113 healthy subjects and 16 post-stroke patients	Upper Arm	Oculus Rift, Chai3D	The VBBT (virtual BBT) task required users to move virtual blocks as many as possible from one compartment of a virtual box to the other within one minute. During the task, a haptic device was used to collect data, including the trajectory, velocity, and grasping force	Quantitative performance in the VBBT showed improved reliability compared to that of the BBT, although subjects' performance in the VBBT presented a stronger age-related correlation than that of BBT.	Assessment: with Mini-Mental State Examination (MMSE), Brunnstrom Stage, FMA-UE, ARAT and BBT. Evaluation: - intrinsic motivation inventory (IMI) - questionnaire - Haptic device data analyses.	8/9
2	Batista, D. [55] Institute for Systems and Robotics - Lisboa, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal *Effect of head-mounted virtual reality and*	2023	Testing Motor Imagery-BCI (MI-BCI) setup for evoking stronger sensorimotor rhythms in VR	19 healthy	Upper arm	Oculus Rift CV1. EEG by LiveAmp; Brain Products GmbH. Oculus Rift hand controllers.	A set of 6 conditions were used (various combinations of MI and VR/no VR). Two of them (non-VR and non-embodied abstract feedback) are used as controls.	Through the acquisition of EEG signals and analysis of Alpha and Beta ERD and the utilization of a virtual environment, NeuRow, along with haptic feedback implemented as	Evaluation: EEG Data Analysis	7/8

	vibrotactile feedback in ERD during motor imagery Brain-computer interface training BRAIN-COMPUTER INTERFACES						Two conditions involved vibrotactile stimulation.	vibrotactile stimulation in this research, resulted in significantly enhanced contralateral ERD. These enhancements were comparable to those observed during actual motor execution. However, the use of VR HMD alone did not yield comparable outcomes, akin to merely utilizing a computer monitor without haptic feedback.		
3	Wenk, N. [60] University of Bern *Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment* Virtual Reality	2023	The goal of this study was to evaluate the potential benefits of more immersive technologies using head-mounted displays (HMD), compared to a standard 2D screen.	Twenty healthy participants (15 females, five males) without known motor or cognitive disorders, aged from 19 to 42 years old.	Upper arm	HTC Vive, Meta 2 AR. Unity 3D. MakeHuman	This study compares three modalities: Immersive VR, AR, and a 2D screen. In each modality, participants performed the same dual-task visualized with different displays. The motor task consisted of sequentially reaching 120 fruits that	The average subjective cognitive load (RTLX) was lower with IVR compared to other modalities, but the differences did not reach statistical significance. However, the authors observed a significant effect of the modality on the physical demand subscale of the RTLX. Interest and enjoyment were	Evaluation: The questionnaire is divided into six subjective subscales that target Mental and Physical. Demand, Temporal Demand, Performance, Effort, and Frustration	7/8

							appeared randomly in one of 22 possible locations. After performing the dual motor-cognitive task with each modality, participants were requested to fill in questionnaires to report their subjective cognitive load, motivation, technology's usability, and embodiment.	reported to be higher with IVR compared to the 2D screen. Additionally, interest and enjoyment with IVR were also higher than with AR, and AR exhibited a trend of higher interest and enjoyment compared to the 2D screen.		
4	Ventura, S. [49] Department of Psychology, University of Bologna, Bologna, Italy *Embodied the Healthy Arm: Virtual Reality Rehabilitation for Stroke Patients with Proprioceptive Upper-Limb Deficit* Cyberpsychology, Behavior, and Social Networking	2023	The aim of the project is to investigate whether patients who embody a virtual arm with their injured one would induce the motor rehabilitation of the upper limb after a stroke.	Three patients (2 male, one woman).	Upper limb.	HMD not specified, Khymeia SW.	The patients are invited to perform exergames (pinching, grasping, single fingers coordination) with the injured arm in two different sessions: IVR and non-VR.	After the rehabilitation, all patients improved their motor abilities, assessed by Fugl-Meyer, Motricity Index, Box, and Blocks. In the VR sessions, patients perceive the virtual arm as their injured one.	Fugl Meyer, Motricity Index, Box, and Blocks assessment and evaluation.	6/8

5	Phelan, I. [45] College of Social Sciences and Arts, Sheffield Hallam University *Home-based immersive virtual reality physical rehabilitation in pediatric patients for upper limb motor impairment: a feasibility study* Virtual Reality	2023	This feasibility study aimed to explore the perceptions and impacts of an immersive and interactive VR scenario suitable for Upper limb motor impairment rehabilitation (ULMI) for children at home.	Three boys and five girls	Upper limb.	Meta Quest. Unreal Engine 4.23, 3ds Max 2021, and Substance Designer 11.3.	The patients are invited to play a 3D exergames with two levels: Forest level acts as a tutorial for the archery mechanic, followed by the Tower to introduce climbing. Children were then asked to use the IVR system for approximately 15 minutes twice a day at home for three weeks.	IVR for ULMI home rehabilitation could be easy to learn and acceptable, improve motor function, reduce the difficulty in the reproduction of therapeutic movements.	Assessment and evaluation: - A goniometer (Standard BASELINE® 12-inch) was used by the physiotherapist to measure a Range of Movement (ROM) of the affected and unaffected upper limb joint (flexion, extension, abduction, and adduction) before and after the at-home trial. Paediatric Quality of Life Inventory (Version 4.0 – UK English) (PedsQL) is a standardized assessment for children aged 5–18 and was completed by patients before and after the IVR rehabilitation at-home trial. System Usability	8/8

									Scale. Semi structured interviews	
6	Camardella, C. [62] Institute of Mechanical Intelligene, Scuola Superiore Sant'Anna, Pisa *Introducing wearable haptics for rendering velocity feedback in VR serious games for neuro-rehabilitation of children* Frontiers in Virtual Reality	2023	To show the design, implementation, and first evaluation of a gaming scenario for upper limb rehabilitation of children with cerebral palsy.	Eight healthy participants.	Upper limb	Oculus quest 2	The VR environment depicts a magical training ground for wizards, surrounded by mountains and trees, with a large rune on the floor marking the spell-casting area. Players use their index finger as a wand to draw symbols in the air, casting spells at enemies. The accuracy of symbol drawing determines spell potency, with reference to a 2D sample provided. Two custom lightweight haptic thimbles provide tactile feedback. Conditions studied include speed reference	Preliminary examinations conducted on healthy participants revealed that the introduction of haptic feedback didn't notably change the perception of absolute speed or the capability to uphold a steady self-selected reference speed. Nevertheless, when participants were directed to adhere to a predetermined reference speed, the incorporation of haptic feedback improved performance by enhancing smoothness and diminishing speed-tracking errors. However, it's worth noting that only smoothness demonstrated statistically significant improvement.	Evaluation: Analysis of the dataset built using the recorded hand speed as a feature.	7/8

							presence and feedback type—haptic or visual—related to tracking velocity.			
7	Song, Z. [63] School of Biological Science and Medical Engineering, Beihang University, Beijing *The third-person perspective full-body illusion induced by visual-tactile stimulation in virtual Reality for stroke patients* Consciousness and Cognition	2023	To induce the third-person perspective full-body illusion (3PP-FBI) with virtual reality (VR) in stroke patients.	19 stroke patients (6 females, 13 males)	Full body	Valve Index VR headset + controllers	Four experimental conditions were tested: synchronous visual-tactile stimulation on the back (Back-S), synchronous visual-tactile stimulation on the arm (Arm-S), non-synchronous visual-tactile stimulation on the back (Back-NS), and non-synchronous visual-tactile stimulation on the arm (Arm-NS). During the experiment, the experimenter randomly touched the participant's back or arm with a physical bar. In synchronous conditions,	The findings demonstrated that virtual reality (VR) could trigger the sensation of ownership of a third-person perspective (3PP-FBI) in stroke patients, akin to how it does in healthy individuals, through synchronous visual-tactile stimulation of a specific body part (such as the back or upper limb). Furthermore, it was observed that stimulating the back could evoke a more pronounced sense of 3PP-FBI compared to stimulating the affected upper limb. This suggests that for stroke patients experiencing limb dysfunction,	Questionnaire scores reflect the subjective experience of the participants, and self-location drift values reflect the objective self-location perception.	8/8

