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Robotic Devices and Brain Machine Interfaces for Hand Rehabilitation Post-stroke: Current State and Future Potentials

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Abstract
This paper reviews the current state of the art in robotic-aided hand physiotherapy for post-stroke rehabilitation, including the use of brain machine interfaces (BMI). The main focus is on the technical specifications required for these devices to achieve their goals. From the literature reviewed, it is clear that these rehabilitation devices can increase the functionality of the human hand post-stroke. However, there are still several challenges to be overcome before they can be fully deployed. Further clinical trials are needed to ensure that substantial improvement can be made in limb functionality for stroke survivors, particularly as part of a programme of frequent at-home high-intensity training over an extended period. This review serves the purpose of providing valuable insights into robotics rehabilitation techniques in particular for those that could explore the synergy between BMI and the novel area of soft robotics.

Keywords: Lower Arm Rehabilitation; Stroke Rehabilitation; Brain-Machine Interface; Robotic-aided physiotherapy; Exoskeleton; End-Effector

Introduction
Strokes are a global issue affecting people of all ethnicities, genders and ages [1]; approximately 20 million people per year worldwide suffer a stroke [2, 3]. Five million of those patients remain severely handicapped and dependent on assistance in daily life [4]. Once a stroke has occurred the patient may be left with mild to severe disabilities, depending on the type and severity of the stroke. This paper will focus on the primary issues experienced which are the clawing of the hand and stiffening of the wrist. In recent years, several new forms of rehabilitation have been proposed using robot-aided therapy. This work reviews the current state-of-the-art robotic devices and brain-machine interfaces (BMI) for post-stroke hand rehabilitation, analysing current challenges, highlighting the future potential and addressing any inherent ethical issues.

Potential Consequences of a Stroke
After a stroke, the patient will normally begin rehabilitation immediately, with the first phase taking place in a hospital under the supervision of a physiotherapist. However, after the patient is discharged from hospital they are usually given a set of exercises to perform (unaided and unsupervised) which comprises the next stage of their rehabilitation. A lack of resources available to health services worldwide, such as a shortage of physiotherapists and the limited availability of mobile or affordable equipment [5] is the reason behind unsupervised rehabilitation. Hand rehabilitation is considered to be a lower priority than the recovery of the shoulder and upper arm, which itself is secondary to the recovery of the motion of the trunk.
of the body and lower body motion, such as walking through gait re-learning. Thus, when the rehabilitation of the hand begins, it is often towards the end of, or after, the ideal rehabilitation timespan, leading to less-than-satisfactory results shown by Triandafilou and Kamper [6] and Kwakkel et al. [7]. To counteract these problems, robotics has been suggested by Sivenius et al. [8], by both supervising the rehabilitation and storing and providing access to data for the physiotherapist to analyse. Recently, some new recovery strategies, e.g., constraint-induced movement therapy (CIMT), or robot-assisted therapy were clinically tested for stroke rehabilitation and have proved to be effective, although restricted in their applications. This fact is due to that they can be used only on stroke patients with residual movement capabilities, which account for 50% to 70% of the cases [9]. Where these systems cannot be used, there is no accepted and efficient rehabilitation strategy available for patients with chronic stroke and no residual hand movements [10].

Brain Machine Interface in Stroke Rehabilitation

Another novel technology with potential in the area of medical robotics is the use of brain-machine interfaces (BMI) systems, which utilise physiological signals originating in the brain to activate or deactivate external devices or computers. Birbaumer and Cohen [11] suggested this technology as a possible solution for those who suffered a stroke and subsequently needed to rehabilitate a completely paralysed limb and a damaged brain at the same time, shown by Birbaumer et al. [12] hypothesised that re-establishing the lost connectivity between ipsilesional (i.e., located in the area of the brain damaged by stroke) cortical activity related to the execution of finger movements and proprioceptive (haptic) feedback through the use of a BMI system would strengthen the ipsilesional sensorimotor loop. In turn, feedback would foster neuroplasticity, facilitating motor recovery as shown in work by Birbaumer and Cohen [11], Dimyan and Cohen [13] and Dobkin [14]. Initial studies of stroke rehabilitation using BMI showed that, in general, patients learnt to control the rehabilitation device properly using their brain waves over a few weeks of training, but such a short trial period meant that they did not improve significantly in terms of motor function [15]. However, further studies combining BMI training with goal-directed behavioural therapy over a longer period led to significant improvements of motor and cognitive capacities of severely affected chronic stroke survivors [16]. Based on these findings, a larger controlled clinical trial with 32 chronic stroke survivors without residual finger movements was conducted; it showed that 20 sessions of ipsilesional BMI training combined with goal-directed behavioural therapy led to motor improvements superior to those found in a control group that trained under random BMI feedback, but receiving the same goal-directed behavioural therapy [17]. A more recent clinical study conducted Ang et al. [18] involving 26 chronic stroke survivors with less severe paralysis, which compared conventional robot-assisted therapy with BMI-controlled robotic training found similar results. Other, less controlled studies with smaller samples by Mukaino et al. [19] and Varkuti et al. [20] appear to further corroborate this trend. Although there is increasing clinical evidence showing the benefits of BMI-related tools in stroke neurorehabilitation, more and larger clinical studies are needed to fully establish the systems’ efficacy as demonstrated by Kansaku and Cohen[21]. We begin by describing the common
physiotherapy exercises required for hand rehabilitation post-stroke, followed by a classification of hand and wrist rehabilitation robotics. We then present a comprehensive review of lower arm robotic devices and an overview of BMI in the context of stroke rehabilitation. We conclude with a discussion on the current challenges and future directions.

Robotic Devices for Hand Rehabilitation Post-Stroke

There are three key exercises which are given to the patient to aid in the recuperation of the full motion of the wrist and the hand. The first is the opening of the hand from a closed position to a fully open position and then allowing the hand to relax again. Typically the first exercise used due to the majority of stroke patients initially having their hand locked into a ‘claw’ shape, which this exercise attempts to eliminate. The patient normally attempts the exercises unaided to gauge severity, after which a physiotherapist will manipulate the fingers into the correct position to fully open the hand.

