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Review article

Commercial device-based hand rehabilitation systems for stroke patients: State of the art and future prospects

Bo Sheng [a], Jianyu Zhao [a], Yanxin Zhang [b], Shengquan Xie [c], Jing Tao [a,*]

[a] *School of Mechatronic Engineering and Automation, Shanghai University, 99 Shangda Road, Baoshan, Shanghai, China*
[b] *Department of Exercise Sciences, The University of Auckland, 4703906, Newmarket, Auckland, New Zealand*
[c] *School of Electronic and Electrical Engineering, University of Leeds, 3 LS2 9JT, Leeds, United Kingdom*

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ABSTRACT

Various hand rehabilitation systems have recently been developed for stroke patients, particularly commercial devices. Articles from 10 electronic databases from 2010 to 2022 were extracted to conduct a systematic review to explore the existing commercial training systems (hardware and software) and evaluate their clinical effectiveness. This review divided the rehabilitation equipment into contact and non-contact types. Game-based training protocols were further classified into two types: immersion and non-immersion. The results of the review indicated that the majority of the devices included were effective in improving hand function. Users who underwent rehabilitation training with these devices reported improvements in their hand function. Game-based training protocols were particularly appealing as they helped reduce boredom during rehabilitation training sessions. However, the review also identified some common technical drawbacks in the devices, particularly in non-contact devices, such as their vulnerability to the effects of light. Additionally, it was found that currently, there is no commercially available game-based training protocol that specifically targets hand rehabilitation. Given the ongoing COVID-19 pandemic, there is a need to develop safer non-contact rehabilitation equipment and more engaging training protocols for community and home-based rehabilitation. Additionally, the review suggests the need for revisions or the development of new clinical scales for hand rehabilitation evaluation that consider the current scenario, where in-person interactions might be limited.

1. Introduction

Stroke, also known as cerebrovascular accident (CVA), is a cerebral blood circulation disorder leading to a sudden loss of brain function [1]. According to the Global Burden of Disease Study 2016 (GBD2016) and 2017 (GBD2017), the incidence of stroke remains high. The mortality and disability-adjusted life-years (DALYs) caused by stroke reached 6.16 million deaths and 132 million DALYs in 2017, with a significant increase from 5.5 million deaths and 116 million DALYs in 2016 [2,3]. According to the GBD2019 Stroke Collaboration [4], stroke is still the third leading cause of death and disability globally. Among the countries, China bears the highest burden of stroke, with the DALYs caused by stroke ranking first in the world [5]. According to the "China Cardiovascular Health and Disease Report", the national stroke population in China was 13 million in 2020 [6], and the morbidity and mortality rate continues to

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[*] Corresponding author.
E-mail address: taojing1016@shu.edu.cn (J. Tao).

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increase year by year [7], with an anticipated increase of 35% by 2050. Studies indicate that around 85% of stroke patients worldwide have hand dysfunction, with 60% still suffering from upper limb disorders, particularly in the fingers and wrists, after treatment and discharge [5]. Hand dysfunction causes difficulties in performing the most basic activities of daily living (ADLs), such as tying shoelaces, twisting towels, and picking up and manipulating objects, greatly impacting the individual's quality of life [8].

The rehabilitation of fine hand activity is important for recovering upper limb function. Traditional treatment requires patients to receive regular and continuous physical therapies in professional rehabilitation institutions or hospitals [9]. The therapist assesses the patient's conditions through observation, communication, questionnaires, and functional tests [10]. Current clinical scales used for upper limb assessment include the Fugl-Meyer Assessment (FMA) [11], Wolf Motor Function Test (WMFT) [12], Box and Block Test (BBT) [13], and Action Research Arm Test (ARAT) [14], and they have been validated through the existing reports. However, these scales are focused on upper limb movements rather than hand movements, and they are time-consuming, subjective, and inflexible [15]. For example, the Jebsen-Taylor Hand Function Test (JTHFT) [16] is a specific test for hand function, but it is not frequently updated, which raises doubts about its effectiveness. Conventional rehabilitation training is dependent on the therapist's experience and can be labor-intensive and time-consuming; this can lead to a heavy work burden for physical therapists, which can affect the effectiveness of treatment [17]. Therefore, with the development of robotic and smart technologies, advanced rehabilitation devices and innovative approaches are emerging as alternative solutions to rehabilitation treatment.

Stroke rehabilitation is typically classified into three stages based on the level of the patient's clinical manifestations: acute, recovery, and tertiary [18]. It can also be classified as mild, moderate, and severe based on the degree of injury. In the acute stage, patients are mostly unable to perform basic life skills independently and require professional rehabilitation staff to arrange occupational therapy (OT) [19]. Rehabilitation in this stage is primarily carried out in rehabilitation centers and may include the use of rehabilitation robots (e.g., powered exoskeleton or end-effect based rehabilitation robotics) and physiological signal-based equipment (e.g., brain-computer interface (BCI) and functional electrical stimulation (FES)) [20].

During the recovery and tertiary stages, the conditions of mild or moderate stroke patients are relatively stable, and they are eager to return home [21]. Rehabilitation in the community and at home is a more practical setting for post-rehabilitation, but providing patients with complicated and costly equipment in these settings is risky and impractical. This situation calls for the development of community and home-use rehabilitation devices or technology that are safe, easy to use and store, and low cost. Patients prefer non-contact devices as they are easier to use and highly adaptable. Additionally, non-contact devices do not need to be sterilized regularly, making them particularly practical during the COVID-19 pandemic [22].

Hand rehabilitation after a stroke is a long process, and motivation is crucial for the patient's outcome [23]. The treatment outcome depends not only on the physical therapist's rehabilitation process but also on the patient's motivation for the training protocols [24]. To make rehabilitation more appealing, game-based training protocols are incorporated into the training system, such as 2D games, 3D games [25], virtual reality (VR) games [26], augmented reality (AR) games [27], etc. The use of games in training improves the enjoyment of rehabilitation, allowing patients to perform voluntary or active exercises and providing feedback and encouragement repeatedly [28]. It is worth noting that the use of virtual reality in game-based training protocols meets both the physiological and psychological needs of patients. VR creates a dynamic and motivating environment by merging touch, hearing, and vision, making patients more likely to participate in clinical or home training [29]. However, developing an effective rehabilitation game is challenging. Games that are too challenging for patients can be frustrating, and games that are too easy can quickly lose the patient's interest [30].

Some patients may indeed experience failure and lack confidence when first playing training games for rehabilitation, which lead to decreased motivation to continue playing [31]. It is particularly true for stroke patients recovering from hand disorders, as there are currently limited options for games that are specifically designed to target these conditions. Some studies have shown positive outcomes from using games in rehabilitation [32], but more research is needed to develop games tailored to the specific needs of stroke patients with hand disorders.

Many hand rehabilitation devices and game-based training protocols have been reported, but most of them are self-made and have not been clinically tested. Meanwhile, few reviews have focused on the effectiveness of the existing commercial training systems with various game-based training protocols for hand rehabilitation. Therefore, this systematic review focused on evaluating the existing commercial training systems and the various game-based protocols used in hand rehabilitation. Furthermore, the review analyzed the hardware, game-based training protocols, and clinical outcomes. This review also provided future perspectives to guide the development of hand rehabilitation in the community and home settings during and after the COVID-19 pandemic.