							virtual and physical bar stimulation matched temporally and spatially.	stimulating the back may be more effective in inducing a robust sense of ownership from a third-person perspective.		
8	Buetler K. [58] Motor Learning and Neurorehabilitation Laboratory, ARTORG Center for Biomedical Engineering Research, University of Bern, Bern, Switzerland *"Tricking the Brain" Using Immersive Virtual Reality: Modifying the Self-Perception Over Embodied Avatar Influences Motor Cortical Excitability and Action Initiation.* Frontiers in Human Neuroscience	2022	Testing the adaptation of motor commands based on perceived modified reality, using a "Stone Arm Illusion."	Ten healthy participants		HTC Vive with trackers. Unity 3D, The Black Box response buttons, Magstim 200 Mono Pulse stimulator. A TMS navigation system	The participants viewed in VR an avatar from a first-person perspective. The surface of the avatar was gradually transformed from human to stone. This visual change was reinforced by repeatedly touching the participant's real arm and the avatar's arm with a virtual hammer while progressively replacing the sound of the hammer hitting the skin with the sound of the hammer hitting a stone via a loudspeaker. TMS was used to evaluate changes in	Participants reported a complete immersion in the "stone arm illusion." Through immersive virtual reality (VR) and multisensory feedback, they perceived their arm as colder, heavier, stiffer, and less sensitive when they experienced illusory ownership over a stone arm compared to a human avatar. The extent of the stone illusion influenced participants' perception of their ability to control their arm, yet they consistently regarded the virtual stone arm as their own.	Two questionnaires to assess the subjectively reported embodiment and the perceptual correlates of the stone arm illusion. Evaluation: - Motor evoked potentials amplitudes - kinematic variables data analysis.	7/8

							motor cortical excitability associated with the illusion. Additionally, to investigate if the "stone illusion" affected motor control, participants performed a reaching task with both the human and stone avatar.			
9	Fregna, G. [50] Univ Ferrara, Doctoral Program Translat Neurosci & Neurotechnol, Ferrara, Italy *A novel immersive virtual reality environment for the motor rehabilitation of stroke patients: A feasibility study* FRONTIERS IN ROBOTICS AND AI	2022	Testing the substantial subjective impressions of ownership of the virtual body.	Feasibility study in a cohort of 16 stroke patients. No age restrictions were applied, but patients affected by severe cognitive impairments or other co-existing clinical conditions were excluded.		Oculus Quest 2. Unity3D	The patients are immersed in a VR environment by means of a head-mounted display. In this environment, they can see different objects with which they can interact with a series of tasks. The program running on the HMD wirelessly communicates with a client app running on a remote PC.	Nearly all participants provided the highest rating for their experience, and in a standardized survey, they indicated a strong sense of possession of the virtual hands and control in the VR setting generated by those virtual hands. The findings demonstrate that using virtual hands resulted in significant subjective perceptions of owning the virtual	Assessment: Fugl-Meyer Assessment for Upper Extremity Evaluation: - Subset of a standardized questionnaire proposed by Gonzalez-Franco and Peck (2018). - A satisfaction questionnaire. - Trajectories data analysis.	8/8

								body and having agency among the participants.		
10	Pais-Vieira, C. [42] Instituto de Ciências da Saúde (ICS), Universidade Católica Portuguesa, Porto, Portugal *Embodiment Comfort Levels During Motor Imagery Training Combined With Immersive Virtual Reality in a Spinal Cord Injury Patient* Frontiers in Human Neuroscience	2022	Testing level and comfort of embodiment experience. Reducing pain.	Single case study on a SCI (spinal cord injury) participant. Five weeks duration.	Hand	HTC Vive Pro Eye, custom-developed thermal-tactile sleeves with thermal stimulation, EEG Brain Products GmbH, Gilching, OpenVibe, Cycling 74 Max,	Each session consisted of three different phases: habituation, data acquisition, and real-time decoding. 1) During habituation, the participant triggered each step of the avatar using the hand controller and received visual, auditory, and thermal-tactile feedback. 2) During the data acquisition phase, neural data was recorded while the subject performed the motor imagery task and received visual, auditory, and thermal-tactile feedback 3) The neural decoding phase was similar in all aspects to the	Participants reported high levels of embodiment experiences and a reduction in pain, expressing comfort with the embodiment encounters. The EEG decoding performance averaged at 75 +/- 23%.	Comfort evaluation questionnaire EEG Data analysis.	8/8

							data acquisition phase, with the exception that the classifier, trained with the data acquired in the second phase, would now decode in real-time neural activity recorded from the participant.			
11	Wenk, N. [59] Artorg Center for Biomedical Engineering Research, University of Bern *Hiding Assistive Robots during Training in Immersive VR Does Not Affect Users' Motivation, Presence, Embodiment, Performance, Nor Visual Attention* IEEE Signal Processing Letters	2022	This study explores how motivation, embodiment, and presence are impacted if neurorehabilitation robots are not displayed in VE during sessions.	Twenty-eight healthy participants aged from 21 to 64.	Upper arm	BURT Upper-limb rehabilitation end-effector robot. HTC Vive Pro Eye + trackers. Unity 3D	Participants immersed in the virtual environment (VE) from a first-person perspective controlled an avatar's head and right arm. They were instructed to navigate paths quickly and accurately, collecting coins along the way using a sphere held by the avatar's hand, similar to the real sphere held by participants on the robot end-effector. Paths were	Following each trial, participants were instructed to remove the head-mounted display (HMD) and complete a series of questionnaires. The authors documented the participants' gaze behavior throughout the task. The authors did not observe a significant main effect of the robots' visibility in the virtual environment (VE). Additionally, no interaction effect was detected between visibility and the level of assistance provided by the robots.	Evaluation: Questionnaires on presence, embodiment, and motivation. Trajectories and gaze data analysis.	8/8

							defined by cubic Bezier curves scaled to the participant's workspace. Coins disappeared upon collection, accompanied by a sound effect. Participants completed two laps on each of the seven paths, aiming to improve their second lap time for applause. Path order was randomized, and a user interface provided lap time feedback.			
12	Sanford, S. [57] Altorfer Complex Stevens Institute of Technology, Hoboken, NJ, United States *Investigating features in augmented visual feedback for virtual reality rehabilitation of upper-extremity function through isometric muscle*	2022	This study represents an initial exploration into the impact of different levels of complexity and intermittency in augmented visual guidance on the performance of an isometric muscle control task using a computerized platform.	Thirteen healthy participants (seven males, six females)	Upper arm	Position-adjustable brace that isometrically supports the upper arm. Trigno Wireless EMG System. g.USBamp EEG. Shimmer3 GSR. Headset not specified.	This study utilized augmented training guidance through visual cues indicating deviations from the shortest path between starting positions and targets. A semi-transparent "ghost" robot avatar was	When aiming to enhance upper-extremity function through training, emphasizing end-effector accuracy alone, without supplementary visual feedback for the forearm and upper arm, leads to improved motor performance and increased arousal. Training with	Evaluation: EMG, EEG, EDA data analisys	8/8

	control Frontiers in Virtual Reality						displayed alongside the participant-controlled avatar during training, projecting the participant's movements onto the optimal path. Four modes of augmented visual feedback were created by varying complexity (amount of visual information) and intermittency (frequency of visual information), each tested at two levels.	simpler feedback led to shorter completion times and minimized path lengths, whereas intermittent feedback enhanced muscle-level control and decreased cognitive activity. These results imply that investing resources in physical engagement and performance yields favorable outcomes.		
13	Matsumiya, K. [47] Tohoku Univ, Grad Sch Informat Sci Japan *Awareness of voluntary action, rather than body ownership, improves motor control*	2021	To determine the functional roles of agency and body ownership in motor control.	Twenty participants (7 women, 13 men; mean age 22.75 [range 19–28] years) were recruited in experiment 1, and 29		HTC Vive, PHANToM force-feedback device, Eye tracker	A session consisted of a hand-movement task and a finger-tracking task. During the task, an eye tracker records eye movement. In the passive condition, the participant's	The research findings indicate that in the synchronous condition, both agency and motor commands were effective, whereas only agency appeared to be effective in the asynchronous	Evaluation: Questionnaire - Gaze analysis	8/8