Secondly, there is the grasping motion, which aims to help the patient regain the ability to hold an object in their hand just as they would do in everyday life. Similar to the initial exercise of opening the hand; however, it then adds in the concept of holding an object, requiring different positions of the fingers depending on the item used. Common examples are the cylindrical grasp, where a patient will open their hand as much as possible before closing it slowly around a cylindrical object such as a can, or the precision (pinch) grasp, bringing the thumb and forefinger together to form a pinch motion. Both sequences are shown in Figure 1.

The third common exercise set performed is a wrist movement: the flexion and extension of the hand as illustrated in Figure 2. In a flexion motion, the patient would assume a neutral or flat wrist orientation and then move the wrist downwards as far as possible. The extension is where the patient begins with the hand in a neutral or flat wrist orientation and then tilts the hand upwards as far as possible. Again a combination of movements is performed to aid the patient in eliminating the ‘claw-like’ shape of their wrist and hand after the stroke. Due to the layout of the muscles in the human arm, if either the extensor or flexor muscles become overextended the motion of the fingers and of the wrist become compromised, with a high tendency for the range of motion to become extremely limited.

There are also four other wrist motions patients may be advised to perform for rehabilitation; these, however, are of a far lower priority than the flexion and extension motions. Abduction and adduction are the acts of moving the wrist from side to side in alignment with the arm, and pronation and supination are the motion of rolling the wrist so that the hand would turn from palm up to palm down.

Existing hand and wrist rehabilitation robotics can be divided into categories based on several criteria: firstly, whether the devices are commercially available or whether they are at the research stage, and secondly, the type of mechanism used to achieve the desired movement. These are either end-effectors (fixed systems) such as the Haptic Knob by the National University of Singapore and Imperial College London [22], or exoskeleton-based systems such as the PMHand by Heriot-Watt University [23].
End-effector Systems

End-effector systems in the context of rehabilitative robotics interact with the patient through a single point that is either attached to the patient’s hand as shown by Bien and Stefanov [24] or is gripped by the hand such as the Haptic Knob by et al. [22]. This allows the patient to perform their given exercises within the robot’s predefined XYZ Cartesian space, which can be represented graphically on a monitor to show progress in a more realistic manner [25]. These systems ensure that the patient is restricted to the correct motions by controlling the paths along which the joints can move. They can also include extra sections to support the patient’s arm if needed. Sometimes these systems can be incorporated into bilateral therapy, through the use of a second system on the non-paretic arm. Allowing for the collection of motion data from the non-paretic ‘master’ arm to be recorded and translated into movement of the paretic ‘slave arm’. An excellent example of data collection is in the system built by Kawsaki et al. [26].

Exoskeleton Systems

In contrast, exoskeleton systems are devices that are fully mounted on the patient such as the work by Pons [27], allowing for a more realistic and engaging treatment. However, as a worn device, they do apply an extra weight to the patient if they are not aided by any form of cable mount. Figure 3 shows a simplistic example of the differences between the types of end-effector and exoskeleton systems.

Rehabilitation System Attributes

Within these categories, another key element to consider is whether systems are passive or active. In passive systems, there is no input from the system in the form of actuation. However, the patient is still constrained into the appropriate range of motion. Active systems are interactive and aid the hand or wrist in its attempt at the correct range of motion through the use of actuators. There are also hybrid-style active systems, called ‘backdrivable’, which include a mode allowing them to be used in a similar manner to a passive device, offering no resistance to the patient.

A critical design decision when creating these devices is minimising the sense of technological intrusion experienced whilst using the proposed systems. They have to mimic as closely as possible the manner in which a physiotherapist would interact with the patient during their rehabilitation. This allows a greater sense of continuity and a smooth transition between the use of the device and interaction with the physiotherapist. Device aesthetics and user comfort (both physical and psychological) are not a trivial concern; patients must feel comfortable with the device if they are to continue using it. Previous surveys on the use of artificial hands revealed that up to 50 of the amputees quizzed were not using their prosthetic hands regularly, citing reasons of low functionality, poor cosmetic appearance, and low controllability [28]. Moreover, the devices will be used on a diverse range of patient demographics [5] and will need to be able to cope with a large range of anthropomorphic parameters [29, 30]. The device should be able to provide the patient with a safe range of motion, suited to their individual measurements, at all times when assisting in performing a movement. In addition, the system should also provide the physiotherapist with the required data to track the progress of
the patient through the raw data from the device, as well as displaying processed data for ease of analysis. Interaction can also be aided by using the device data to demonstrate to the patients that they are making progress through the potential use of interactive games.

**Lower Arm Robotic Devices**

There have been many in-depth reviews, meta-analyses and comparisons of the ideas, theories and practises of different physiotherapy schools. Within these, the effects of intensity of training, timing in relation to the stroke occurring and the specific motions that should be used have all been discussed by Kalra et al. [7], Kwakkel et al. [31] and Lincoln et al. [32].

Several of the systems discussed will either manipulate the upper arm by default or can be an attachment for those systems. However, as the focus of the paper is the hand and wrist, upper-arm stroke rehabilitation will not be discussed. Further information on rehabilitation of the upper arm can be studied in a review article by Loureiro et al. [33].

This section will cover two areas: commercial devices currently available for purchase and research-based devices that are either at the prototype or clinical trial stage.

**Commercial Hand and Wrist Devices**

There are multiple commercial rehabilitation aid devices available; the most prevalent ones are detailed in Table 1.

Two extremes of rehabilitation style mentioned in Table 1 are pictured in Figure 4. On the left the Power-Web is shown, a non-responsive piece of rubber used to guide stretches which cost £10, whilst the Kinetec Maestra, shown on the right, is an advanced mounted exoskeleton. The Kinetec Maestra provides continuous force to create motion in the fingers and feedback; however, each unit costs approximately £4000.

**Non-Commercial Hand and Wrist Devices**

Discussed here is a brief history and review of existing non-commercial devices, split into two categories based on the device type (end-effector or exoskeleton). Additional information on the devices listed can be found in Table 2 and 3.