2. Method

2.1. Search strategy

Articles from the following 10 electronic databases were searched between 2010 and 2022: Neurological Sciences, IEEE Xplore, ScienceDirect, SpringerLink, JAMA Network, ResearchGate, MDPI, PubMed, Web of Science, and Google Scholar. The search key words.

i. "Stroke", Or "Hand Stroke", Or "Cerebrovascular Accident", Or "Cerebrovascular Disorder";
ii. "Hand", Or "Upper Limb", Or "Finger";
iii. "Rehabilitation Robot", Or "Robotic", Or "Exoskeleton"; Or "End-effector";
iv. "Brain-Computer Interface", Or "BCI";

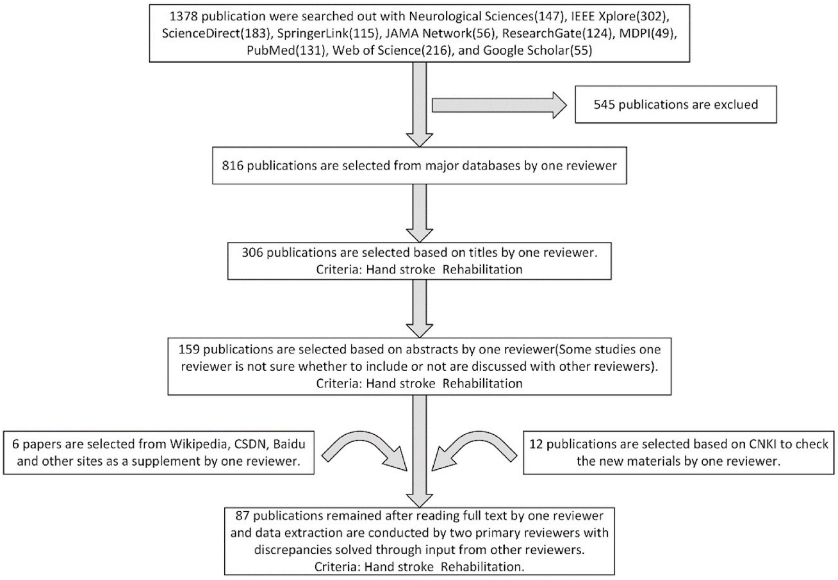

Fig. 1. Schematic diagram of the selection process for the final review.

v. "Functional Electrical Stimulation", Or "FES";
vi. "Date Glove", Or "Smart Glove", Or "Glove", Or "Rehabilitation Glove";
vii. "Kinect", Or "RealSense", Or "Leap Motion", Or "Depth sensor", Or "Sensor", Or "Depth Camera";
viii. "Virtual Reality", Or "VR", Or "HMD".

CNKI was additionally searched and screened for valuable Chinese articles. Google, Wikipedia, CSDN, and Baidu search engines were used for valuable knowledge points. References in related articles were also an essential supplement to this work.

Based on the above keywords, 1378 articles were retrieved. With the screening on title, abstract, and conclusion, 159 articles were remained. The overall workflow of the reviewing and screening is shown in Fig. 1.

2.2. *Inclusion and exclusion criteria*

In the aspect of hardware equipment, only devices that are commercially available and suitable for use in community and home settings were considered in this review. Examples of such devices included small exoskeleton robots, rehabilitation gloves, and depth sensor-based devices. Devices that are only used in experimental settings or are still in the prototype phase were not included in the review. Similarly, for the game-based training protocols, only games that have been evaluated in clinical trials were considered in this review, and the one that is only used by healthy subjects or in experimental settings were not included.

In the aspect of clinical trials, patients of any gender, age, race, and stage of stroke were included to make this review accurate and have a better overview of different conditions. Some articles did not have clinical outcomes to support the conclusions that would affect their findings; therefore, studies without clinical trials were excluded.

2.3. *Selection results*

After excluding non-commercial devices, game-based training protocols without clinical evaluation, and studies without clinical outcomes, 87 articles were selected for further analysis. These articles were divided into four categories based on their hardware: 21 robot studies, 18 physiological signal-based studies, 19 rehabilitation glove studies, and 29 depth sensor studies.

3. Hardware equipment

Various commercial rehabilitation technologies have been developed for hand rehabilitation in the recent decade, providing more options for therapists and patients. This section describes these technologies based on their hardware equipment. Specifically, the hardware equipment was classified into contact and non-contact categories. The commonly used robots, physiological signal-based equipment, and data gloves were reviewed for the contact-type equipment. In contrast, for the non-contact-type equipment, the Leap Motion, Microsoft Kinect, and Intel RealSense were examined due to their high levels of market recognition. Detailed information about the equipment used is presented in Table 1.

Table 1
Overview of hardware classification.

Device	Price	Type	Training Type	Reference	Year	Advantage	Disadvantage	Conclusion
Amadeo (TYROMOTION)	$100,000	End-effector	Active-assistive Active-resistive Passive	P. Sale et al. [42] X. Huang et al. [25] M. Torrisi et al. [136] X. Huang et al. [102]	2012 2018 2017 2021	1. Easy to use 2. No side effects 3. Multiple training models	1. Only suitable for patients with mild stroke	The Amadeo device offers a variety of training modes for patients to choose from.
CyberGrasp (CyberGlove Systems)	$102,765	Exoskeleton	Active-assistive Active-resistive Passive	A. Boos et al. [38] L. Meli et al. [40] Official Website [39] A. Boos et al. [156] J. Perret. et al. [157]	2011 2014 2009 2011 2018	1. Lightweight 2. Easy to wear 3. High adjustability	1. Complex structure 2. Cost high	Despite the potential of GyberGrasp in the medical field, its high cost may hinder its use in community and home-based rehabilitation.
HandTutor (MediTouch)	$1000	Data Glove	Active-assistive Passive	E. Carmeli et al. [66] Official Website [63] L. Kuchinke et al. [67] O. Bayındır et al. [68]	2010 2021 2016 2022	1. Low cost 2. High sensitivity 3. Having specialized rehabilitation software	1. Only passive mode 2. Dedicated to clinical treatment	The device has the potential to improve grip strength, but there is limited research available on its effectiveness.
Music Glove (FlintRehab)	$349	Data Glove	Active-assistive	N. Friedman et al. [69] N. Friedman et al. [96] L. Kuchinke et al. [67] D. Zondervan et al. [94]	2011 2014 2016 2016	1. Low cost 2. High interest	1. Single content 2. Participants performed sequentially worse with pincer grips with the middle, ring, and little fingers	The device is suitable for patients with mild to moderate hand injuries and can improve the ability to grasp small objects. However, the entertainment value of the rehabilitation game needs to be improved.
RAPAEL Smart Glove (Neofect)	$1920	Data Glove	Active-assistive	L. Kuchinke et al. [67] H. Jung et al. [72] Official Website [65]	2016 2017 2021	1. Low cost 2. Diversity 3. High sensitivity 4. Available for Home and Community Rehabilitation	1. The wearing comfort of the device is not good	The device has a comprehensive rehabilitation system and is suitable for use in the community and home-based rehabilitation.
The Fesia Grasp (Fesia Tech)	non-public	FES device	Passive	Official Website [50] Official Website [56] Official Website [57] A. Martín-Odriozola et al. [58] A. Martín-Odriozola et al. [59]	2022 2022 2022 2021 2022	1. Lightweight 2. Palm free 3. Wireless 4. Flexible 5. High selectivity of stimulation	1. Need to be accompanied by a professional physical therapist 2. Not suitable for the community and home rehabilitation	The Fesia Grasp device offers a variety of hand flexion and extension exercises that could potentially be used in community-based settings in the future.

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Table 1 (*continued*)

Device	Price	Type	Training Type	Reference	Year	Advantage	Disadvantage	Conclusion
NeuSen W& Mustim FES system (Neuracle)	non-public	EEG-FES device	Passive	Official Website [51] Official Website [60] Official Website [61] Official Website [62]	2022 2022 2022 2022	1. Easy to wear 2. High sample rate 3. Suitable for a wide range of environments 4. Low cost	1. Need to be accompanied by a professional physical therapist 2. May cause side effects	The system currently lacks significant clinical data to confirm its feasibility and remains in the experimental stage.
IpsiHand (Neurolutions)	non-public	BCI device	Passive	Official Website [49] Official Website [52] J. Humphries et al. [53]	2022 2022 2022	1. Lightweight 2. Adjustable 3. Wireless 4. Easy to use	1. Mild fatigue, dizziness, and temporary skin flushing may occur	As a device that has received marketing approval from the FDA, IpsiHand may offer a new treatment option for patients with post-stroke hand movement disorders.
Microsoft Kinect V1/V2 (Microsoft)	$474.14	Microsoft Kinect	Active-assistive	R. Madeira et al. [76] P Bamrungthai et al. [114] L. Kuchinke et al. [67] S. Adilkhan et al. [77]	2014 2015 2016 2021	1. Low cost 2. Flexible 3. Easy to set up 4. Convenience	1. Need space and lighting conditions 2. Low motion tracking accuracy	As an accessory for a physical gaming console, its tracking reliability decreases as the movement's complexity increases.
Microsoft Azure DK (Microsoft)	$472.40	Microsoft Kinect	Active-assistive	L. Romeo et al. [78] J. Albert et al. [80] M. Antico et al. [81] Official Website [79]	2021 2020 2021 2021	1. Higher resolution 2. Can track multiple users. 3. Higher quality of tracking for spatial parameters	1. Motion tracking quality is low in fast movement 2. The tracking movement tracking along the focal axis is lost under a single device	Azure has improved gesture-tracking accuracy as an alternative to the Kinect and is more suitable for the community and home-based rehabilitation.
Intel RealSense SR300 (Intel)	$391.77	Intel RealSense	Active-assistive	R. House et al. [85] F. Siena et al. [158] A. Zabatani et al. [83]	2017 2018 2020	1. Small size 2. Low latency. 3. Low power consumption	1. When using two-dimensional tracking, the light in the room may affect the camera's performance or even lose the target completely	The RealSense SR300 is suitable for hand tracking, but its operation and setup can be somewhat complex. Its accuracy is affected by the environment and may not be suitable for community and home-based rehabilitation.
Leap Motion Controller (Ultraleap)	$89.95	Leap Motion	Active-assistive	L. Kuchinke et al. [67] P. Breedon et al. [82] M. Alimanova et al. [86] Official Website [75]	2016 2017 2017 2021	1. Small size. 2. Lightweight 3. High accuracy	1. Unable to deal with three fingers other than the thumb and index finger	The Leap Motion Controller is a proven gesture-detection device that can be used in clinical, community, and home-based rehabilitation settings.
Ultraleap Stereo IR170 (Ultraleap)	$253.33	Leap Motion	Active-assistive	A. Rachmat et al. [90] Official Website [75] Official Website [89]	2021 2021 2021	1. Wide FOV 2. High and wide tracking accuracy 3. Small size	1. Some hand gestures cannot be detected due to occlusion 2. The size of the grasped object may affect data accuracy	The device has the ability to accurately capture 16 grasping poses, making it a highly promising device for hand rehabilitation.