	SCIENTIFIC REPORTS			participants (13 women, 16 men; mean age 22.66 [range 19–28] years) were recruited in experiment 2.			entire right arm, which was concealed from view, was moved by the arm of a force-feedback device attached to the participant's right index finger. In the synchronous condition, the CG hand moved in perfect sync with the participant's hand movements. In the asynchronous condition, whether the participant's hand was moved actively or passively, the CG hand movements were delayed by 0.5 seconds. Consequently, four conditions were defined: active-synchronous, active-asynchronous, passive-synchronous,	condition. Specifically, participants reported a sense of agency over the CG hand in both the active-synchronous and active-asynchronous conditions. However, motor commands aligned with the visual feedback of the moving hand (i.e., the CG hand in motion) only in the active-synchronous condition, not in the active-asynchronous condition.		

							and passive-asynchronous.			
14	Odermatt, I.A. [61] Univ Bern, ARTORG Ctr Biomed Engn Res *Congruency of Information Rather Than Body Ownership Enhances Motor Performance in Highly Embodied Virtual Reality* FRONTIERS IN NEUROSCIENCE	2021	To investigate the effect of body ownership and congruency of information on motor performance in immersive virtual reality, modulating body ownership by providing congruent vs. incongruent visuo-tactile stimulation.	50 healthy participants (35 females, 15 males)	Hand / Upper arm	HTC Vive + controllers, 4-button response box. GSR g.Sensor, g.tec Medical Engineering Unity 3D, MakeHuman	Participants received visuo-tactile stimulation during a simple task with the controllers and the buttons. Directly after the tasks, a threat, i.e., a virtual knife, fell from above the vision field and stabbed the virtual hand. GSR data were captured during the sessions.	The findings of the author indicate that virtual reality (VR) motor tasks, which offer consistent sensory feedback across multiple senses and promote a sense of body ownership and agency through visual-motor synchronizations, are most beneficial for motor training. Utilizing immersive VR from a first-person perspective could streamline the creation of effective training environments, particularly in the field of (robotic) neurorehabilitation.	Evaluation: - Questionnaire - GSR data analysis	8/9
15	Tambone, T. [52] Department of Psychology, University of Turin *Using Body Ownership to Modulate the Motor System in Stroke Patients*	2021	Testing body ownership illusion, confronting FP e TP perspective.	A group of 12 patients with left hemisphere damage and chronic motor deficits	Full body	Oculus Rift CV1 (Oculus VR, Irvine, CA) equipped with two PenTile organic light-emitting diode displays. Unity3D.	The experiment consisted of two scenes seen in VR in two different sessions, one in FPP (first-person perspective) and the other in TPP	According to a questionnaire, for the embodiment group (first-person perspective), the median score for the illusion question was significantly higher than the median	Eight types of gait tests for assessment and post-trial evaluation. Evaluation with questionnaire on the feelings	8/8

	Psychological Science						(third-person perspective).	score for the control question for ownership (third-person perspective)	of ownership and agency over the avatar on a Likert-type scale	
16	Garcia-Hernandez N. [46] Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV-IPN), Saltillo, Mexico *Virtual body representation for rehabilitation influences on motor performance of cerebral palsy children* Virtual RealityVolume 25	2021	To examine how the subjective experience of seeing and controlling a half-body avatar, or an abstract hand representation in a moderate immersion virtual environment (VE), for training upper limb movements may affect CP children's motor performance	19 subjects with cerebral palsy (13 males, six females)	Upper limb	KinectV2, 50' flat screen (no headset), Unity3D	Children visualized a virtual scene from a third-person perspective, behind the avatar or abstract object. They have to reach three target balls located over their shoulder level and release them in a box below their shoulder level; four trials were performed with a TPP avatar and four with an abstract avatar (a sphere)	Humans improve their movement efficiency by reducing specific cost factors. Findings indicate that the virtual representation of the body notably impacts task performance indicators and cost factors associated with upper limb movements, especially in reaching tasks as opposed to releasing tasks. When children with cerebral palsy (CP) visualize hand movements using an abstract object, they complete tasks 22% faster, with 28% less overall movement, and exhibit 62% fewer jerky movements compared to visualizing the entire arm through	Evaluation: Movevements data analisys	8/8

								a realistic avatar.		
17	Matamala-Gomez, M. [64] University of Milano-Bicocca *Changing Body Representation Through Full Body Ownership Illusions Might Foster Motor Rehabilitation Outcome in Patients with Stroke* FRONTIERS IN PSYCHOLOGY	2020	Assessment and modulation of the internal representation of the affected upper limb in stroke patients	Not specified	Upper limb	Not specified	Patients will observe the virtual body (360 VIDEO) that will be collocated with their real body and will represent the patient's described distorted representation of the upper limb from a first-person perspective. Then, they observe the progressive transformation of the affected upper limb from a distorted representation to a normal one.	Not specified	Not specified	7/8
18	Langlotz, T. [51] Department of Information Science, University of Otago, Dunedin, New Zealand *My hands? Importance of personalized virtual hands*	2020	To demonstrate that the higher realism of virtual hands achieved (AV, Augmented virtuality) by a novel texturing approach alters perceived embodiment.		Hands	Oculus Rift CV1. Leap Motion	In the first experiment, to test the AV hands, participants interacted with two randomly assigned hand visualizations and experienced both mirrored	The findings from the questionnaires indicate that healthy users can experience a strong sense of embodiment with virtual hands in augmented reality (AV). Additionally, the second study	Evaluation: - Hand Visualisation Realism Questionnaire - Embodiment Virtual Reality Questionnaire (Lin and Jörg adaptation,	8/8

	in a neurorehabilitation scenario Virtual Reality						and non-mirrored conditions for each. In a second experiment, the authors wanted to investigate how participants perceived their own hand size in a virtual environment by allowing them to resize the virtual hand model to what they perceived to be their real hand size.	illustrates that the size of the virtual hands in AV environments has minimal to no impact on this sense of embodiment.	2016)	
19	Lim, H. [56] Keimyung University, Daegu, Republic of Korea *Transcranial Direct Current Stimulation Effect on Virtual Hand Illusion* Cyberpsychology, behavior and social networking	2020	To investigate whether a mirror virtual hand illusion could be modulated by tDCS	48 participants (30m, 18f)	Hand	tCDS stimulator, Wearable Sensing DSI-24 EEG. Headset not specified.	Virtual mirror tasks are conducted with and without tCDS on two different days. In the task, participants flex their right arm while seeing the corresponding movement in the left hand.	A more pronounced proprioceptive change occurred during tasks involving tCDS, indicating support for employing the integrated system in the rehabilitation of post-stroke patients.	Evaluation: - EEG data analysis. - Questionnaire about ownership and control of the mirrored virtual hand.	7/8
20	Kaneko F. [65] Keio Univ, Sch Med, Dept Rehabil	2019	This study aimed to clarify the effect of the kinesthetic perception illusion	Eleven patients with severe paralysis in	Upper limb	Augmented reality system using monitors.	The cognitive phenomenon of KINVIS can be described as the	The results of motor function (Fugle-Meyer Assessment, FMA)	Assessment and evaluation: - Fugl-Meyer	8/8

Preprint JMIR Publications

	Med, Tokyo, Japan *A Case Series Clinical Trial of a Novel Approach Using Augmented Reality That Inspires Self-Body Cognition in Patients with Stroke: Effects on Motor Function and Resting-State Brain Functional Connectivity.* Frontiers in Systems Neuroscience		induced by visual stimulation (KINVIS) on upper limb motor function and the relationship between motor function and resting-state brain networks.	the upper limbs (4 women).		fMRI is used to evaluate motor functions and resting-state brain functional connectivity.	feeling of one's body moving during sensory input, even though the body is actually in a resting state. The subjects were applied visual stimulation for 20 min together with neuromuscular electrical stimulation. The patients were seated at a chair with their forearms on the table. The hand movement of the unaffected side was recorded before the intervention. The movement task involved hand opening and closing. This task was executed using the unaffected side and was flipped to mirror the movement of the affected side.	and spasticity (Modified Ashworth Scale, MAS) showed significant improvement following the intervention.	assessment, - Modified Ashworth Scale, - Action Research Arm test, - Box and Block Test, - Motor Activity log, - MRI data analysis.	