**End-effector Devices**

The first end-effector device developed for hand and/or wrist rehabilitation was based on the haptic sensor device known as the SPIDAR, which was conceived in 1989 by Tokyo Institute of Technology [34]. They also developed all of the future SPIDAR iterations. The initial SPIDAR was a single-point interaction system, where one finger was attached to the device and the patient could interact with the virtual reality (VR) system. This idea was based on the patient interacting with an orb in the centre of the device and manipulating objects in a VR environment. There were many iterations of the SPIDAR device, such as the SPIDAR-II, which allowed a pinch motion to more accurately reflect reality, followed by the Both-Hand SPIDAR which, as its name suggests, allowed the use of both hands, to the Big SPIDAR,
a full-body interactive system. There was also the SPIDAR-G, which used a ball mounted in the centre of a link system to allow the patient to grasp objects in a more realistic manner. The current iteration is the SPIDAR-8 [35], which is a two-handed multi-finger interactive device designed to incorporate all of the advantages of the previous devices, and is currently undergoing clinical trials.

In a similar manner to the SPIDAR-8, the Rutgers Master II created in 2002 by Bouzit et al. [36], is an end-effector based device that attaches to the fingers through palm side individual grip and uses a piston combination to show the force that a patient could apply, then reflect it in a VR game. HIFI by Mali and Munih [37] is the first end-effector device capable of both aiding the patient in the movement, being able to provide up to 10Newtons of force, and collecting feedback data on the force being generated by the patient. However, the HIFI can only manipulate a single finger and is a very elaborate system when compared to the SPIDAR and Rutgers Master II systems, which for the same size and complexity can manipulate the entire hand. The HIRO, created by Kawasaki and Mouri [38] in 2003, and the HIRO II+, created in 2007, are both end-effectors modelled in the mirror image of a human hand with 15 DOF. The HIRO II+ has the additional feature of providing force feedback, allowing it to create a more realistic rehabilitation environment by simulating a human hand to interact with. It can also provide feedback in a VR environment.

The Haptic Knob, developed in 2007 by Lambercy et al. [22], uses an adjustable grip that can be used as a stand-alone grip for any number of fingers, or to allow everyday items to be clamped into the device for more realistic rehabilitation. It provides force feedback by both the strength of the patients grip and in the motion of the wrist. HandCARE ‘Cable Actuated REhabilitation’ built by Dovat et al. [39] was created in 2008 and is a system which uses a single motor to provide a feedback system for the force exerted by the patient who is connected to the device through the finger tips. HandCARE is also portable as it is lightweight and easy to set up. The device can also exert a force on the patient’s fingers to allow for a resistance similar to what they would feel in reality.

Gentle/G by Loureiro et al. [40] is a whole-arm motion system; however, in 2009, the Grasp Assistance Robot Module was developed for it, in which the patient uses a full-hand monitoring system that reflects their grasping motion and strength on VR system. Gentle/G is a combination of exoskeleton and end-effector, as the mounting could be considered an exoskeleton due to it encasing the entire hand, whilst it could also be classed as an end-effector due to its grasping method.

Master Finger-2, developed by Ueki et al. [35] in 2011, is a haptic end-effector that uses the finger and thumb to simulate a pinching motion. It can also use other fingers and provide force feedback for VR use. Master Finger-2 is similar to the SPIDAR-II, Rutgers Master II and the Haptic Knob in terms of the rehabilitation exercise motion that would be performed by the patient.

Several of these devices have gone through small-scale trials of both healthy and stroke patients; for example, the Haptic Knob was tested using three stroke patients and 12 healthy volunteers. All of the end-effector devices considered are listed in Table 2.
Exoskeleton Devices

HWARD was the first stroke rehabilitation exoskeleton to be developed, created in 2005 by Takahashi et al. [41], and it incorporated the wrist and the full hand in a 3 DOF arrangement, allowing it to move the wrist in flexion and extension, as well as a grasp motion for the fingers. Due to an exposed palm design, the patient could also feel the object they were grasping for additional realism. The HWARD was designed to both translate the force that the patient can generate and apply a force to help the patient’s motion. The AFX by Worsnopp et al. [42] is a single-finger rehabilitation system created as a reach to pinch system with one motor providing force for extension and another to provide force for flexion on each finger. Full actuation for each joint in the finger is provided. Gifu University’s initial device was a semi-exoskeleton by Kawasaki et al. [26], which used a 2-finger mounted exoskeleton that mounted in an end-effector style, allowing support for a pinching motion. Their next device was the NEDO agsin by Kawasaki et al. [43]; a semi-exoskeleton that encased both the hand and wrist in an end-effector-style unit. Allowing for full flexion and extension of the fingers, whilst aiding in wrist stability. Each joint of the fingers was controlled by its own individual motor; with a passive joint to ensure complete alignment, the wrist arrangement used a single motor to provide motion. NEDO both provided the power to move the hand for exercise and recorded the motion for use in a VR environment. The HANDEXOS by Chiri et al. [44] was an hand-mounted exoskeleton designed to open and close the fingers. With an open palm to allow for interaction with everyday objects, this system used an arrangement of wire tendons fed back through a specifically-designed kinematic setup that ensured the fingers could not move in the wrong alignment. The HandSOME by Brokaw et al. [45] systems developed in 2011 were exoskeleton systems designed to train the patient in one particular aspect of the hand rehabilitation process: the pinch motion. An elastic cord was used to aid with the extension of the hand; this could, however, lead to issues when the device was being used by a patient with weak flexion abilities. The IHRG exoskeleton was developed in 2013 by Popescu et al. [46] and used a plastic moulded glove with a mechanical structure mounted to the back of the hand to control the motion of each finger individually. The IHRG system is still in development. An initial soft-exoskeleton-based system named the Pneu-Glove, was developed in 2009 by Connelly et al. [47]; this device used a combination of servos and a pneumatic pump arrangement to inflate a bladder in each finger, pushing the finger into extension. In combination with a VR game and headset to allow for a more interactive rehabilitation experience. Soft robotic devices were advanced again in 2013 when the Walsh group at Harvard University specifically Polygerinos et al. [48] developed a soft robot glove that would also allow for grasping of an object by using inflatable cells mounted on the back of the fingers. This device showed it was fully capable of grasping an object in a realistic manner, and, due to its soft robot construction, reduced the chance of injury. A more recent device is the PMHand by McConnell et al. [23]; which uses a 3D-printed low-profile exoskeleton and a wire-tendon-motor linked system to allow for both a flexion and extension motion to be achieved. Data from all the exercises is also collected to judge a patient’s progress. The most recent device by Conti et al. [49] created in 2015, entitled the Hand Exoskeleton System (HES). Is a 3D printed, low cost and portable exoskeleton system designed to run as a cable driven single-phalanx motion system,
this device allowed for grasping of different objects successfully and is currently being deployed for patient testing. Whilst major progress is being made in developing the physical construction of assistive apparatuses, such as lightweight and versatile prostheses or exoskeletons [50–53], creating intuitive and reliable control systems for such devices still presents an enormous challenge [54]. Further specifications of the devices mentioned can be found in Table 3.