Fig. 2. Two types of hand rehabilitation robots: (a) CyberGrasp [36] and (b) Amadeo [37].

3.1. *Contact types*

A contact-type device is defined as a device that must be in contact with the injured hand of a patient and uses sensors to detect motion and measure data. Depending on the modality, rehabilitation training can be divided into passive and active training (active-assistive or active-resistive training) [32]. Therefore, choosing a contact rehabilitation device with different training types is crucial, depending on the stage of stroke recovery. In recent decades, the commonly used contact-type hand rehabilitation equipment includes hand rehabilitation robots, physiological signal-based equipment, and data gloves, all of which have the characteristics of prompt feedback and strong interaction and are gradually being accepted by therapists and patients. These three types of rehabilitation equipment were discussed in the following section.

3.1.1. *Hand rehabilitation robot*

Robot-assisted training is considered to be an effective and reliable method for impaired hands through computer-driven robotics. It can provide repetitive exercises, which are necessary to stimulate neuroplasticity after stroke onset. According to Ref. [33], robotic devices are divided into exoskeletons, end-effectors, and orthoses. Exoskeletons can perform long-term tasks that involve repetitive movements, ensure the intensity, effect, and accuracy of rehabilitation training, and have good movement consistency [34]. End-effector devices differ from exoskeletons, their movement is controlled by the distal interphalangeal (DIP) joint, and they focus more on finger rehabilitation while also fulfilling rehabilitation training [35]. Most orthoses use flexible gloves as a carrier and focus on finger movements. However, this work did not review orthoses due to the lack of actuators and sensors. The representative images of the exoskeletons and end-effectors are shown in Fig. 2.

3.1.1.1. CyberGrasp. CyberGrasp (Fig. 2(a)) is a lightweight exoskeleton developed by CyberGlove Systems (San Jose, CA, USA), which provides extension force to a single finger through a cable system passing through the back of the hand [38]. CyberGrasp is used to measure the movement of the hand and fingers and provide force feedback. It can also apply external force to assist patients in completing rehabilitation movements during active and passive training. This device allows patients to feel the shape and size of computer-generated 3D objects in a simulated virtual world [36].

CyberGrasp weighs only 16 ounces and is easy to wear. The execution module can be worn in the GraspPack backpack for portable operation, effectively increasing the working space [39]. CyberGrasp has 5 independent brakes, one for each finger, which are installed in the “brake housing” and separated from the exoskeleton by a cable of approximately 2 feet. These 5 actuators can be individually programmed to prevent the generated virtual 3D objects from being penetrated or squeezed by the user’s fingers [36]. However, the complex structure of this device has led to a high price (up to $6000) [40].

3.1.1.2. Amadeo. Amadeo (Fig. 2(b)) is an end-effector device for hand and finger rehabilitation produced by Tyromotion GmbH (Steiermark, Graz, Austria). It enables patients to perform rehabilitation exercises at the appropriate intensity by setting limits for movement speed, range of movement, and strength [41].

The Amadeo robot has five degrees of freedom (DOF). It can provide independent movement of each finger due to the passive rotation joint placed between the fingertip and the laterally moving entity (the thumb has two passive rotation joints). All five translational DOF are independent and provide wide coverage of the finger’s workspace (not 100% covered). The interface between the human hand and the machine is established through an elastic band or plaster, and the wrist’s movement is restricted by velcro tape [42]. Therapists can select different training modes (active or passive assisted training) according to the rehabilitation progress and provide an optimal training plan for each patient. Amadeo can also be used in conjunction with EMG signals, allowing for passive training even if the patient lacks muscle strength. However, it can be concluded from clinical trials that the device is only suitable for patients with mild stroke, and patients with severe stroke do not show significant improvement in their conditions [21]. The device is sold only to medical institutions and costs up to $100,000.

Fig. 3. Three representative devices: (a) IpsiHand [49], (b) The Fesia Grasp [50], and (c) NeuSen W& Mustim FES system [51].

3.1.2. Physiological signal-based rehabilitation

Studies have indicated that utilizing physiological signals to control rehabilitation devices, such as robots, can enhance the interaction between patients and machines. Furthermore, this type of equipment can offer passive training that proves beneficial for patients suffering from severe strokes. The research in this work identified three categories, as shown in Fig. 3.

I)Brain-computer interface technology (BCI). BCI was first proposed by Vidal in 1973 [43]. It is a kind of control signal that directly converts the subject's brain activity into an external device without the participation of peripheral nerves and muscles [44]. In order to complete the neural circuit from signal sending to receiving, the BCI system needs to be combined with other devices or technologies, such as robotic devices, data gloves, and visual feedback technology (augmented reality (AR) and virtual reality (VR)) [33].

II)Functional electrical stimulation (FES). FES directly activates muscles to perform functional tasks by applying appropriate and precise electrical stimulation via an auxiliary electrical stimulation device [45]. Some reports have demonstrated that FES can be helpful in recovering hand function, such as muscle weakness, joint incoordination, and spasticity, in stroke patients [46,47].

III)Hybrid systems. Physiological signals or systems often combine to enhance brain command decoding. For example, a hybrid brain-computer interface (hBCI) combines multiple senses (e.g., tactile, auditory, and visual), several brain modalities (e.g., P300, steady-state visual-evoked potential (SSVEP)), motor imagination (MI), or more than two physiological signals (e.g., electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electro-oculogram (EOG)) [48].

3.1.2.1. IpsiHand (BCI). The IpsiHand device (Fig. 3(a)) is a functional upper extremity (hand, wrist, and arm) rehabilitation device for stroke patients developed by Neurolutions (Santa Cruz, CA, USA) [49]. The device received marketing authorization from the Food and Drug Administration (FDA) in 2021, making it the first FDA-approved device that can use BCI to enhance rehabilitation efficiency for stroke patients [52].

The IpsiHand device contains three parts: a wearable robotic handpiece, an EEG-based biometric headset, and a tablet computer. The system converts brain signals from the uninjured or ipsilateral brain hemisphere into robotic hand movement. It is helpful for patients with severe stroke since IpsiHand can physically open and close their hands based on their thoughts and passively retrain muscles. IpsiHand has been tested in clinical trials and has provided statistically and clinically significant results for patients in the recovery stage [53]. Additionally, its compact design makes it suitable for the community and home rehabilitation. However, according to some reports [54,55], some subjects using the BCI device to collect signal data experienced mild fatigue, dizziness, and temporary skin redness.

3.1.2.2. The Fesia Grasp (FES). The Fesia Grasp (Fig. 3(b)) is a hand neurological rehabilitation device based on functional electrical stimulation (FES) developed by Fesia Technology (Donostia-San Sebastián, Spain) [50]. It generates surface electrical stimulation of the forearm muscles to trigger eight different flexion and extension movements of the wrist and fingers to restore function, freedom, and independence of the patient's hand after stroke [56].

The Fesia Grasp contains stimulators, multi-field electrodes (32 cathodes and 8 anodes), textile garments, and a tablet. The device's main feature is its multi-field electrodes, which are designed to fit subjects better and perform more natural movements [57]. The Fesia Grasp also includes an application called Fesia Pro, which wirelessly connects to the device via Bluetooth. Using Fesia Pro, therapists can configure desired stimulation parameters, monitor patients' training statuses, and easily manage collected data. Several studies have shown that the Fesia Grasp can help restore hand impairment in stroke patients [58,59]. To prevent muscle spasms or other secondary damages, the Fesia Grasp should only be conducted by professionals who can select appropriate electrical stimulation parameters based on patients' different conditions.