21	Borrego A. [53] Instituto de Investigación e Innovación en Bioingeniería, Universitat Politècnica de València *Embodiment and Presence in Virtual Reality After Stroke. A Comparative Study with Healthy Subjects* Frontiers in Neurology	2019	To determine and compare the sense of embodiment and presence elicited by a virtual environment under different perspectives and levels of immersion in healthy subjects and individuals with stroke	46 healthy subjects (25M + 21F) and 32 individuals with Stroke (18M + 14F)	Full body	Oculus Rift CV1, Microsoft Kinect	The VE consisted of an infinite checkered floor, with a central grey circle and a gender-matched mesomorph avatar, which synchronously mimicked the participants' movements. Playdough-colored items (cubes, spheres, and cones) appeared on the floor in front of the central circle. The objective of the task was to step on the items before they disappeared with the closest avatar foot while keeping the other foot inside the central circle. In between stepping on the items, the foot used had to be moved back into the circle. The task has to	Consistently higher levels of embodiment and presence were observed in healthy subjects when using the first-person perspective. These findings highlight that utilizing a first-person perspective through a head-mounted display (HMD) induced a stronger feeling of body ownership and self-location compared to embodying a virtual avatar, leading to an enhanced sense of presence across both populations. However, the sense of agency remained relatively consistent across different conditions. Notably, participants with stroke consistently reported less immersive experiences compared to their healthy counterparts.	Evaluation: - Adapted version of the Embodiment of Rubber Hand Questionnaire. Slater- - Usoh Steed Questionnaire.	8/9

							be performed in two modes: FPP and TPP (screen)			
22	Caola, B. [66] University of East London Italy *The bodily illusion in adverse conditions: virtual arm ownership during visuomotor mismatch* Perception	2018	Exploring whether it is possible to induce a sense of body ownership over a virtual body part during visuo-motor inconsistencies, with or without the aid of concomitant visuo-tactile stimulations.	45 healthy (22 female)	Upper limb.	Oculus Rift DK2. Unity 3D A small vibrator was placed in the middle of the right participant's hand dorsum and controlled via an Arduino board.	From a first-person perspective, the participant watched a virtual tube moving or an avatar's arm moving, with or without concomitant synchronous visuo-tactile stimulations on their hand. Three different virtual arm/tube speeds were also investigated, while all participants kept their real arms still.	The primary discovery from this research is that it's feasible to generate a feeling of ownership over a virtual body part, even in the presence of a significant discrepancy between the real and virtual limb's visual and motor aspects. These findings were derived from a questionnaire-based approach.	Evaluation: Questionnaire (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008).	7/8
23	Inamura, T. [67] Natl Inst Informat, Principles Informat Res Div, Tokyo, Japan *Development of VR platform for cloud-based neurorehabilitation*	2017	To determine the feasibility of the VR system – specifically, whether it has enough effect on sense of agency (SoA) and sense of ownership (SoO) for healthy subjects	12 (8 males, 2 Females)	(Phantom) Limb	SIGVerse system. Oculus Rift DK2 Kinect V2	VR system in which a virtual avatar performs a motion identical to that of the subject by means of a motion-capturing device. The	The findings indicated that the perceived length of the arm was altered based on the displayed arm's length within the virtual reality (VR) setting. Through analysis of	Evaluation: - Questionnaire. - Gesture data analysis (after the induction movement, the subjective sense of the length of the	7/8

	and its application to research on sense of agency and ownership ADVANCED ROBOTICS		– before conducting experiments for actual phantom limb patients				subject wears a 3D head-mounted display to experience seeing through the eyes of the avatar. Six conditions of avatar representation were used: two appearances of a normal human arm and a robot arm and three lengths of the arm (short, medium, and long). The subject executes elbow flexion-extension movement of the right arm, which causes the same movement in the VR avatar's arm.	questionnaire responses, it was determined that there was no adverse impact on the Sense of Agency (SoA). Additionally, it was observed that the Sense of Ownership (SoO) was stronger when participants viewed a natural human avatar compared to when they observed a robot arm.	right arm is measured by a pointing gesture of the left hand.)	
24	Pozeg, P. [68] École Polytechnique Fédérale de Lausanne, Campus Biotech, Geneva, Switzerland *Virtual reality improves*	2017	To investigate changes in body ownership and chronic neuropathic pain in patients with spinal cord injury (SCI) using multisensory own body illusions	20 patients with SCI with paraplegia and 20 healthy control participants (HC)		Not specified	Virtual leg illusion + full-body illusion, using asynchronous or synchronous visuo-tactile stimulation. The HMD	The findings reveal that individuals with Spinal Cord Injury (SCI) exhibit reduced sensitivity to multisensory stimuli that generate the illusion of leg	Assessment and evaluation: - VLI was assessed with a 9-item questionnaire adapted from body illusions studies.	9/9

	embodiment and neuropathic pain caused by spinal cord injury Neurology		and virtual reality (VR).				shows the real-time (or delayed) video of dummy legs from the distance and angle that corresponds to the participant's first-person viewpoint.	ownership in comparison to those without such injuries (HC). Furthermore, the sense of leg ownership diminished over time following SCI. Interestingly, there were no discernible distinctions between the groups in terms of overall body ownership, as assessed by the FBI.	- The FBI was assessed with a 7-item questionnaire. actual neuropathic pain has been assessed with a visual analog scale	
25	Shokur, S. [54] AASDAP, Neurorehabil Lab, Sao Paulo, Brazil *Assimilation of virtual legs and perception of floor texture by complete paraplegic patients receiving artificial tactile feedback* Scientific Reports	2016	Reproducing lower limb somatosensory feedback in paraplegics by remapping missing leg/foot tactile sensations onto the skin of the patient's forearms.	7 SCI patients		HMD not specified. "Tactile shirt" with eccentric mass (ERM) vibrators to deliver somatosensory feedback	Immersive virtual reality system where the subjects' lower limbs were simulated by a human-like 3D avatar seen in FPP with a HMD. Tactile and proprioceptive sensations generated by the avatar's virtual legs were mapped on the patients' forearms by means of arrays of vibrators that defined a haptic	After the experiment, six out of eight patients reported in a questionnaire that they experienced again the vivid sensation of walking on the three chosen ground surfaces.	Evaluation: - Questionnaire. - Analyze the experiment data (keypress timings, performance score, etc.)	8/8

							display. Two months later, a second session without feedback was administered.			
26	Llobera, J. [43] EVENT Lab, University of Barcelona, Barcelona *Virtual reality for assessment of patients suffering chronic pain: a case studies* Experimental Brain Research	2013	The case study wants to show that the induction of virtual body ownership combined with simple electrophysiological measures could be useful for the diagnosis of patients with neurological conditions.	A case study on a patient with fixed dystonia, + 5 controls		NVIS SX111 HMD. InterSense IS900 head tracker. EMG+EEG gUSBAmp. 6-degrees-of-freedom Wand device for visuo-tactile experience.	Authors propose a method that exploits ownership of a virtual body in combination with a simple brain-computer interface (BCI) and basic physiological measures to complement neurological assessment. Steps of the trial: (a) Induction of body ownership. (b) Opening of the virtual hand using BCI (c) Reducing the size of the ball using BCI (d) Repeat (b). (e) Repeat (c). The EMG was measured throughout to assess the	Despite the small scope of this particular case study, the findings indicate that the sense of owning a virtual body, combined with basic electrophysiological equipment such as a single-surface EMG electrode and a single electrode BCI, can be utilized to evaluate movement-related disorders in neurological examinations.	Assessment and evaluation: - EMG and EEG data analysis. - Questionnaire on body ownership.	8/9

							impact of the visual feedback on the muscular activity of the real hand.			