**Brain-Machine Interfaces**

Brain-machine interfaces integrate recorded brain signals with controllable devices in order to re-establish or expand sensorimotor limitations by Pfurtscheller and Neuper [55]. They can rely on passively or actively generated brain signals, in which neuronal activity is modulated either spontaneously (by internal or external stimuli) or volitionally, respectively. Non-invasive BMIs relate to systems that gather brain signals without surgical procedures. To accomplish that, the experimental setup includes bulky, expensive options such as the functional magnetic resonance imaging (fMRI) or the magnetoencephalography (MEG), to light and relatively cheap approaches such as the electroencephalogram (EEG) or the electromyography (EMG), and recently Near-infrared spectroscopy (NIRS). For its availability and ease of use, the EEG is largely employed in clinical stroke rehabilitation; thus, it constitutes the focus of this review. The usage of BMI in stroke rehabilitation can be branched into two main approaches: a monitoring mechanism, with probed brain signals serving as feedback for concentration levels of the physiotherapy practice; or a control framework, in which an artificial actuator is driven at will. Motor Imagery (MI) to operate, which we discuss below. Post-stroke, a significant number of patient’s present hand motor impairment. In addition, loss of concentration limits the efficacy of physiotherapy. Mental practice of voluntary movement (i.e. MI) has been envisaged to alleviate that [56], possibly promoting neural plasticity and engagement of relevant sensorimotor regions of the brain [57, 58]. Nevertheless, further studies are needed to elucidate the effects and mechanisms of MI in stroke rehabilitation. In this sense, EEG-based BMI is appealing for it combines MI with active orthosis control. More specifically, voluntary movement or motor intention of the arm, hand and wrists activate the primary sensorimotor area, which is characterised by a desynchronisation of the 8-20 Hz brain rhythms over the hemisphere contralateral to the limb in use [18]. This neural signature can be detected in the EEG signals and processed to provide control signals for an artificial actuator, thereby bypassing the physical impairment or highlighting the engagement with the task, Figure 5. Two issues challenge the advancing of BMI in post-stroke rehabilitation robotics. Firstly, not every patient can consistently modulate their mu and beta rhythms in response to MI tasks, preventing the extraction of reliable control signals. Secondly, the small signal-to-noise ratio combined with the poor spatial resolution inherent to EEG systems result in low bit rates, Figure 6, which in turn prohibit sophisticated control strategies for the orthosis. Nevertheless, recent studies point that training and transcranial direct current stimulation: ERD-Based Online Brain–Machine Interfaces (BMI) in the Context of Neurorehabilitation: Optimizing BMI Learning and Performance may improve the reliability of evoked MI rhythms [59]; also, sophisticated signal processing algorithms may alleviate the control burden and support more complex orthosis. In work by Prasad et al. [60], the
authors submitted five post-stroke participants to a six-weeks BMI programme in which neurofeedback was given proportional to MI measured activity – the more subjects could modulate their mu and beta rhythm synchronisation, the greater the performance in a goal-directed task. Considering the action research arm test as a benchmark, all participants improved their scores even though only two had significantly different ERD/ERS from that prior to the protocol. This emphasises the importance of incorporating BMI strategies into post-stroke rehabilitation protocols despite the heterogeneous subject MI capabilities. The first double-blinded randomised clinical trial to assess the efficacy of Brain-Machine-Interfaces (BMIs) in stroke has been done by Soekadar et al. [52] in a study comprising 32 patients. They showed that the group who could volitionally control a BMI-based orthosis improved their motor control as measured by the Fugl-Meyer Assessment (FMA) score more than that submitted to random orthosis movement. Furthermore, subjects presented cortical activity reorganisation linked to BMI training. These results further corroborate that robotics and BMI may be essential to enhance post-stroke physiotherapy. Finally, Pichiorri et al. [61] conducted a related study with 28 sub-acute stroke patients and found the significantly higher probability of achieving a clinically relevant increase in the FMA score in subjects submitted to BMI training than those involved solely in MI training. Taken together, there is increasing evidence on the efficacy and relevance of incorporating BMI in stroke rehabilitation. In this sense, in addition to further studies with more patients, adapting the current BMI strategies to use with commercial orthoses and other robotic devices is fundamental to the progress of this therapy.

Discussion

Of the devices reviewed, it can be seen that each device type comes with its own advantages as well as its flaws. These are further discussed in this section, as well as reviewing how each new iteration solves previous problems whilst also expanding the abilities and usability of the devices – both in terms of physiotherapy practice and BMI applicability. End-effector systems can provide accurate feedback and apply resistance to the patient in the alignment with what they are experiencing in a virtual reality (VR) simulation. The majority of the commercial systems currently available are of the end-effector build. However, they cannot aid in the full movement of the fingers or wrist and are primarily only available at fixed locations. Additionally, whilst they can simulate the approximate force/resistance an object would offer, they cannot provide the texture or true tactile interface of a real object, as the patient would normally have to grip the end-effector and not the object in question. Recently, exoskeletons have been developed that counteract some of the flaws found in end-effector systems, such as aiding the motion of the fingers and wrist. These also provide accurate feedback to a VR system but are still overall bulky and intimidating. Only the most recent of the exoskeleton-based systems start to overcome the problems of portability and requiring supervised use, such as the Harvard Soft Robot Hand by Polygerinos et al. [48]. There have also been attempts at a hybrid end-effector/exoskeleton-based system, such as the Gifu NEDO [43]. This overcomes the problem of not being able to provide force to move the fingers and wrist; however, this does come with the downside of requiring a
large and complex system. Even with these issues, there has been an increase in the number of devices now reaching small-scale clinical trials.