3.1.2.3. NeuSen W& Mustim FES system (EEG-FES). The NeuSen W& Mustim FES system (Fig. 3(c)) is a rehabilitation system developed by Neuracle (Changzhou, China) that combines EEG-based BCI and FES [51]. The system is designed to help patients in the recovery stage regain motor function.

The system consists of the NeuSen W wireless EEG acquisition device [60] and the Mustim FES device [61]. The NeuSen W device is well-suited for data acquisition in complex environments due to its low input noise and high sampling rate. It is also capable of synchronizing high-precision data with multiple devices simultaneously. The Mustim FES device uses biphasic rectangular pulses and can be controlled manually. The advantages of using an EEG-FES system can be concluded as 1) easy to wear, 2) high signal quality, 3) low cost, and 4) suitable for various environments [62]. However, combining these two technologies may also result in side effects, and the presence of professionals is necessary to manage these potential risks.

3.1.3. Data glove

A data glove is a treatment device for the rehabilitation of stroke patients' hand motor function, including active rehabilitation, passive rehabilitation, and game-based rehabilitation evaluation. Patients can independently complete the entire rehabilitation treatment process without needing one-on-one guidance from a therapist, making rehabilitation training more convenient and cost-effective. Theoretically, data gloves can be used in home-based settings. Three types of commercial rehabilitation gloves were introduced, and pictures can be seen in Fig. 4.

3.1.3.1. HandTutor. The HandTutor (Fig. 4(a)) is a training system developed by MediTouch (Netanya, Israel) to achieve functional fine muscle movements, including finger and wrist rehabilitation through active flexion and extension exercises [66]. The system includes ergonomic wearable gloves and professional training software. The HandTutor can be used with FES to enhance motor performance via passive training. When the patient wears the glove, his/her movements are captured by built-in sensors and displayed on a computer screen, where a therapist can guide the patient to work within his/her exercise capacity [63]. The professional training software provides patients with enhanced injury-oriented feedback. However, it should be noted that the HandTutor system primarily focuses on the range of finger motion and is not designed to allow patients to complete daily pinch and grasp movements on their own. As the device is intended for clinical treatment rather than home use [67,68], it is relatively expensive with a cost of around $1000.

3.1.3.2. Music Glove. The Music Glove (Fig. 4(b)) is a low-cost device for active training that is based on customized gloves designed by Flint Rehab (Irvine, CA, USA). It uses music as an interactive medium to evaluate users' progress quantitatively [69]. Music Glove is similar to HandTutor, but its musical elements make training more accessible and engaging for patients. As of 2022, the Music Glove has been used in over 300 rehabilitation hospitals and by more than 10,000 families [70].

The customized glove has six sensors evenly distributed on the proximal interphalangeal joints of each fingertip and the outer side of the index finger. Patients can practice actions in daily life by making contact between the sensor on the thumb fingertip and one of the other five sensors in time [71]. Although using music as a medium, the Music Glove has reduced operability and availability due to the limitation of five grips and its price ($349) [67].

3.1.3.3. RAPAEL Smart Glove. The RAPAEL Smart Glove (Fig. 4(c)) is a commercial wearable rehabilitation device developed by Neofect (Seongnam, Gyeonggi-do, South Korea) in 2015 that measures wrist and finger movements [65]. Like the HandTutor, the RAPAEL Smart Glove measures finger and wrist movements and velocities to provide active assistive training to subjects.

The RAPAEL Smart Glove contains a nine-axis motion and position sensor with three acceleration channels, one angular velocity

Fig. 4. Three representative data gloves: (a) HandTutor [63], (b) Music Glove [64], and (c) RAPAEL Smart Glove [65].

Fig. 5. Three types of non-contact treatment products: (a) Azure Kinect DK [73], (b) Intel RealSense SR300 [74], and (c) Leap Motion Controller [75].

channel, and three magnetic field channels, which are used to measure the motion and velocity of the wrist. It also has five bending sensors that are used to measure finger movements. The RAPAEL Smart Glove is accompanied by video games designed to perform the required wrist and finger movements, including forearm supination/protonation, wrist flexion/extension, wrist radial/ulnar deviation, and finger flexion/extension [72]. The RAPAEL Smart Glove offers more than fifty serious games, but the wearing comfort of the device has been reported as unsatisfactory [67].

3.2. *Non-contact types*

Non-contact equipment is a type of sensing device that detects a patient's movements and records data through optical or depth sensors. This data is then analyzed by an evaluation system to determine the patient's rehabilitation progress. The advantage of non-contact equipment is that it does not require physical contact with the device, making it more suitable for the community and home rehabilitation during the COVID-19 pandemic. However, it should be noted that the tracking accuracy of non-contact equipment is generally not as good as that of contact equipment, as they are sensitive to environmental conditions, particularly lighting. Some commonly used non-contact hand rehabilitation equipment includes Microsoft Kinect, Intel RealSense, and Leap Motion (Fig. 5).

3.2.1. *Microsoft Kinect series*

Microsoft Kinect is an Xbox game controller released in 2010 by Microsoft (Redmond, WA, USA). It is a motion-sensing input device that uses computer vision technology called structured lighting to capture user movements. The user does not need to be equipped with additional sensors. In terms of rehabilitation medicine, Microsoft Kinect is a suitable VR rehabilitation device as it is cheap, easy to set up, and can be used in both community and home settings, allowing patients to practice frequently and voluntarily [76]. However, Kinect has limitations on space, lighting, and distance from the user, and the accuracy of hand tracking is also unsatisfactory [77]. Unfortunately, Microsoft Kinect V2 was officially discontinued in 2017 and was replaced by a newer device called Azure Kinect DK. A comparison of parameters between Microsoft Kinect V2 and Azure Kinect DK can be found in Table 2.

Azure Kinect DK (Fig. 5(a)) consists of an RGB camera and an IR camera, and it adopts the principle of time-of-flight [78]. The 7-microphone array is used for far-field voice and sound capture. Azure Kinect also has an IMU sensor composed of a three-axis accelerometer and a gyroscope, which can estimate its position in space [79]. Studies have shown that the tracking accuracy of Azure Kinect is higher than that of Kinect V2 [80]. However, M. Antico et al. [81] showed that, in the case of fast movement, Azure Kinect's motion tracking quality is low, and the tracking of movement along the focal axis is lost in the case of a single Kinect device. Additionally, as shown in Table 2, Azure Kinect has high requirements for external device performance and is more expensive.

3.2.2. *Intel RealSense*

Intel RealSense is a real sense 3D depth-sensing camera released by Intel (Santa Clara, CA, USA) in 2014. It can provide users with 3D scanning, facial and gesture recognition, and other functions [82]. In the RealSense depth camera series, SR300 (Fig. 5(b)) is the most commonly used product for hand rehabilitation. It is based on coded light technology combined with an RGB camera, which can output infrared video graphic array (VGA) images and 1080p color images with a transmission speed of 30fps [83]. It is currently one of the market's smallest 3D depths and 2D camera modules and is often used as a front camera for laptops or for 3D scanning and

Table 2
The comparison of Kinect V2 and Azure Kinect DK.

Items	Microsoft Kinect V2	Azure Kinect DK
RGB Camera	1920 × 1080 px@30fps	3840 × 2160px@30fps
Depth Camera Resolution/FOV	512 × 424 px@30fps	640 × 576 px@30fps 512 × 512px@30fps 1024 × 1024px@15fps
Connectivity Synchronization	RGB & Depth internal only	RGB & Depth internal, external device-to-device
Dimension	249 × 66 × 67 mm	103 × 39 × 126 mm
Weight	970 g	440 g
GPU Requirement	GTX 660 and above	GTX 1070 and above
Price	$447.45(2014)/$295.81(2022)	$445.81(2022)

Table 3
The comparison of Leap Motion Controller and Ultraleap Stereo IR170.

Items	Leap Motion Controller	Ultraleap Stereo IR 170
Interaction Zone Depth	Depth between 10 cm and 60 cm preferred, up to 80 cm maximum	Between 10 cm and 75 cm preferred, up to 1 m maximum
Product Dimensions	80 × 30 × 11.3 mm	105 × 10mm × 7.7 mm
Field of View (FoV)	140 × 120° typical field of view	170 × 170° typical field of view (160 × 160°minimum)
Weight	32 g	22 g
Price	$89.95	$250

gesture/facial recognition [84]. The cursor mode of the SR300 is a notable feature and can ensure faster and more accurate hand tracking with low latency and energy consumption. Overall, it is a hardware device suitable for hand rehabilitation. However, a study [85] reported that when using two-dimensional tracking, the camera's performance was affected by the room's lighting, and the target was lost entirely in some conditions.