Preprint JMIR Publications

Discussion

Summary of Evidence

This review delves into the burgeoning trend of utilizing virtual reality (VR) in neurorehabilitation, a field witnessing a surge in research activity. A comprehensive search across four databases—PubMed, Embase, Scopus, and Web of Science—conducted on December 7th, 2023, yielded a total of 110 records. Following a meticulous screening process, 26 studies (20%) met the inclusion criteria, signifying a notable interest in this area. Notably, over 80% of these studies were published within the past five years, indicating a recent surge in research attention.

Geographically, the studies were predominantly conducted in Italy, Switzerland, and Japan. They covered a diverse array of neurological conditions, including post-stroke rehabilitation, spinal trauma, cerebral palsy, and others. Notable contributors to this body of research include Phelanet al. (2023) [45], Hernandez et al. (2021) [46], Tambone et al. (2021) [52], Borrego et al. (2019) [53], Pais-Vieira et al. (2022) [42], Shokuret al. (2016) [54] and Matsumiya et al. (2021) [47].

Interestingly, the assessment methods employed varied widely across studies. While questionnaires were the most utilized tool to evaluate the effectiveness of VR interventions, several studies also relied on physiological data analysis, manual controllers, and even gaze analysis. Despite this heterogeneity, a common theme emerged regarding the need for more objective and standardized evaluation methods, as the current reliance on self-report questionnaires lacks complete clarity and objectivity.

Quality assessment revealed that the studies generally attained a sufficient level of quality, albeit with some limitations. These limitations primarily stemmed from issues such as small sample sizes and inadequate reporting of results. It's worth noting that a significant portion of the studies reviewed focused on feasibility and usability rather than strictly efficacy.

In the last two decades, VR technologies have evolved from bulky systems requiring high-performance computers to more affordable and agile alternatives. Devices like Oculus Rift and HTC Vive have significantly advanced VR research. Among the reviewed studies, 7 used the Oculus Rift, 3 used Oculus Quest, 6 used HTC Vive, 1 used Valve Index, and six did not specify the device. Two studies used large monitors instead of head-mounted displays (HMDs).

Hand trackers are commonly used for navigation in VR, but only five studies mentioned them explicitly. Some studies used Microsoft Kinect and Leap Motion for interaction, while one used an Intersense 6-degree wand. Most studies employed a first-person perspective (FPP), with two comparing FPP and third-person view (FPV), finding higher embodiment in FPP.

For feedback, some studies used custom devices like thermal tactile sleeves, tactile t-shirts, and force feedback devices. Five studies recorded brain responses using EEG, while others used transcranial stimulators, eye trackers, and additional displays.

Overall, this review underscores the burgeoning interest and promising potential of VR in neurorehabilitation while also advocating for more standardized evaluation methods to ensure robustness and comparability across studies.

Comparison with Prior Work

The landscape of neurorehabilitation is undergoing a profound change due to the growing interest in and exploration of virtual reality (VR) technologies. The body of literature surrounding the use of VR in neurorehabilitation reflects a diverse array of findings and perspectives, shedding light on both the promises and challenges of integrating this innovative technology into clinical practice [28,35].

Ventura et al. (2023) [49] conducted a systematic review that underscored the potential of body ownership illusion through VR in limb rehabilitation post-stroke, highlighting its role in accelerating motor recovery by fostering a sense of embodiment [69]. This finding resonates with embodied cognition theories, which emphasize the reciprocal relationship between bodily states and cognitive functions, particularly evident in language processing among individuals with neurological disorders [70]. Leeb and Pérez-Marcos (2020) [71] further explored the synergies between brain-computer interfaces (BCIs) and VR, highlighting their transformative potential in redefining neurorehabilitation paradigms by integrating motor-cognitive training with evidence-based neuroscience principles.

In a meta-analysis, Maier et al. (2019) [72] delved into the comparative efficacy of specific VR (SVR) and nonspecific VR (NSVR) systems for upper-limb rehabilitation post-stroke, revealing that SVR systems tailored explicitly for rehabilitation yielded superior outcomes compared to NSVR systems [72]. These findings underscore the importance of designing VR interventions that are specifically tailored to address the unique rehabilitation needs of patients with neurological conditions. Moreover, immersive VR environments have emerged as promising tools for alleviating pain and modulating body perception, offering novel therapeutic avenues for managing conditions characterized by distorted body image [73,74].

Perez-Marcos et al. (2018) [75] emphasized the role of VR in empowering patients through engaging and motivating training approaches, integrating motor-cognitive training with evidence-based principles to foster self-management and ownership of the rehabilitation process.

While the potential of VR in neurorehabilitation is vast, Tieri et al. (2018) [34] cautioned against overstating its superiority over conventional rehabilitation techniques, highlighting the need for a nuanced understanding of its efficacy across diverse patient populations and clinical contexts. Similarly, Dieguez and Lopez (2017) [76] underscored the importance of clinical reporting in comprehensively understanding abnormal body representations in neurological disorders, paving the way for targeted interventions informed by empirical evidence. Furthermore, Pulay et al. (2015) [77] proposed leveraging eye-tracking and EMG devices in VR to facilitate cognitive and motor development in children with severe physical disabilities, offering a glimpse into the transformative potential of technology-assisted interventions in enhancing rehabilitation outcomes.

In parallel, Christ and Reiner (2014) [78] explored the theoretical underpinnings and clinical applications of the rubber hand and virtual hand illusion, offering insights into their implications for rehabilitation; additionally, Hesse et al. (2003) [79] traced the evolution of robotic devices for motor rehabilitation, highlighting their role in delivering intensive and task-specific therapy approaches for stroke and spinal cord injuries, thereby opening new vistas for optimizing motor recovery outcomes.

In summary, the integration of VR into neurorehabilitation represents a paradigm shift in clinical practice, offering unprecedented opportunities to enhance patient outcomes and quality of life. However, continued research efforts are essential to elucidate the mechanisms of action underlying VR-based interventions and optimize their therapeutic efficacy across diverse patient populations and clinical settings.

Limitations

This review acknowledges several limitations that could affect the synthesis and interpretation of results. Important differences were observed among the studies reviewed that include variations in sample size, duration of follow-up, treatment protocols, and study design. Variability in the sample population, particularly in terms of demographics and pathology, emerges as a significant limitation, along with small sample sizes in some studies, which may reduce statistical power and compromise the reliability of comparative analyses.

Limitations related to heterogeneity in treatments arise from variations in dose, duration and adherence to standard protocols, which consequently introduce uncertainty in intervention effects. The absence of comparison/control groups in some studies could affect the validity of the results. Despite the methodological rigor applied - following guidelines such as those of Smith et al. for systematic reviews and the PRISMA reporting guideline - several limitations therefore remain. Furthermore, it was of course not possible to conduct a meta-analysis precisely because of the heterogeneity of the research we decided to include; with more evidence and the use of more consistent measures, a meta-analysis would be a valuable addition to the literature.

While the review encompassed a comprehensive search across major electronic databases, the exclusion of other databases and grey literature may have overlooked relevant studies. Moreover, limiting the analysis to English-language articles potentially excludes methodologically robust studies published in other languages, leading to information loss.

Conclusions

Systematic reviews play a pivotal role in consolidating knowledge and informing decision-making in various domains, including academia and clinical practice. They offer a comprehensive overview of existing literature, allowing for a thorough evaluation of evidence and identification of gaps in knowledge. As the body of research on virtual reality (VR) and neurorehabilitation continues to expand, systematic reviews have become increasingly prevalent, offering insights into the efficacy and limitations of VR-based interventions [80].

VR technology holds tremendous potential in neurorehabilitation by providing immersive, multisensory experiences that can enhance neural plasticity and facilitate functional recovery. Through repetitive, task-specific training and reinforcement learning mechanisms, VR interventions offer personalized and engaging rehabilitation approaches [80]. Furthermore, the incorporation of animated avatars within VR environments enables users to engage with their virtual representations, facilitating motor learning processes through the activation of mirror neuron systems [81].