Several of these devices have been used in combination with another upper limb rehabilitation aid to get a better view of robotic rehabilitation overall. Thus, the development and provision of assistive machines that are independent of the peripheral nervous system’s integrity represent a promising and appealing perspective, particularly, if controlled intuitively and without requiring extensive training to gain reliable control [54]. BCI/BMI systems promise to enhance the applicability of assistive technology in humans with a compromised or damaged motor system [54]. For the trials and testing of the systems for hand rehabilitation, several measurements are being used, such as the Upper Extremity Fugl-Meyer by Sullivan et al. [62], Motor Activity Log (MAL) by Uswatte et al. [63], Manual Ability Measure-36 by Chen and Bode [64] and Jebsen Hand function test by Spaulding et al. [65].

Due to the nature of research not all of the clinical trials performed used either the same measurement or the full list of measurements stated; however, all used chronic stroke patients. Multiple clinical trials using robotic-aided rehabilitation have already taken place; however, the most comprehensive trial was conducted in 2010 by Lo et al. [66] and reported in the New England Journal of Medicine on upper limb rehabilitation. This showed mixed evidence for the benefits of robotic-aided rehabilitation after a stroke. Using the In-motion robot (MIT-Manus with horizontal, vertical, wrist and hand modules), where they found using the device over 36 1-hour robotic therapy sessions was equally beneficial to 36 1-hour high-intensity traditional therapy sessions in terms of improvement which were measured over both 12 and 36-week periods. The commercially-available Amadeo system has been used in a hand-specific trial involving 12 patients performing exercises for 18 hours total by Stein et al. [67]. This showed comparable improvements in all of the measurements previously stated to the standard physiotherapy treatment that a patient would undertake; it was also noted that this improvement lasted past the six months mark after a stroke. The Haptic Master II created by Timmermans et al. [68] was used in a single-blind randomised controlled trial involving 22 patients over an 8-week period, with the exercises being performed 4 times per week, twice a day for 30 minutes. Testing showed a significant improvement in the action research arm test using the robot system, a significant but similar improvement on the MAL for both robot and standard rehabilitation. For the initial length of rehabilitation, again no significant improvement was shown over conventional rehabilitation; however, it was noted that the effects of the robotic therapy proved to last after the trial was completed whilst those of the conventional therapy did not. The PneuGlove by Connelly et al. [47] was used in a six-week trial with seven stroke sufferers; each performed the exercise in eighteen training sessions over the trial period. This study showed significant improvement in the patients’ Fugl-Meyer assessment scores, which was also maintained over a one month period after the sessions had ended. There have been multiple other studies for robotic-aided rehabilitation that show either comparable or, in some cases, greater progress in patients’ recovery measured against a traditional approach. These trials, it should be noted, do state that their sample size is not large enough to draw statistically significant conclusions, but so far all of the trials show a pattern of the benefits of robot therapy
outlasting the standard treatment. Robotic rehabilitation does have its pitfalls, despite its promising early trials. As more of these devices are being used, one issue which has arisen is their aesthetic appearance. If the machine appears intimidating, it may affect the patient’s progress or desire to use the device. A way to mitigate this problem is to include the patients in the design process [69, 70], whereby, using an iterative process of consultations with patients, researchers could design a device that proved practical and which the patients found visually reassuring. Another issue is how the device is controlled – whilst the use of integrated exercise apps or a function for remote control by a physiotherapist can be made very user-friendly, arguably the end goal would be to remove that intruding interface layer entirely. The ultimate in non-intrusive assistive devices would be able to respond to the user’s thought of ‘open hand’ by doing just that. Therefore, the development and provision of rehabilitative robotics integrating BCI technology, particularly those which can function even with damage to the patient’s peripheral nervous system, represent a promising avenue of research. If devices can be controlled intuitively and without requiring extensive training to gain reliable control [54], BCI/BMI systems promise to enhance assistive technology for stroke patients, and even for wider application treating other forms of neurological damage [54]. These issues aside, the biggest problem currently faced by robotic rehabilitation devices is their predominantly high prices and lack of clinical evidence on a large scale. This can lead to most healthcare providers being unwilling or unable to purchase a still largely untested device when it would be safer to use that budget for conventional treatments with a physiotherapist and medication. This then leads to a lack of large-scale evaluations of the robotic devices, which itself then contributes to the cyclical problem of staging clinical trials. Another issue has arisen, which is their aesthetic appearance. If the machine appears intimidating, this may affect the patient’s progress or desire to use the device.

**Conclusion**

Despite the broad range in the size and focus of the trials that have been conducted in this area, an increasing body of evidence has been found that robot aided rehabilitation can be highly beneficial to stroke patients. From the trends seen in current research, it would appear that a combination of robotic and traditional treatment would produce the best results. At present, a constant failing in the rehabilitation cycle is that the assigned exercises have to be performed unsupervised at the patient’s home, with too little monitoring or correction. However, starting to be corrected: as discussed previously in this paper, more devices are being designed which are specifically aimed at independent use in this form of social environment. This should lead to patients performing their exercises in more often and in the correct manner, which has been shown in the overall area of stroke rehabilitation research to be one of the key aspects to fully regaining the use of the limb in question. There is also an opportunity to incorporate a greater number of sensors into future systems, allowing for a more in-depth analysis of patients’ progress to be made. This could be used by the device itself to aid in patients’ recovery by adjusting its own internal parameters, or by incorporating the data into interactive games for the patient. It would also allow the physiotherapist to use the data to
examine and compare progress between patients, allowing for a greater knowledge of the changes and challenges each patient faces through their recovery. From the trend towards developing systems capable of gathering a great deal of patient data, many questions and issues arise, from the aspects of safety of the patient using a device that is potentially evolving unsupervised, to the ethical use of the data that would be collected on the patient. These points are discussed in more depth by [69]. The next generation of devices will need to be portable, easy to attach, simple to use and safe. These factors can restrict the use of the traditional hard robotic approach, in which movement is fully controlled by motors and the direction of motion is controlled by rigid mechanical frames. Instead of this approach, the use the new soft robotics approach can be embraced to create a system that provides the correct motion whilst using soft silicone-based materials to allow for a lighter and safer device. Initially, one such system, created by [48], does exist and has been shown to allow for the grasping exercise to be performed, though no clinical trials have been reported as yet. However, current advancements in this field of work show great potential for wider development and distribution of these types of devices. For now, these are the forerunners of the potential progress and innovation that can, and will, be made in this area and the field of robotic rehabilitation as a whole.