3.2.3. *Leap Motion Controller*

The Leap Motion Controller (Fig. 5(c)) is a gesture detection device released in 2013 by Ultraleap (Bristol, UK) that interacts with a computer by recognizing the movement of hands and fingers. It has the characteristics of being small and lightweight [82]. The device has been updated to the third generation and is still evolving. The optical hand-tracking module, which consists of two cameras and three infrared LEDs, captures the movement of the user's hand and fingers and interacts with digital content [86]. The controller can recognize 27 hand elements, including bones and joints [87]. However, our previous experiments have shown that the tracking accuracy for the thumb and index fingers is better than for the other three fingers when using the Leap Motion Controller [88].

The Ultraleap Stereo IR 170, the latest product from Ultraleap, claims to be more powerful hand-tracking hardware than older versions [89]. The device uses the same core software as the Leap Motion Controller and can identify 27 different hand elements. Compared to the Leap Motion Controller, the Ultraleap Stereo IR 170 has a wider field of view, a greater tracking range, lower power consumption, and a smaller size [90]. The comparison of parameters is shown in Table 3. To complement the Ultraleap Stereo IR 170, Ultraleap has released the latest hand-tracking platform called Gemini, a hand-tracking engine that offers strong stability and high accuracy compared to ORION. According to the report [89], the Ultraleap Stereo IR 170 with Gemini achieved a noticeable improvement in tracking both hands, even when the hands overlap or interact. Currently, Gemini has been integrated into various XR headsets, aiming to provide users with a better interactive experience in the future [91].

4. Game-based training protocols

Traditional hand rehabilitation training relies on mechanical systems to manipulate or assist patients with repetitive training. However, game-based training protocols induce patients to interact with rehabilitation products and actively conduct rehabilitation training. The enjoyable games can alleviate the negative emotions generated by patients during treatment, enhancing the rehabilitation experience. The specially designed game scale can also reflect the patient's involvement in real-time, enabling therapists to design better treatment plans. This work divides rehabilitation software into non-immersion and immersion types according to the hardware dependence of the utilized rehabilitation games. The rehabilitation games involved in this work are shown in Table 4.

4.1. *Non-immersion types*

With a non-immersive system, the user plays the game without any VR devices [92]. In this work, the games are divided into finger-training and wrist-training games based on the targeting part (function) of the hand.

4.1.1. *Finger-training game*

In order to accurately distinguish the hand area targeted by the rehabilitation game, finger joints are divided into two parts: 1) metacarpophalangeal joints and 2) interphalangeal joints. The metacarpophalangeal joint is closest to the palm, while the interphalangeal joints are the two joints farther away from the palm (the thumb is one joint). Three rehabilitation games were selected for hand rehabilitation targeting these two parts: "Fret on Fire," "Squeezing Oranges," and "Shoot-out."

4.1.1.1. Fret on Fire. "Fret on Fire" is a music-based rehabilitation game (shown in Fig. 6(a)). Its operation principle is similar to that of "Guitar heroes" (the player presses corresponding buttons on the guitar controller according to the notes scrolling on the game screen) [93]. The patient plays the game with a sensor glove. As shown in Fig. 6(b), during the game, the patient needs to complete specific grips associated with the colored notes falling. If the patient completes the action on time, positive visual feedback is provided, while negative sound feedback is provided if they fail [69].

In the previous clinical trials conducted by Friedman et al. [69,96], the Box and Blocks (B&B) test proved that music gloves could effectively improve the grasping ability of patients' hands and are superior to traditional treatments. In 2016, Zondervan et al. [94] designed a family-based single-blind, randomized controlled experiment. Seventeen volunteers were selected and divided into two groups to participate in the study. The music glove rehabilitation group (8 stroke persons) used music gloves for rehabilitation treatment, and the traditional group (9 stroke persons) used traditional training. All participants were required to complete a 3-h

Table 4
Overview of software classification.

Game	Device	Type	Training position	References	Year	Pathology and Sample Size	Training duration	Outcome measures
Fret on Fire	Music Glove	Non-immersive	MCP	N.Friedman et al. [69] N.Friedman et al. [96] D. Zondervan et al. [94]	2011 2014 2016	10/Stroke 12/Stroke 15/Stroke	1 Test 2 Weeks 1 Month	B&B B&B, IMI B&B, MAL, QoM, AoU
Squeezing oranges	RAPAEL Smart Glove	Non-immersive	IPJ	Official Website [65] J.Shin. et al. [98] M.Lansberg et al. [97]	2021 2016 2021	N/A 46/Stroke 20/Stroke	N/A 7 Weeks 8 Weeks	N/A FM, JTHFT, SIS UE-FM, JTHFT, SIS, LSQ
Wiping game	RAPAEL Smart Glove	Non-immersive	WEF	H.Jung et al. [72]	2017	13/stroke	3 Weeks	WMFT, ARoM
Flappy Bird	Amadeo	Non-immersive	WRUD	X. Huang et al. [102] X. Huang et al. [25] N. Haghbin et al. [100]	2018 2017 2021	1/Stroke 8/Stroke 10/Healthy	18 Weeks 6 Weeks 1 Test	ROM, FMA, MAS, TFOI ROM, FMA, MAS, TFOI N/A
Space War RGS	Amadeo	Immersive	Entire Hand	X. Huang et al. [25]	2017	8/Stroke	6 Weeks	ROM, FMA, MAS, TFOI
Lifting Game	Leap Motion Controller	Immersive	Entire Hand	P. Dias et al. [128]	2019	12/Stroke	1 Test	N/A
Move-IT Game	Leap Motion Controller	Immersive	Entire Hand	M. AlMousa et al. [106]	2020	5/Stroke	4 Test	N/A
Shoot-out Game	Amadeo& EEG	Non-immersive	MCP	M. Butt et al. [99]	2022	4/Health&2/Stroke	N/A	MRCP

Abbreviations: MCP = metacarpophalangeal joints, B&B=Box and Blocks. IMI= Intrinsic Motivation Inventory, MAL = Motor Activity Log, QoM = Quality of Movement, AoU = Amount of Use, IPJ = interphalangeal joints, FM=Fugl-Meyer, JTHFT = Jebsen-Taylor hand function test, SIS=Stroke Impact Scale, UE-FM= Upper Extremity Fugl-Meyer, LSQ = Likert-scale Questionnaire WEF=Wrist Extension and Flexion, WMFT=Wolf Moter Function Text, ARoM = Active Range of Motion, WRUD=Wrist Radial Ulnar Deviation, ROM = Range Of Motion, FMA=The Fugl-Meyer Assessment, MAS = The Motor Assessment Scale, TFOI = The Force Output Intensity, MRCP = Movement-Related Cortical Potential.

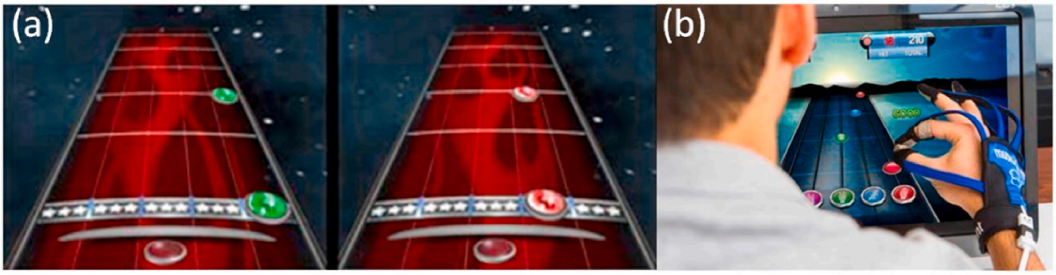

Fig. 6. Fret on Fire: (a) Game interface [94] and (b) Fret on Fire operation demonstration [95].

rehabilitation experiment at least 3 times a week for 3 weeks. The results of the study were evaluated by B&B scores, Motor Activity Log (MAL), Quality of Movement (QoM), Amount of Use (AoU) scales, and a one-month follow-up test. The data showed that the B&B scores of the two groups were enhanced, but only the music glove group's grasping function improvement could be measured by the MAL score. Follow-up tests showed no significant change in conventional treatment at the end of treatment and one month later. By comparison, after one-month treatment, the scores of MAL, QoM, and AoU scales showed a significant improvement with the Music Glove. The Action Research Arm Test (ARAT) score of the music glove group was also significantly higher than that of the traditional group [71].