The level of immersion in VR environments, determined by the extent of sensory and motor engagement, influences the user's sense of presence, bodily ownership, and agency within the virtual space [34,82]. This immersive experience fosters a deeper engagement with rehabilitation tasks, potentially leading to more effective outcomes in motor and cognitive recovery [34].

However, despite the growing interest in VR-based neurorehabilitation, there are notable limitations and challenges that need to be addressed. One such limitation is the lack of diversity in reported studies, with few exploring the integration of augmented reality (AR) technologies alongside immersive VR environments [60]. AR technology offers unique advantages, such as the ability to overlay virtual content onto real-world environments, enhancing the relevance and transferability of rehabilitation exercises to daily life contexts. The potential of AR in post-stroke rehabilitation lies in its ability to leverage familiar environmental cues and facilitate skill transfer to everyday activities. By integrating virtual objects and visual cues into real-world settings, AR-based interventions can enhance the embodiment mechanism and improve motor control and coordination. Moreover, AR preserves the natural context of rehabilitation exercises, allowing patients to feel more connected to their surroundings and promoting greater engagement in therapy [60].

In conclusion, while VR has emerged as a promising tool in neurorehabilitation, the integration of AR technologies holds considerable potential for enhancing rehabilitation outcomes, particularly in post-stroke patients. Future research should explore the synergistic effects of VR and AR interventions and their impact on motor recovery and quality of life in clinical populations. Additionally, efforts to address the limitations of existing studies and promote standardized reporting practices will contribute to advancing the field of VR-based neurorehabilitation. This multifaceted exploration underscores the transformative potential of VR that could possibly reshape the neurorehabilitation landscape, heralding a new era of personalized, technology-driven rehabilitation approaches. It is at the same time important to emphasize that the contribution of the neurologist, physiatrist and physical therapist is absolutely indispensable in the construction and implementation of these tools. At present, new technologies are complementary and not comparable means to the clinician's work in case assessment and functional rehabilitation care, both cognitive and motor.

References

1. Ivanenko YP, Dominici N, Daprati E, Nico D, Cappellini G, Lacquaniti F. Locomotor body scheme. Hum Mov Sci 2011 Apr;30(2):341–351. PMID:21453667

2. Berlucchi G, Aglioti SM. The body in the brain revisited. Exp Brain Res 2010

Jan;200(1):25–35. PMID:19690846

3. Moayedi M, Noroozbahari N, Hadjis G, Themelis K, Salomons TV, Newport R, S. Lewis J. The structural and functional connectivity neural underpinnings of body image. Hum Brain Mapp 2021 Aug;42(11):3608–3619. doi: 10.1002/hbm.25457

4. Craighero L. The Role of the Sensorimotor System in Cognitive Functions. Brain Sci 2022 May 5;12(5):604. PMID:35624991

5. Rizzolatti G, Fogassi L. The mirror mechanism: recent findings and perspectives. Philos Trans R Soc Lond B Biol Sci 2014;369(1644):20130420. PMID:24778385

6. Brooks JX, Cullen KE. Predictive Sensing: The Role of Motor Signals in Sensory Processing. Biol Psychiatry Cogn Neurosci Neuroimaging 2019 Sep;4(9):842–850. PMID:31401034

7. Lohse M, Zimmer-Harwood P, Dahmen JC, King AJ. Integration of somatosensory and motor-related information in the auditory system. Front Neurosci 2022 Oct 18;16:1010211. doi: 10.3389/fnins.2022.1010211

8. Bolognini N, Maravita A. Interactions between Senses: Updating on Neural Mechanisms and Behavioral Evidence. Front Psychol 2012;3:122. PMID:22563323

9. Cienfuegos M, Kim T, Schack T. Variations of Sensorimotor Representation (Structure): The Functional Interplay between Object Features and Goal-Directed Grasping Actions. Brain Sci 2022 Jun 30;12(7):873. PMID:35884679

10. Sattin D, Parma C, Lunetta C, Zulueta A, Lanzone J, Giani L, Vassallo M, Picozzi M, Parati EA. An Overview of the Body Schema and Body Image: Theoretical Models, Methodological Settings and Pitfalls for Rehabilitation of Persons with Neurological Disorders. Brain Sci 2023 Oct 4;13(10):1410. PMID:37891779

11. Shenton JT, Schwoebel J, Coslett HB. Mental motor imagery and the body schema: evidence for proprioceptive dominance. Neurosci Lett 2004 Nov;370(1):19–24. doi: 10.1016/j.neulet.2004.07.053

12. Sereno MI, Huang R-S. Multisensory maps in parietal cortex. Curr Opin Neurobiol 2014 Feb;24:39–46. doi: 10.1016/j.conb.2013.08.014

13. Peelen MV, Downing PE. The neural basis of visual body perception. Nat Rev Neurosci 2007 Aug;8(8):636–648. PMID:17643089

14. Serino A. Peripersonal space (PPS) as a multisensory interface between the individual and the environment, defining the space of the self. Neurosci Biobehav Rev 2019 Apr;99:138–159. doi: 10.1016/j.neubiorev.2019.01.016

15. Maselli A. Allocentric and egocentric manipulations of the sense of self-location in full-body illusions and their relation with the sense of body ownership. Cogn

Process 2015 Sep;16 Suppl 1:309–312. PMID:26220702

16. Darling S, Uytman C, Allen RJ, Havelka J, Pearson DG. Body image, visual working memory and visual mental imagery. PeerJ 2015;3:e775. PMID:25737815

17. Fuentes CT, Pazzaglia M, Longo MR, Scivoletto G, Haggard P. Body image distortions following spinal cord injury. J Neurol Neurosurg Psychiatry 2013 Feb;84(2):201–207. PMID:23204474

18. Bailey KA, Gammage KL, van Ingen C, Ditor DS. Managing the stigma: Exploring body image experiences and self-presentation among people with spinal cord injury. Health Psychol Open 2016 Jan;3(1):2055102916650094. PMID:28070405

19. Lo Buono V, Corallo F, Bonanno L, Quartarone A, De Cola MC. Body Image and Emotional Status in Patients with Acquired Brain Injury. J Clin Med 2023 Jun 15;12(12):4070. PMID:37373763

20. Corallo F, Tarda D, Coppola V, Bonanno L, Lo Buono V, Palmeri R, De Cola MC, Di Cara M, Romeo L, Raciti L, Todaro A, Logiudice AL, Bramanti P, Marino S, Formica C. The relationship between body image and emotional and cognitive impairment after brain damage: A preliminary study. Brain Behav 2021 Jun;11(6):e02181. PMID:34002955

21. Flor H, Diers M, Andoh J. The neural basis of phantom limb pain. Trends Cogn Sci 2013 Jul;17(7):307–308. PMID:23608362

22. Sarva H, Deik A, Severt WL. Pathophysiology and treatment of alien hand syndrome. Tremor Hyperkinetic Mov N Y N 2014;4:241. PMID:25506043

23. Luque-Moreno C, Oliva-Pascual-Vaca A, Kiper P, Rodríguez-Blanco C, Agostini M, Turolla A. Virtual Reality to Assess and Treat Lower Extremity Disorders in Post-stroke Patients. Methods Inf Med 2016;55(1):89–92. PMID:26660161

24. Iosa M, Aydin M, Candelise C, Coda N, Morone G, Antonucci G, Marinozzi F, Bini F, Paolucci S, Tieri G. The Michelangelo Effect: Art Improves the Performance in a Virtual Reality Task Developed for Upper Limb Neurorehabilitation. Front Psychol 2020;11:611956. PMID:33488478

25. dos Santos Mendes FA, Pompeu JE, Modenesi Lobo A, Guedes da Silva K, Oliveira T de P, Peterson Zomignani A, Pimentel Piemonte ME. Motor learning, retention and transfer after virtual-reality-based training in Parkinson's disease--effect of motor and cognitive demands of games: a longitudinal, controlled clinical study. Physiotherapy 2012 Sep;98(3):217–223. PMID:22898578