Competing interests
The authors declare that they have no competing interests.

Author’s contributions
Alistair McConnell is the main author of the introduction, robotic devices for hand rehabilitation post-stroke, and was responsible for all sections basic content, including introduction, discussion and conclusion. Fabricio Brasil and Renan Moioli are the main authors of the section on brain-machine Interfaces and contributed to the introduction and discussion on neurological rehabilitation. Marta Vallejo contributed to the style and structure of the paper as well as performing general revisions of the document sections. She also proof read the paper. Patricia Vargas provided guidance on report construction and contributed directly to the abstract, introduction, discussion, conclusion, and reviewed the other sections. She also proof read the paper. Adam Stokes advised on paper construction and contributed to technical analysis of the systems. He also proof read the paper. David Corne provided guidance on the paper overall structure and the links with the current work. He also proof read the paper.

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References


Figures

Figure 1: **Chain of Motion.** The chain of motions required to perform the cylindrical grasps and the precision grasp. The top row begins with an open hand position and moving to grasping a cylindrical object while the second row begins with an open hand position and moves to a precision grasp or a 'pinch' position.

Figure 2: **Patient Exercise.** An example of the two exercises a patient should perform to regain the full range of motion and use of their wrist and hand. The first in the flexion where the patient moves from a neutral palm down position to bring the palm closer to the underside of the arm, while the second begins in the same manner but the hand is then raised so the back of the hand is closer to the underside of the arm.
Figure 3: **Generic Exoskeleton.** A generic full hand exoskeleton. On the right is an example of a end-effector setup in a Unilateral configuration.

Figure 4: **PowerWeb.** The Power-Web: Consisting of a simple circular rubber sheet containing multiple small spaces, the Power-Web [71] allows the patient to insert their fingers and then move the fingers in different motions with the rubber providing a form of resistance training. The Kinetic Maestra: Worn mounted to the wrist and the tips of the fingers, the Kinetic Maestra [72] can open and close the fingers in one motion. Through raising the arm on which the device is worn, the user can achieve a full opening and closing motion.

Figure 5: **Brain Framework.** Brain-machine interface framework. Electrophysiological signals are extracted and processed to produce control signals for external actuators, which in turn provide visual and somatosensory feedback to the user.

Figure 6: **BitRate.** Bit Rate, defined as:

$$\text{BitRate} = \log_2 N - \frac{P \log_2 P + (1-P) \log_2(1-P)/(N-1)}{(1-P)/(N-1)} * \frac{1}{t},$$