4.1.1.2. Squeezing oranges. "Squeezing oranges" is a game designed for knuckle exercise, as shown in Fig. 7. The user plays the game using a smart sensor glove (RAPAEL Smart Glove). During the game, the user is directed to virtually squeeze oranges, and the grip strength of the hand is measured by the amount of orange juice squeezed out, allowing users to understand their recovery status directly. However, in subsequent reports, some users suggested that the game was too simple to meet the training requirements [97, 98].

M. Lansberg et al. [97] conducted a 10-week study (including a 2-week preparation and an 8-week training) and employed the Upper Extremity Fugl-Meyer (UE-FM) and Jebsen-Taylor Hand Function Test (JTHFT) as the evaluation scales. The Stroke Impact Scale (SIS) was performed before and after the 8 weeks of the intervention study. In the study, 20 stroke patients were asked to use gloves only for 50 min per day, at least 2 days per week, for 8 weeks. The clinical results showed a significant improvement in JTHFT, but no achievement was found in UE-FM. Participants reported that the game content was slightly monotonous, and wearing gloves was somewhat uncomfortable, even though the utilized games were interesting.

Fig. 7. Squeezing Oranges game interface [97].

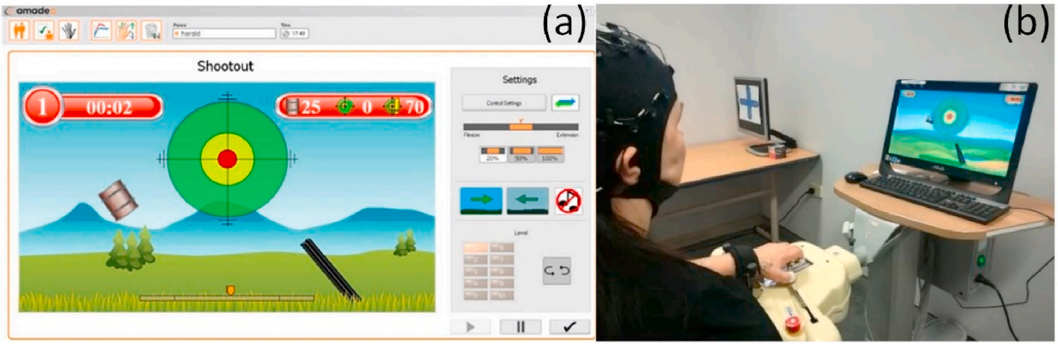

Fig. 8. Shoot-out game: (a) Game interface and (b) Practical operation [99].

4.1.1.3. Shoot-out. "Shoot-out" is a game for finger exercise (as shown in Fig. 8(a)). The patient plays the game by imagining flexion for firing or extension for loading ammunition. The game utilizes a 32-channel EEG acquisition device to collect the patient's physiological signals, which are then sent to an Amadeo robot to drive the patient's hand through the designed movement, such as flexion and extension of fingers.

M. Butt et al. [99] used this game to conduct a hand rehabilitation experiment on stroke patients. Six volunteers (4 healthy male subjects and 2 stroke patients (1 male and 1 female)) were recruited to participate in the study and divided into two groups. Subjects in Group A followed text or picture commands to complete the training (finger flexion or extension) using an EEG signal-based device and the Amadeo robot. Group B used the same device to play the shoot-out game for training (Fig. 8(b)). All patients were required to take part in 23 studies. The outcome of the trial was assessed using Movement-Related Cortical Potential (MRCP) patterns, and patients' motor intent was detected using a support vector machine (SVM)-based model. The experimental results showed that the average accuracy for motor intent detection was 67.56% and 79.7% for healthy subjects in Group A and Group B, respectively. Slightly worse results were found for stroke patients in Group A (56.24%) and Group B (66.64%). Additionally, healthy and stroke subjects in Group B who received game-based training were more motivated to participate. These results demonstrated the feasibility of physiological signal-based hand rehabilitation and the effectiveness of game-based training.

4.1.2. Wrist-training games

According to previous research [100], wrist movement is divided into two categories: extension/flexion and ulnar/radial deviation. Wrist extension refers to raising the back of the hand upward, while wrist flexion refers to bending the back of the hand toward the arm. Ulnar deviation refers to bending the wrist toward the little finger, and radial deviation refers to bending the wrist toward the thumb. This section introduces two games: "Wiping game and Vegetable-Cutting game" and "Flappy Bird.

4.1.2.1. Wiping game and Vegetable-Cutting game. "The Wiping game" (Fig. 9(a)) and "Vegetable-cutting game" (Fig. 9(b)) is designed to rehabilitate radial-ulnar deviation. After patients put on the RAPAEL Smart Glove (Fig. 4(c)), they can perform repeated radial movements of the wrist while wiping a table or cutting vegetables. A score query system is added to the game to check and understand patients' conditions after finishing the games. Patients can also compare their game scores to those of other users via the built-in social system. Additionally, the games will be updated regularly to enhance training interaction and clinical efficiency.

Fig. 9. Two types of hand radial ulnar deviation rehabilitation games: (a) Wiping game [72] and (b) Vegetable-Cutting game [103].

Jung et al. [72] designed a set of randomized controlled trials using the RAPAEL Smart Glove (Fig. 4(c)) and games for wrist rehabilitation, including the “Wiping game.” In the experiment, 13 patients were divided into Group A and Group B. Group A used the RAPAEL Smart Glove for 30 min of rehabilitation training, followed by 15 stages of traditional training. Group B received 30 min of regular training twice per day, five days per week for three weeks. At the end of the experiment, the Wolf Motor Function Test (WMFT) and Active Range of Motion (ARoM) scales were utilized to evaluate the rehabilitation efficacy. The results showed that the WMFT score of Group A was better than that of Group B, and Group A’s WMFT score in the first 15 stages was better than that of the last 15 stages. The conclusions also presented statistical significance, indicating that the device and game have a positive recovery effect on stroke patients.

4.1.2.2. Flappy Bird. “Flappy Bird” is a traditional casual mobile game in which the user controls the bird to pass through pipes of different lengths by tapping the screen. In the hand rehabilitation version, the user controls the movement of the bird through the flexion and extension of their wrist (as shown in Fig. 10) [100]. The extension of the wrist makes the bird fly upward, and the flexion of the wrist makes the bird fly downward. When the bird is about to reach a pipe, a directional arrow will appear on the screen to indicate the location of the next pipe to the player, and there will also be audio prompts in the earphones. In this way, users can play the game involuntarily and achieve rehabilitation effects [25].

Nehrujee et al. [101] recruited 5 patients, and each patient was asked to complete 2 sessions of rehabilitation training. Each session lasted 2 days and 1 h per day. A Plug-and-Train Robotic Kit was used as the hardware device, and games such as “Flappy Bird” were used for the training protocols. The System Usability Scale (SUS) and User Experience Questionnaire (UEQ) were used for evaluation. The experimental results concluded that patients, caregivers, and therapists have a positive attitude towards the rehabilitation glove combined with games for rehabilitation. There were no complaints about the entire rehabilitation system, and more interesting games were requested by the therapists and patients. According to Huang et al. [102], it was noticed that the patient’s rehabilitation performance was improved via the Fugl-Meyer Assessment (FMA) and The Motor Assessment Scale (MAS) scales, and his/her flexion and extension forces increased as well. Range of motion (ROM) analysis represented a significant improvement in the first few weeks, and the growth trend became flat after the sixth week and slowly improved after 12 weeks. These results indicated that utilizing the robotic device and game-based training protocols can improve rehabilitation efficiency.

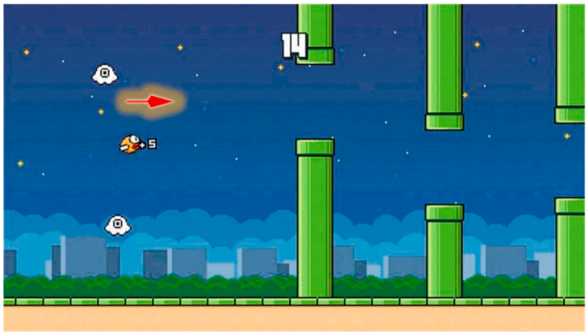

Fig. 10. Flappy Bird game interface [104].