26. Foloppe DA, Richard P, Yamaguchi T, Etcharry-Bouyx F, Allain P. The potential of virtual reality-based training to enhance the functional autonomy of Alzheimer's disease patients in cooking activities: A single case study. Neuropsychol Rehabil 2018 Jul;28(5):709–733. PMID:26480838

27. Rose FD, Brooks BarbaraM, Rizzo AA. Virtual Reality in Brain Damage Rehabilitation: Review. Cyberpsychol Behav 2005 Jun;8(3):241–262. doi: 10.1089/cpb.2005.8.241

28. Ravi DK, Kumar N, Singhi P. Effectiveness of virtual reality rehabilitation for children and adolescents with cerebral palsy: an updated evidence-based systematic review. Physiotherapy 2017 Sep;103(3):245–258. PMID:28109566

29. Ogourtsova T, Souza Silva W, Archambault PS, Lamontagne A. Virtual reality treatment and assessments for post-stroke unilateral spatial neglect: A systematic literature review. Neuropsychol Rehabil 2017 Apr;27(3):409–454. PMID:26620135

30. Matthie NS, Giordano NA, Jenerette CM, Magwood GS, Leslie SL, Northey EE, Webster CI, Sil S. Use and efficacy of virtual, augmented, or mixed reality technology for chronic pain: a systematic review. Pain Manag 2022 Oct;12(7):859–878. PMID:36098065

31. Parsons TD, Rizzo AA. Affective outcomes of virtual reality exposure therapy for anxiety and specific phobias: a meta-analysis. J Behav Ther Exp Psychiatry 2008 Sep;39(3):250–261. PMID:17720136

32. Provenzano L, Porciello G, Ciccarone S, Lenggenhager B, Tieri G, Marucci M, Dazzi F, Loriedo C, Bufalari I. Characterizing Body Image Distortion and Bodily Self-Plasticity in Anorexia Nervosa via Visuo-Tactile Stimulation in Virtual Reality. J Clin Med 2019 Dec 30;9(1):98. PMID:31906009

33. Magrini M, Curzio O, Tampucci M, Donzelli G, Cori L, Imiotti MC, Maestro S, Moroni D. Anorexia Nervosa, Body Image Perception and Virtual Reality Therapeutic Applications: State of the Art and Operational Proposal. Int J Environ Res Public Health 2022 Feb 22;19(5):2533. PMID:35270226

34. Tieri G, Morone G, Paolucci S, Iosa M. Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies. Expert Rev Med Devices 2018 Feb 1;15(2):107–117. doi: 10.1080/17434440.2018.1425613

35. Dockx K, Bekkers EM, Van den Bergh V, Ginis P, Rochester L, Hausdorff JM, Mirelman A, Nieuwboer A. Virtual reality for rehabilitation in Parkinson's disease. Cochrane Database Syst Rev 2016 Dec 21;12(12):CD010760. PMID:28000926

36. Renner RS, Velichkovsky BM, Helmert JR. The perception of egocentric distances in virtual environments - A review. ACM Comput Surv 2013 Nov;46(2):1–40. doi: 10.1145/2543581.2543590

37. Massetti T, Da Silva TD, Crocetta TB, Guarnieri R, De Freitas BL, Bianchi Lopes P, Watson S, Tonks J, De Mello Monteiro CB. The Clinical Utility of Virtual Reality in Neurorehabilitation: A Systematic Review. J Cent Nerv Syst Dis 2018 Jan;10:117957351881354. doi: 10.1177/1179573518813541

38. Riva G, Mancuso V, Cavedoni S, Stramba-Badiale C. Virtual reality in neurorehabilitation: a review of its effects on multiple cognitive domains. Expert Rev Med Devices 2020 Oct 2;17(10):1035–1061. doi: 10.1080/17434440.2020.1825939

39. Khan A, Podlasek A, Somaa F. Virtual reality in post-stroke neurorehabilitation – a systematic review and meta-analysis. Top Stroke Rehabil 2023 Jan 2;30(1):53–72. doi: 10.1080/10749357.2021.1990468

40. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009 Jul 21;6(7):e1000097. PMID:19621072

41. Murad MH, Sultan S, Haffar S, Bazerbachi F. Methodological quality and synthesis of case series and case reports. BMJ Evid-Based Med 2018 Apr;23(2):60–63. PMID:29420178

42. Pais-Vieira C, Gaspar P, Matos D, Alves LP, da Cruz BM, Azevedo MJ, Gago M, Poleri T, Perrotta A, Pais-Vieira M. Embodiment Comfort Levels During Motor Imagery Training Combined With Immersive Virtual Reality in a Spinal Cord Injury Patient. Front Hum Neurosci 2022;16:909112. PMID:35669203

43. Llobera J, González-Franco M, Perez-Marcos D, Valls-Solé J, Slater M, Sanchez-Vives MV. Virtual reality for assessment of patients suffering chronic pain: a case study. Exp Brain Res 2013 Mar;225(1):105–117. PMID:23223781

44. Dong Y, Liu X, Tang M, Huo H, Chen D, Wu Z, An R, Fan Y. A haptic-feedback virtual reality system to improve the Box and Block Test (BBT) for upper extremity motor function assessment. Virtual Real 2023 Jun;27(2):1199–1219. doi: 10.1007/s10055-022-00727-2

45. Phelan I, Carrion-Plaza A, Furness PJ, Dimitri P. Home-based immersive virtual reality physical rehabilitation in paediatric patients for upper limb motor impairment: a feasibility study. Virtual Real 2023 Dec;27(4):3505–3520. doi: 10.1007/s10055-023-00747-6

46. Garcia-Hernandez N, Guzman-Alvarado M, Parra-Vega V. Virtual body representation for rehabilitation influences on motor performance of cerebral palsy children. Virtual Real 2021 Sep;25(3):669–680. doi: 10.1007/s10055-020-00481-3

47. Matsumiya K. Awareness of voluntary action, rather than body ownership, improves motor control. Sci Rep 2021 Jan 11;11(1):418. PMID:33432104

48. Althubaiti A. Information bias in health research: definition, pitfalls, and adjustment methods. J Multidiscip Healthc 2016 May;211. doi: 10.2147/JMDH.S104807

49. Ventura S, Lullini G, Riva G. Embodied the Healthy Arm: Virtual Reality Rehabilitation for Stroke Patients with Proprioceptive Upper-Limb Deficit.

Cyberpsychology Behav Soc Netw 2023 Nov 1;26(11):874–875. doi: 10.1089/cyber.2023.29295.ceu

50. Fregna G, Schincaglia N, Baroni A, Straudi S, Casile A. A novel immersive virtual reality environment for the motor rehabilitation of stroke patients: A feasibility study. Front Robot AI 2022;9:906424. PMID:36105763

51. Heinrich C, Cook M, Langlotz T, Regenbrecht H. My hands? Importance of personalised virtual hands in a neurorehabilitation scenario. Virtual Real 2021 Jun;25(2):313–330. doi: 10.1007/s10055-020-00456-4

52. Tambone R, Giachero A, Calati M, Molo MT, Burin D, Pyasik M, Cabria F, Pia L. Using Body Ownership to Modulate the Motor System in Stroke Patients. Psychol Sci 2021 May;32(5):655–667. PMID:33826456

53. Borrego A, Latorre J, Alcañiz M, Llorens R. Embodiment and Presence in Virtual Reality After Stroke. A Comparative Study With Healthy Subjects. Front Neurol 2019;10:1061. PMID:31649608

54. Shokur S, Gallo S, Moioli RC, Donati ARC, Morya E, Bleuler H, Nicolelis MAL. Assimilation of virtual legs and perception of floor texture by complete paraplegic patients receiving artificial tactile feedback. Sci Rep 2016 Sep 19;6:32293. PMID:27640345

55. Batista D, Caetano G, Fleury M, Figueiredo P, Vourvopoulos A. Effect of head-mounted virtual reality and vibrotactile feedback in ERD during motor imagery Brain–computer interface training. Brain-Comput Interfaces 2023 Oct 18;1–10. doi: 10.1080/2326263X.2023.2264000