where $N$ is the number of classes, $P$ is the task performance, and $t$ is the time (in seconds) needed to reach peak performance in a trial. In the figure, $N = 2$. Note that if a patient is to control a more complex device (which requires more bits/trial) whilst maintaining trial duration, it implies on significantly higher performance in the task (accuracy).
Table 1: List of the current commercial rehabilitation devices. The first row illustrates the designation of the device, their developer, appropriate reference, type (End-effector or Exoskeleton), arm segment they aid, number of degrees of freedom if they are passive or active and a brief description of their function.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Developer/Creator</th>
<th>Reference</th>
<th>Type</th>
<th>Lower Arm Segment</th>
<th>DOF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amadeo</td>
<td>Tyromotion</td>
<td>[73] [67]</td>
<td>End-effector</td>
<td>Full Hand</td>
<td>5 passive</td>
<td>Floor mounted device allows the patient to grasp an object</td>
</tr>
<tr>
<td>Cyber Grasp</td>
<td>Immersion</td>
<td>[74]</td>
<td>Exoskeleton</td>
<td>Full hand</td>
<td>5 active</td>
<td>This device allows for extension and flexion of each finger</td>
</tr>
<tr>
<td>Digi-Flex</td>
<td>Cando</td>
<td>[75]</td>
<td>End-effector</td>
<td>Full Hand</td>
<td>5 passive</td>
<td>Patients grasp this device to compress springs to build strength</td>
</tr>
<tr>
<td>Hand Mentor</td>
<td>Kinetic Muscles</td>
<td>[76]</td>
<td>Exoskeleton</td>
<td>Full Hand</td>
<td>1 active</td>
<td>Mounted orthotic device that moves the fingers as one in a grasping motion</td>
</tr>
<tr>
<td>Kinetec Maestra</td>
<td>Sammons Preston</td>
<td>[72]</td>
<td>Exoskeleton</td>
<td>Full Hand</td>
<td>4 active</td>
<td>Helps by providing continuous motion of the fingers</td>
</tr>
<tr>
<td>Power-Web</td>
<td>Pwrweb Internation</td>
<td>[71]</td>
<td>End-effector</td>
<td>Full Hand</td>
<td>1 passive</td>
<td>Circular rubber sheet with holes to allow stretching</td>
</tr>
<tr>
<td>Thera-Band Hand Exerciser</td>
<td>Thera-Band</td>
<td>[77] [78]</td>
<td>Elastic Band</td>
<td>Full Hand</td>
<td>1 passive</td>
<td>Hand opening and closing. Fingers move as on</td>
</tr>
<tr>
<td>SaeboFlex</td>
<td>Saebo</td>
<td>[79]</td>
<td>Exoskeleton</td>
<td>Full Hand</td>
<td>5 passive</td>
<td>Uses springs to replicate each tendon in the hand that the patient can work against to aid rehabilitation</td>
</tr>
<tr>
<td>SaeboStretch</td>
<td>Saebo</td>
<td>[80]</td>
<td>Exoskeleton</td>
<td>Full Hand</td>
<td>2 passive</td>
<td>Single piece of flexible rubber mounted to a wrist orthotic device for grasping</td>
</tr>
<tr>
<td>Hand of Hope</td>
<td>Rehab-Robotics</td>
<td>[81]</td>
<td>Exoskeleton</td>
<td>Full Hand</td>
<td>1 active</td>
<td>Full hand exoskeleton with and EMG trigger to extend the fingers</td>
</tr>
</tbody>
</table>
Table 2: List of the current non-commercial hand and wrist end-effectors. This table is only for the current end-effectors and is arrayed in chronological order of their development. It features in the first row the devices designation, developer, the year they were first published, relevant reference, what part of the hand or wrist they aid, the number of degrees of freedom and if these are passive or active as well a brief description of their function.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Developer/Creator</th>
<th>Year Ref</th>
<th>Hand &amp; Wrist Segment</th>
<th>DOF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIDAR-8</td>
<td>Tokyo Institute of Technology</td>
<td>2000 [34]</td>
<td>Both Hands</td>
<td>6 active</td>
<td>Dual fixed end-effector which hands interact with to play virtual games.</td>
</tr>
<tr>
<td>No-Name</td>
<td>MIT</td>
<td>2001 [82]</td>
<td>Wrist</td>
<td>3 active</td>
<td>Wrist attachment for the MIT-MANUS allowing for wrist exercises.</td>
</tr>
<tr>
<td>Rutgers Masters II</td>
<td>The State University of New Jersey</td>
<td>2002 [36]</td>
<td>3 Fingers + Thumb</td>
<td>4 active</td>
<td>Finger manipulation device primarily designed to sense force and position.</td>
</tr>
<tr>
<td>MR CHIROD</td>
<td>Northeastern University</td>
<td>2005 [38]</td>
<td>Full Hand</td>
<td>1 active</td>
<td>Gripper that both reads the force applied and also applies a variable resistive force.</td>
</tr>
<tr>
<td>HIFI</td>
<td>University of Ljubljana, Slovenia</td>
<td>2006 [37]</td>
<td>1 Finger</td>
<td>2 active</td>
<td>Device allows the extension/flexion of 1 finger.</td>
</tr>
<tr>
<td>HIRO II+</td>
<td>Gifu University, Japan</td>
<td>2007 [38]</td>
<td>NA</td>
<td>15 with 3 per finger</td>
<td>Device allows normal movement of the human hand to be mimicked by interacting with a replica robotic counterpart.</td>
</tr>
<tr>
<td>Haptic Knob</td>
<td>National University of Singapore and Imperial College London</td>
<td>2007 [22]</td>
<td>Full hand</td>
<td>2 passive</td>
<td>Used for training the hand to open and close and to manipulate a knob.</td>
</tr>
<tr>
<td>HandCare</td>
<td>National University of Singapore and Imperial College London</td>
<td>2008 [39]</td>
<td>Full Hand</td>
<td>5 passive</td>
<td>Using a clutch system each finger is allowed independent movement with only 1 actuator with force feedback.</td>
</tr>
<tr>
<td>RiceWrist</td>
<td>Rice University, Houston</td>
<td>2008 [84]</td>
<td>Wrist</td>
<td>6 active</td>
<td>Wrist-mounted attachment for the MIME system.</td>
</tr>
<tr>
<td>Gentle/G: Grasp Assistance Robot</td>
<td>University of Reading, UK</td>
<td>2009 [40]</td>
<td>Wrist and full hand</td>
<td>1 active, 2 passive</td>
<td>An addition for the Gentle/G neuro-rehabilitation system to create a more complete exercise routine.</td>
</tr>
<tr>
<td>No-Name</td>
<td>Yeungnam University College of Medicine, Korea</td>
<td>2012 [86]</td>
<td>Full Hand</td>
<td>1 passive</td>
<td>Simple device designed to control and aid in the action of grasping.</td>
</tr>
<tr>
<td>No-Name</td>
<td>Universiti Teknologi Malaysia</td>
<td>2014 [87]</td>
<td>Wrist</td>
<td>1 active</td>
<td>Adjustable device for multiple wrist orientation movement.</td>
</tr>
<tr>
<td>No-Name</td>
<td>Italian Institute of Technology, Genova</td>
<td>2014 [88]</td>
<td>Wrist</td>
<td>3 active</td>
<td>Full range of wrist motion allowed as well as being backdrivable.</td>
</tr>
<tr>
<td>Shape-Changing Robot</td>
<td>Hanyang University</td>
<td>2014 [89]</td>
<td>Hand</td>
<td>1 active</td>
<td>Tactile surface for interactive games and interaction.</td>
</tr>
<tr>
<td>No-Name</td>
<td>Biomedical Neuro-engineering Research Group, Miguel Hernandez University</td>