4.2. Immersion types

The immersive game-based training protocols can provide users with an immersive experience via virtual reality games and related devices [105]. The user can wear a head-coupled display (HCD) or a head-mounted display (HMD) to see the contents of the games. The senses of sight, hearing, and touch are delivered to users through the head display unit, speakers, data gloves, etc. Users can also complete additional virtual activities using mouses, hand-sensing devices, and joysticks [92]. In this work, three games named “Space War RGS”, “Lifting Game”, and “Move-IT” were introduced.

4.2.1. Space War Game

“Space War Game” is realized by wearing an Amadeo robot and an Oculus Rift VR HMD device. Before starting the game, the Amadeo robot is set to free mode, in which the robot will no longer interfere with the user’s hand operation. In the game, the user controls the flying position of the spacecraft by moving his/her fingers or applying pressure on the Amadeo robot to avoid meteorites in the sky (shown in Fig. 11(a)). With the Oculus Rift VR HMD device, users can get an immersive experience closer to reality by looking around, which significantly enhances the enjoyment of the game [25,102].

Huang et al. [25] conducted a research experiment on hand stroke rehabilitation. Eight stroke patients (3 males and 5 females) with different degrees of stroke were recruited as research subjects. These patients were required to undergo 6 weeks of research training, three days per week, once per day. In the study, the Amadeo robot was used as the hand hardware device for training, and the Oculus Rift HMD was used as the VR device for watching. To avoid the side effects of the VR, the wearing time was limited to 5 min. Game-based training protocols employed a 3D immersive game called “Space War 3D RGS” (Fig. 11(a)) as well as several 2D games similar to the games mentioned above (Fig. 10). Meanwhile, 2 clinical scales (FMA and MAS) and 2 specific features (ROM and The Output Force Intensity (TOFI)) were used for rehabilitation evaluation. According to the clinical results, the recruited stroke patients improved significantly except for one with severe stroke. Meanwhile, the Min-Max ranges of the FMA and MAS scales were raised from 6.16 to 8.48 and 3.00 to 4.16, respectively. The results indicated that the subjects’ rehabilitation effects had improved significantly.

4.2.2. Move-IT

“Move-IT” game is an immersive VR game specially designed for the hand treatment of stroke patients, and the hardware device used is the Leap Motion Controller. The content of the game is similar to the “Post Office Trouble” game (players play a postman and put different color packages into correct containers) [107,108]. Specifically, the user needs to pick up the different color squares on the shelf by hand and put them into the corresponding color boxes (as shown in Fig. 11(b)). Furthermore, the game provides users with four different difficulty levels by setting the height of the shelf and the number of objects. Users can choose the appropriate difficulty level according to their conditions, making rehabilitation more personalized.

Maram et al. [106] conducted a study to explore the feasibility and effectiveness of immersive VR in stroke rehabilitation. Five male patients who met the experimental requirements were taken as participants. The patients wore Oculus Rift HMD equipped with the Leap Motion and played the game “Move-IT”. The study conducted the experimental evaluation by collecting patients’ game data (e.g.,

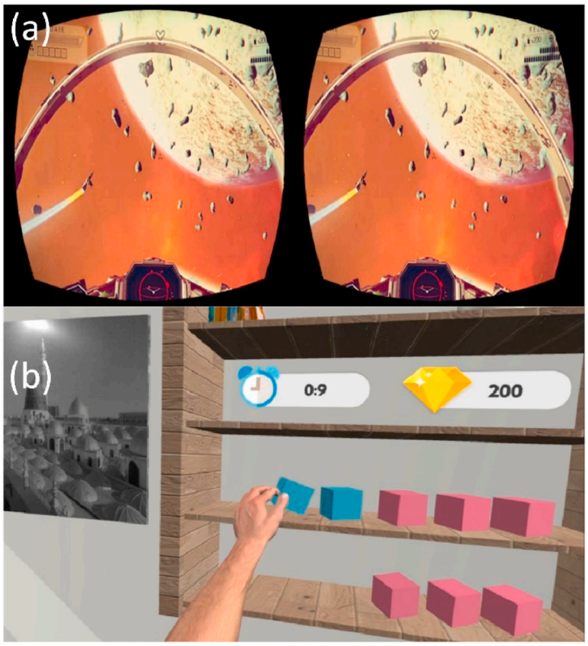

Fig. 11. Three immersive rehabilitation games: (a) Space War Game [25] and (b) Move-IT Game [106].

time to complete the game, number of errors) and their feedback on the game (e.g., experience, opinions, expectations). All patients completed the rehabilitation tasks except for one who could not correctly control the movement of the virtual hand. The experimental results showed that patients could get the highest score within their ability, and the number of errors was minimal. Meanwhile, the satisfaction evaluation showed that patients maintained positive attitudes towards immersive game-based rehabilitation training, which played an essential role in rehabilitation. The experiment also indicated that the immersive type of the game-based training protocol was feasible and effective.

5. Discussion

This work examined the existing commercial system-based hand rehabilitation approaches for stroke patients, including their hardware devices, game-based training protocols, and clinical outcomes. Various approaches for different stroke stages were extracted from 9 electronic databases and CNKI from 2010 to 2022. A total of 12 robotics studies, 10 physiological-based signal technology studies, 13 rehabilitation glove studies, and 18 depth sensor studies were investigated. The main findings of this work are: 1) Devices (especially non-contact devices) had some technical disadvantages (e.g., sensitivity to light), and there were no commercial game-based training protocols that focused entirely on hand rehabilitation; 2) Participants showed some improvement in hand function and were interested in game-based training protocols; and 3) Only a few games were specifically developed for hand exercises, and most of them were not updated regularly. The related suggestions were summarized as: 1) Safer non-contact rehabilitation equipment and more engaging training protocols should be developed for family and community-based rehabilitation due to the COVID-19 pandemic; 2) Relevant clinical scales should be updated or developed for hand rehabilitation; and 3) Rehabilitation assessment should be objective and can be performed within the games.

5.1. *Hardware equipment*

In this work, hardware equipment was classified into robots [37,41,109,110], physiological signal-based equipment [49–51,111,112], data gloves [63,65,70,113], and non-contact motion-sensing devices [75,78,79,89,91,114]. Among them, the common commercial rehabilitation robotic devices include Amadeo [37], Hands of Hope [115], and Myomo mPower 1000 [116], which provide a variety of assisted rehabilitation training modes and support intensive therapies to meet rehabilitation needs [117]. However, similar to clinical scales, most rehabilitation robots focus on the entire upper extremity rather than the hand [118]. Hand rehabilitation robots are also complex, inconvenient to wear, and expensive due to the requirements for multiple DOFs and control precision [119]. Commercial rehabilitation gloves and sensor-based devices are dominated by Senso Glove [113], Maestro Gloves [120], Intel RealSense [121], and Wiimote [122]. They are developed to reduce costs and maintain the effectiveness of community and home-based rehabilitation. Nevertheless, the wearable comfort of the rehabilitation glove can affect the patient's experience, and the data measurement accuracy of the sensor-based device can also affect the final rehabilitation outcome. Detailed information on the involved hardware devices is listed in Table 1, including advantages, disadvantages, prices, and so on. Fig. 12 depicts rehabilitation places for various types of equipment and stroke stages. It is worth noting that rehabilitation orthoses are one of the most commonly used devices for stroke patients [123–126]; however, orthotic devices cannot be regarded as "smart" rehabilitation systems, which were not discussed further in this work.

In terms of physiological signal-based devices, the BCI is often combined with other technology or devices to compensate for hemiplegic hand function or increase neuroplasticity to aid motor recovery [20]. The FES activates paralyzed muscles by stimulating motor neurons with artificial electrical stimulation [127]. Commercially available equipment that utilizes these technologies includes Bioness NESS H200 [112], The Fesia Grasp [50], and RHB-BANGDE [111]. However, to prevent side effects such as muscle spasms caused by excessive stimulation, BCI and FES need to be adjusted and used by medical professionals; therefore, these technologies are only suitable for clinical applications [20]. Additionally, these technologies are generally only appropriate for patients with severe strokes [33], and their suitability for community and home-based settings has not been established [20].