56. Lim H, Kim W-S, Ku J. Transcranial Direct Current Stimulation Effect on Virtual Hand Illusion. Cyberpsychology Behav Soc Netw 2020 Aug;23(8):541–549. PMID:32478563

57. Sanford S, Collins B, Liu M, Dewil S, Nataraj R. Investigating features in augmented visual feedback for virtual reality rehabilitation of upper-extremity function through isometric muscle control. Front Virtual Real 2022 Nov 3;3:943693. doi: 10.3389/frvir.2022.943693

58. Buetler KA, Penalver-Andres J, Özen Ö, Ferriroli L, Müri RM, Cazzoli D, Marchal-Crespo L. “Tricking the Brain” Using Immersive Virtual Reality: Modifying the Self-Perception Over Embodied Avatar Influences Motor Cortical Excitability and Action Initiation. Front Hum Neurosci 2021;15:787487. PMID:35221950

59. Wenk N, Jordi MV, Buetler KA, Marchal-Crespo L. Hiding Assistive Robots During Training in Immersive VR Does Not Affect Users’ Motivation, Presence, Embodiment, Performance, Nor Visual Attention. IEEE Trans Neural Syst Rehabil Eng 2022;30:390–399. doi: 10.1109/TNSRE.2022.3147260

60. Wenk N, Penalver-Andres J, Buetler KA, Nef T, Müri RM, Marchal-Crespo L. Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment. Virtual Real 2023 Mar;27(1):307–331. doi: 10.1007/s10055-021-00565-8

61. Odermatt IA, Buetler KA, Wenk N, Özen Ö, Penalver-Andres J, Nef T, Mast FW, Marchal-Crespo L. Congruency of Information Rather Than Body Ownership Enhances Motor Performance in Highly Embodied Virtual Reality. Front Neurosci 2021 Jul 2;15:678909. doi: 10.3389/fnins.2021.678909

62. Camardella C, Chiaradia D, Bortone I, Frisoli A, Leonardis D. Introducing wearable haptics for rendering velocity feedback in VR serious games for neuro-rehabilitation of children. Front Virtual Real 2023 Jan 6;3:1019302. doi: 10.3389/frvir.2022.1019302

63. Song Z, Fan X, Dong J, Zhang X, Xu X, Li W, Pu F. The third-person perspective full-body illusion induced by visual-tactile stimulation in virtual reality for stroke patients. Conscious Cogn 2023 Oct;115:103578. doi: 10.1016/j.concog.2023.103578

64. Matamala-Gomez M, Malighetti C, Cipresso P, Pedroli E, Realdon O, Mantovani F, Riva G. Changing Body Representation Through Full Body Ownership Illusions Might Foster Motor Rehabilitation Outcome in Patients With Stroke. Front Psychol 2020;11:1962. PMID:32973612

65. Kaneko F, Shindo K, Yoneta M, Okawada M, Akaboshi K, Liu M. A Case Series Clinical Trial of a Novel Approach Using Augmented Reality That Inspires Self-body Cognition in Patients With Stroke: Effects on Motor Function and Resting-State Brain Functional Connectivity. Front Syst Neurosci 2019 Dec 17;13:76. doi: 10.3389/fnsys.2019.00076

66. Caola B, Montalti M, Zanini A, Leadbetter A, Martini M. The Bodily Illusion in Adverse Conditions: Virtual Arm Ownership During Visuomotor Mismatch. Perception 2018 May;47(5):477–491. doi: 10.1177/0301006618758211

67. Inamura T, Unenaka S, Shibuya S, Ohki Y, Oouchida Y, Izumi S. Development of VR platform for cloud-based neurorehabilitation and its application to research on sense of agency and ownership. Adv Robot 2017 Jan 17;31(1–2):97–106. doi: 10.1080/01691864.2016.1264885

68. Pozeg P, Palluel E, Ronchi R, Solcà M, Al-Khodairy A-W, Jordan X, Kassouha A, Blanke O. Virtual reality improves embodiment and neuropathic pain caused by spinal cord injury. Neurology 2017 Oct 31;89(18):1894–1903. PMID:28986411

69. Risso G, Bassolino M. Assess and rehabilitate body representations via (neuro)robotics: An emergent perspective. Front Neurorobotics 2022 Sep 8;16:964720. doi: 10.3389/fnbot.2022.964720

Preprint JMIR Publications

70. Naro A, Maggio MG, Latella D, La Rosa G, Sciarrone F, Manuli A, Calabrò RS. Does embodied cognition allow a better management of neurological diseases? A review on the link between cognitive language processing and motor function. Appl Neuropsychol Adult 2022 Nov 2;29(6):1646–1657. doi: 10.1080/23279095.2021.1890595

71. Leeb R, Pérez-Marcos D. Brain-computer interfaces and virtual reality for neurorehabilitation. Handb Clin Neurol Elsevier; 2020. p. 183–197. doi: 10.1016/B978-0-444-63934-9.00014-7

72. Maier M, Rubio Ballester B, Duff A, Duarte Oller E, Verschure PFMJ. Effect of Specific Over Nonspecific VR-Based Rehabilitation on Poststroke Motor Recovery: A Systematic Meta-analysis. Neurorehabil Neural Repair 2019 Feb;33(2):112–129. doi: 10.1177/1545968318820169

73. Matamala-Gomez M, Donegan T, Bottiroli S, Sandrini G, Sanchez-Vives MV, Tassorelli C. Immersive Virtual Reality and Virtual Embodiment for Pain Relief. Front Hum Neurosci 2019 Aug 21;13:279. doi: 10.3389/fnhum.2019.00279

74. Wittkopf PG, Lloyd DM, Coe O, Yacoobali S, Billington J. The effect of interactive virtual reality on pain perception: a systematic review of clinical studies. Disabil Rehabil 2020 Dec 17;42(26):3722–3733. doi: 10.1080/09638288.2019.1610803

75. Perez-Marcos D, Bieler-Aeschlimann M, Serino A. Virtual Reality as a Vehicle to Empower Motor-Cognitive Neurorehabilitation. Front Psychol 2018 Nov 2;9:2120. doi: 10.3389/fpsyg.2018.02120

76. Dieguez S, Lopez C. The bodily self: Insights from clinical and experimental research. Ann Phys Rehabil Med 2017 Jun;60(3):198–207. doi: 10.1016/j.rehab.2016.04.007

77. Pulay MÁ. Eye-tracking and EMG supported 3D Virtual Reality - an integrated tool for perceptual and motor development of children with severe physical disabilities: a research concept. Stud Health Technol Inform 2015;217:840–846. PMID:26294572

78. Christ O, Reiner M. Perspectives and possible applications of the rubber hand and virtual hand illusion in non-invasive rehabilitation: technological improvements and their consequences. Neurosci Biobehav Rev 2014 Jul;44:33–44. PMID:24661983

79. Hesse S, Schmidt H, Werner C, Bardeleben A. Upper and lower extremity robotic devices for rehabilitation and for studying motor control. Curr Opin Neurol 2003 Dec;16(6):705–710. PMID:14624080

80. Maggio MG, Torrisi M, Buda A, De Luca R, Piazzitta D, Cannavò A, Leo A, Milardi D, Manuli A, Calabro RS. Effects of robotic neurorehabilitation through lokomat plus virtual reality on cognitive function in patients with traumatic brain injury: A retrospective case-control study. Int J Neurosci 2020 Feb;130(2):117–123.

PMID:31590592

81. Calabrò RS, Naro A, Russo M, Leo A, De Luca R, Balletta T, Buda A, La Rosa G, Bramanti A, Bramanti P. The role of virtual reality in improving motor performance as revealed by EEG: a randomized clinical trial. J Neuroengineering Rehabil 2017 Jun 7;14(1):53. PMID:28592282

82. Sanchez-Vives MV, Slater M. From presence to consciousness through virtual reality. Nat Rev Neurosci 2005 Apr;6(4):332–339. PMID:15803164