<td>2015 [90]</td>
<td>Wrist</td>
<td>1 active</td>
<td>Single degree of freedom wrist rehabilitation device with multiple mounting options for simplistic use.</td>
</tr>
</tbody>
</table>
Table 3: List of the current non-commercial hand and wrist exoskeletons. This table is only for the current exoskeletons and is arrayed in chronological order. It features in the first row the devices designation, developer, the year they were first published, relevant reference, what part of the hand or wrist they aid, the number of degrees of freedom and if these are passive or active as well a brief description of their function.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Developer/Creator</th>
<th>Year</th>
<th>Ref</th>
<th>Hand/Wrist Segm.</th>
<th>DOF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(No-Name)</td>
<td>University of Salford</td>
<td>2003</td>
<td>[91]</td>
<td>Wrist + Hand</td>
<td>1 passive</td>
<td>A sensor based unit for the upper body section of an exoskeleton</td>
</tr>
<tr>
<td>HWARD</td>
<td>University of California, USA</td>
<td>2005</td>
<td>[41]</td>
<td>Wrist + Full hand</td>
<td>3 active</td>
<td>Hand and wrist assisting robotic device</td>
</tr>
<tr>
<td>AFX</td>
<td>Northwestern University, Evanston, IL</td>
<td>2007</td>
<td>[92]</td>
<td>1 Finger</td>
<td>3 active</td>
<td>This finger can perform both flexion and extension using 3 independent actuators and measure either force or control</td>
</tr>
<tr>
<td>NEDO</td>
<td>Gifu University, Japan</td>
<td>2007</td>
<td>[24]</td>
<td>Wrist + Full Hand</td>
<td>18</td>
<td>A full-arm exoskeleton which features control for each joint in the arm in addition to the hand</td>
</tr>
<tr>
<td>Cable Orthosis (CO)</td>
<td>Rehabilitation Institute of Chicago</td>
<td>2007</td>
<td>[93]</td>
<td>Whole Hand</td>
<td>2 active</td>
<td>Cable driven portable rehabilitation device</td>
</tr>
<tr>
<td>MR Glove</td>
<td>Washington State University Vancouver</td>
<td>2008</td>
<td>[94]</td>
<td>Whole Hand</td>
<td>10 active</td>
<td>Individual finger joint control for 2 joints per finger used in combination with a CyberGlove</td>
</tr>
<tr>
<td>No-name</td>
<td>Gifu University</td>
<td>2008</td>
<td>[35]</td>
<td>Whole Hand</td>
<td>18 active</td>
<td>Individual joint controlled device with wrist mount</td>
</tr>
<tr>
<td>HANDEXOS</td>
<td>ARTS Lab Scuola Superiore Sant’Anna, Pisa, Italy</td>
<td>2009</td>
<td>[44]</td>
<td>1 Finger</td>
<td>3 passive, 1 active</td>
<td>Device uses a wire-guided system to operate the finger in an extension motion</td>
</tr>
<tr>
<td>PneuGlove</td>
<td>Rehabilitation Institute of Chicago, USA</td>
<td>2009</td>
<td>[47]</td>
<td>Full hand</td>
<td>5 active</td>
<td>Simple set of flexible inflatable cells stitched into various joint positions</td>
</tr>
<tr>
<td>J-Glove</td>
<td>University EIA and CES, USA</td>
<td>2009</td>
<td>[95]</td>
<td>Full Hand</td>
<td>1 active</td>
<td>The thumb moves individually while the fingers move as one</td>
</tr>
<tr>
<td>HEXORR</td>
<td>Centre for Applied Biomechanics and Rehabilitation Research</td>
<td>2010</td>
<td>[87]</td>
<td>Full Hand</td>
<td>2 active</td>
<td>A single-finger active exoskeleton</td>
</tr>
<tr>
<td>HEXOSYS</td>
<td>Italian Institute of Technology, Italy</td>
<td>2010</td>
<td>[53]</td>
<td>1 Finger+1 thumb</td>
<td>4 (1 Active)</td>
<td>Hand Spring Operated Movement Enhancer. The fingers move as one in motion with the thumb</td>
</tr>
<tr>
<td>(No-Name)</td>
<td>Hong Kong Polytechnic University</td>
<td>2010</td>
<td>[92]</td>
<td>Full hand</td>
<td>10 active</td>
<td>Bowden cable driven device for single finger motion</td>
</tr>
<tr>
<td>(No-name)</td>
<td>University of Genova and Italian Institute of Technology</td>
<td>2010</td>
<td>[96]</td>
<td>1 Finger</td>
<td>1 active</td>
<td>Wrist mounted device providing individual finger motion and feedback</td>
</tr>
<tr>
<td>(No-name)</td>
<td>University of Beihang</td>
<td>2011</td>
<td>[97]</td>
<td>1 Finger</td>
<td>3 active</td>
<td>Single finger manipulation device with a wrist mount</td>
</tr>
<tr>
<td>HandsOME</td>
<td>The Catholic University of America</td>
<td>2011</td>
<td>[45]</td>
<td>Full Hand</td>
<td>1 active</td>
<td>A single-finger active exoskeleton</td>
</tr>
<tr>
<td>(No-name)</td>
<td>University of Beihang</td>
<td>2011</td>
<td>[97]</td>
<td>1 Finger</td>
<td>4 active</td>
<td>Hand driven exoskeleton with tendon design and finger recording</td>
</tr>
<tr>
<td>(No-name)</td>
<td>University of Sydney</td>
<td>2012</td>
<td>[98]</td>
<td>Full Hand</td>
<td>4 active</td>
<td>Hand driven exoskeleton with tendon design and finger recording</td>
</tr>
<tr>
<td>IHRG</td>
<td>University Politechnica Bucharest, Romania</td>
<td>2012</td>
<td>[46]</td>
<td>Full Hand</td>
<td>3 per finger+1 for thumb</td>
<td>Intelligent Haptic Robot-Glove provides both feedback and motion aid</td>
</tr>
<tr>
<td>(No-Name)</td>
<td>Rehabilitation Engineering Lab ETH Zurich</td>
<td>2013</td>
<td>[99]</td>
<td>Thumb</td>
<td>1 active + 3 Passive</td>
<td>Active wrist manipulation with force feedback for wrist and fingers</td>
</tr>
<tr>
<td>Soft Pneumatic Glove</td>
<td>Harvard University</td>
<td>2013</td>
<td>[48]</td>
<td>4 fingers</td>
<td>2 active</td>
<td>Soft robotic cells used to close a hand</td>
</tr>
<tr>
<td>PAFEx</td>
<td>Shibaura Institute of Technology</td>
<td>2014</td>
<td>[100]</td>
<td>Full hand</td>
<td>1 active</td>
<td>Pneumatic control system for flexion and extension of the fingers</td>
</tr>
<tr>
<td>PMHand</td>
<td>Heriot-Watt University, Edinburgh</td>
<td>2014</td>
<td>[23]</td>
<td>4 fingers</td>
<td>2 active</td>
<td>Finger manipulation based on tendon design with finger flex recording</td>
</tr>
<tr>
<td>SCRIPT Passive Orthosis</td>
<td>University of Hertfordshire</td>
<td>2014</td>
<td>[101]</td>
<td>Full hand</td>
<td>1 active + 2 passive</td>
<td>Bowden cable driven mounted exoskeleton</td>
</tr>
<tr>
<td>SPRM</td>
<td>Harbin Institute of Technology</td>
<td>2014</td>
<td>[102]</td>
<td>Full hand</td>
<td>2 active</td>
<td>Bowden cable driven device with attachment point on glove allowing for smoother natural motion</td>
</tr>
<tr>
<td>Exo-glove</td>
<td>Seoul National University</td>
<td>2015</td>
<td>[103]</td>
<td>2 Fingers</td>
<td>1 active</td>
<td>Bowden cable driven device with attachment point on glove allowing for smoother natural motion</td>
</tr>
<tr>
<td>HES</td>
<td>University of Florence</td>
<td>2015</td>
<td>[49]</td>
<td>4 Fingers</td>
<td>1 active</td>
<td>Cable driven device designed around single-phalangeal mechanism</td>
</tr>
</tbody>
</table>