As can be seen from Table 1, non-contact motion-sensing devices have recently become a popular research topic [76,77,90,106,108,128,129]. The main reasons for using motion-sensing devices are that they are contactless, small in size, and easy to use. Additionally, motion-sensing devices are less expensive and have more commercial potential than other types of hardware equipment. Due to the COVID-19 pandemic and the related prevention policies, stroke patients are more likely to undergo rehabilitation treatment in the community and home settings rather than rehabilitation centers [9,17,19,22,24,130,131]. Furthermore, wearable devices such as exoskeletons or gloves need to be sterilized after each use, which increases the cost of rehabilitation centers and shortens the service life of the equipment. By contrast, motion-sensing devices are contactless, which may help prevent the spread of COVID-19 and reduce the negative effects of frequent disinfection. However, it is worth noting that there is currently no substantial evidence that motion-sensing devices can achieve better training effectiveness than wearable devices or exoskeletons [67,76,77,106,129,132,133]. Additionally, the tracking precision of motion-sensing devices may not be sufficient to generate robust clinical data [67,77,78,82,86,90,108]. Lastly, due to the high degree of commercialization, there is little research on customizing or modifying existing motion-sensing devices (e.g., Leap Motion, Microsoft Kinect) [134,135].

5.2. *Game-based training protocols*

Game-based training protocols are designed to alleviate the monotony of the treatment process and enhance the patient's self-confidence. These protocols are classified based on the targeted joint, such as finger training protocols [69,71,96,106,136,137] and

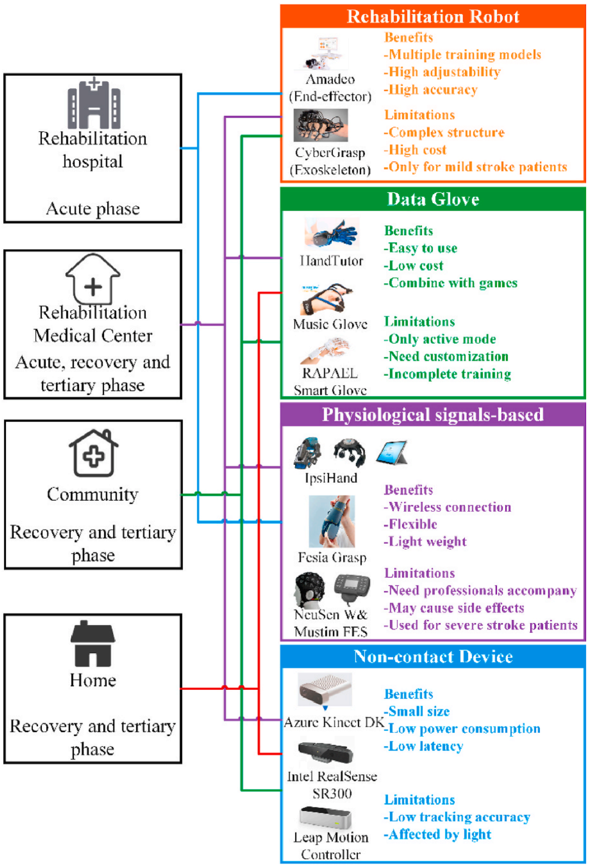

Fig. 12. Rehabilitation sites for various types of equipment and stroke stages.

wrist training protocols [72,100,137,138]. They can also be classified based on their interactive mode, such as 2D [69,71,72,96,97,99], 3D [137,139,140], VR [77,106,128,129,141,142], and AR [27,133,143,144]. Specifically, VR-based or AR-based training protocols create a highly immersive and stimulating environment for users by integrating touch, hearing, and vision, making patients more willing to participate in voluntary and active exercises. The benefits of VR/AR technologies can be summarized as providing a greater degree of freedom, rich game content, and a better patient recovery experience [98,136,145,146]. The studies reviewed indicate that game-based training protocols can effectively increase patient rehabilitation engagement and improve rehabilitation efficiency [24,106,128,131,139]. They also suggest that game-based training protocols can be considered as an auxiliary rehabilitation method with a high degree of feasibility and effectiveness [28,77,128,147].

Although game-based training protocols can improve patients' recovery efficiency, there is currently a lack of specifically designed games for hand rehabilitation. The commercial games that are currently used do not take into account the physiological and psychological needs of stroke patients, such as irritability or low patience [23,100,148]. Games that are too simple can quickly lose their appeal to patients, while games that are too challenging can undermine their self-confidence. Therefore, it is important to develop suitable games for patients, particularly for different stages of stroke recovery. The existing commercial training systems have game libraries [97–99], but the content of these games is often simplistic, and most of them have similar gameplay experiences or even only have one playing mode. Patients can easily become bored with these games, which can negatively affect training efficiency [31]. Therefore, games with self-justified playing contexts or coherent missions should also be considered [26].

It is worth noting that there is currently a lack of discussion on the use of physiological signal-based rehabilitation training with commercial games. Although Gao et al. [149] have reported on several BCI rehabilitation games, most of them are self-made rather than commercialized, and some of the related exercises may not be appropriate for hand rehabilitation [150,151]. Additionally, the commonly used Motor imagery-Brain-Computer Interface (MI-BCI) training has high psychological requirements for patients [150]. Patients must concentrate on the hand's motion frequently for an extended time while being prevented from making any actual movements, which can cause fatigue and negatively impact training outcomes. Therefore, game design should take into account factors such as environment configuration, game length, and game content [54,55,149].

An excellent example of a game-based training protocol can be found in the papers [152,153], which used 'Alice in Wonderland' as the background of the game to make it more engaging for patients. The developed game-based training protocol offered dozens of interesting exercises for patients to play, and the rich and attractive scenes further improved the immersion of patients. The training protocol also provided a great interactive system, where virtual objects react differently depending on the user's force, such as sliding, splashing, shattering, or exploding. This type of game has the potential to provide better concepts and innovations for game-based hand rehabilitation training.

5.3. Clinical trials and effectiveness

In this work, 31 hand rehabilitation experiments were selected from 47 articles, involving a total of 217 participants. The characteristics and results of each clinical trial were summarized, and their effectiveness was evaluated (Tables 1 and 4). Specifically, the number of participants in the clinical trials in articles [71,136,154,155] is not sufficient, and there is no control group in articles [9,25,26,97,102]. Additionally, many research groups only recruited patients in the same stage of stroke recovery [42,71,72,97,136], which lacks evidence for practical applications for stroke patients with various conditions. Articles [38,69,72,102] did not take into account the influence of age and gender on stroke participants, which may lead to uncertainty in clinical outcomes. Moreover, the unequal training volume of the control trials might also affect the training results, as observed in articles [71,72].

Among the articles reviewed, Paulo Dias et al. [128] fully took into account the patient's age and gender and established a control group with well-controlled variables. They used VR-based games as a medium for rehabilitation research and non-contact hardware Leap Motion for data measurement. Physical factors of the patients were also taken into account when using VR-based games, as well as for the control group. While patient satisfaction was collected through questionnaires to evaluate the training efficiency, only 12 patients were recruited for the clinical trial, and no clinical scales were used for evaluation.

As previously mentioned, only a few clinical scales have been specifically developed for hand rehabilitation assessment, such as the JTHFT scale, the Jebsen-Taylor Hand Function Test. The game-based research scales involved in this work are listed in Table 4. These scales are outdated and have not been updated in a long time, which may not be appropriate for evaluating hand function with the use of advanced devices and game-based training protocols. It is necessary to study renewed and suitable clinical scales, such as directly using game scoring results or game evaluation metrics as customized scales for hand functional assessment (for example, the bending angle and speed of the patient's fingers can be used as one of the evaluation metrics in a specific task).

5.4. Limitations of this review

This work has several limitations. The inclusion of only 10 electronic databases from 2010 onwards for hand rehabilitation in stroke patients is limited, even if these articles include conference papers, journals, and abstracts in other languages. Furthermore, due to the rapid replacement of equipment, some articles published in previous years may be outdated, which may slightly affect the conclusions of this work. This work did not include some controlled studies with inconclusive or non-obvious results. Future work should explore the existing commercial system-based hand rehabilitation approaches, and a cost-effective and suitable hand rehabilitation system could be developed based on the results of this work.

6. Conclusion

The worldwide COVID-19 epidemic has highlighted the importance of using contactless devices for community and home-based rehabilitation. While most studies have shown that commercial rehabilitation equipment and game-based training protocols can be beneficial for hand rehabilitation, factors such as key technology, equipment design, economics, patient recovery levels, and physiological and psychological needs should also be taken into consideration during system development. Additionally, commercializing rehabilitation games is crucial, and the integrity, relevance, and enjoyment of game content can have an impact on the patient's rehabilitation process. Rehabilitation game-scoring scales should be appropriate and professional, and it may be worthwhile to consider reflecting patients' recovery directly through the game-scoring scale. Furthermore, there is currently a lack of functional assessment using advanced technologies for hand rehabilitation. Therefore, it is necessary to integrate commercial devices, game-based training protocols, and digital objective assessment more deeply to enhance the efficiency of hand rehabilitation further.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

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Additional information

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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