

Review

# Robotics in Health Care: Perspectives of Robot-Aided Interventions in Clinical Practice for Rehabilitation of Upper Limbs

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**Abstract:** Robot-aided systems to support the physical rehabilitation of individuals with neurological impairment is one of the fields that has been widely developed in the last few decades. However, the adoption of these systems in clinical practice remains limited. In order to better understanding the causes of this limitation, a systematic review of robot-based systems focused on upper extremity rehabilitation is presented in this paper. A systematic search and review of related articles in the literature were conducted. The chosen works were analyzed according to the type of device, the data analysis capability, the therapy method, the human–robot interaction, the safety strategies, and the focus of treatment. As a conclusion, self-adaptation for personalizing the treatments, safeguarding and enhancing of patient–robot interaction towards training essential factors of movement generation into the same paradigm, or the use of lifelike environments in fully-immersive virtual reality for increasing the assimilation of motor gains could be relevant factors to develop more accepted robot-aided systems in clinical practice.

**Keywords:** robotics; neurological; rehabilitation; motor function; upper extremity

## 1. Introduction

Neurological disorders are the leading cause of disability and the second cause of death worldwide, representing a huge public health problem [1,2]. Common neurological disorders include multiple sclerosis, Parkinson’s disease (PD), stroke, and brain injuries, among others. Each year, approximately 500,000 people experience a stroke in the U.S. and about 1.1 million in Europe [1]. In 2016, roughly 6.1 million individuals had PD around the globe, and statistics pointed out the growth in disease prevalence [3]. Hence, the number of patients who need care from clinicians with expertise in neurological conditions is very elevated. Since populations are growing and aging [4] and the prevalence of major disabling neurological disorders steeply increases with age, healthcare providers will face increasing demand for treatment, rehabilitation, and support services for neurological disorders [5].

The needs of patients with a neurological disorder are usually multi-dimensional, including physical, cognitive, psychological, and medical, and they may be very complex. The typical consequences are related to the impairment of upper, lower, or both limb motions. Traditionally, recovery procedures include extremities mobilization and efforts for the patients. Hence, one of the goals of neurorehabilitation is to regain motor function, which is essential to perform activities of daily living (ADL) autonomously.

In this regard, a variety of robot-based devices has been investigated to support clinicians in neurorehabilitation [6,7]. Consequently, there are several studies available that aim to categorize the contribution of this type of system from global or specific perspectives. The global perspective

studies the effect of robot-based treatments [8–11] or the relationship with the rehabilitation cycle as a holistic approach [12]. The specific perspectives analyze different intervention-related aspects of the systems. Thus, scientific literature shows various classifications according to the type of feedback [13], the focus of treatment [14–17], the mechanical modularity of devices [18], the control strategies [19,20], the intervention techniques [21], or the user interfaces (EEG/EMG based) [22–24].

On that basis, robotic rehabilitation systems (RRS) have been proven to reduce costs, improve treatment quality, and increase therapist productivity. However, the number of robotic rehabilitation systems in clinical use is small. Besides, it is not clear which ones are the more useful strategies for transferring the motor gains to the performance of ADL.

In this paper, a systematic review of robot-based systems focused on the rehabilitation of upper extremity (UE) motor function was conducted. This review presents, from the specific perspective of intervention, an analysis of the literature of the RRS in order to identify the treatment strategies, the analytic capability of performance-based metrics, and the gaps in human–robot (patient– and therapist–robot) interaction channels. The way that the RRS address the patient’s safety and the stimulation factors (individual, task, and environment) involved in motion generation are also analyzed. A better understanding of all the above aspects could help to develop new strategies or promote the most effective ones in order to overcome limitations for the use of robot-aided systems in clinical practice. The remainder of this paper is organized as follows: Section 2 provides an overview of neurological rehabilitation and its fundamentals. Essential factors in movement generation are highlighted. Section 3 describes the advances of robotics in the rehabilitation domain. In Section 4, the different strategies in robot-based training are described. In Section 5, the results of the literature review are summarized. These results are presented under different scopes. In Section 6, perspectives and challenges that must be considered when implementing autonomous systems for the rehabilitation of UE motor function are discussed. To conclude, some final remarks are presented in Section 7.

## 2. Neurological Rehabilitation

Neurological rehabilitation or neurorehabilitation can be defined as a process that aims to reduce the functional limitations of a patient. These limitations come from motor control problems, and the final idea is to optimize the person’s participation in society and sense of well-being [1,25]. Therapeutic interventions in neurological rehabilitation are often oriented toward changing movement or increasing the capacity to move of patients who have functional movement disorders due to motor control problems.

Understanding the nature of movement and motor control is critical in clinical practice. Therefore, it is also important to consider the development of robotic rehabilitation systems (RRS) that have the goal of being adopted in clinical settings. Due to the complex nature of the movement, there are several theories of motor control. These theories try to interpret how the brain controls the movement and which factors are involved in the process. According to Shumway-Cook et al. [26], movement is a result of combining three factors: the individual, the task, and the environment.

Despite the variety of motor control theories, motor learning is the principle behind therapeutic intervention techniques. Motor learning is based on the ability to adapt to the central nervous system (CNS) due to changes in the environment or lesions (neural plasticity). Motor learning is defined as a set of internal processes associated with practice or experience. The idea is to produce changes in motor activity that were relatively permanent. Regarding motor function, therapeutic treatments aim to keep the remaining skills, relearn the lost skills, and learn new skills.

Overall, there is not enough convincing evidence to support that any therapeutic approach is more effective in recovery than any other approach. At present, the evidence suggests that effective rehabilitation treatments require the practice of activities in the most relevant possible environments, rather than undertaking analytical exercises aimed at changing impairments [27]. Essential aspects of training include functional exercises, with high intensity and with the active contribution of the patient

in a motivating environment [21]. Sometimes, this is referred to as task-specific training [28], and it is the most considered approach in developing a robot-based system for neurorehabilitation.

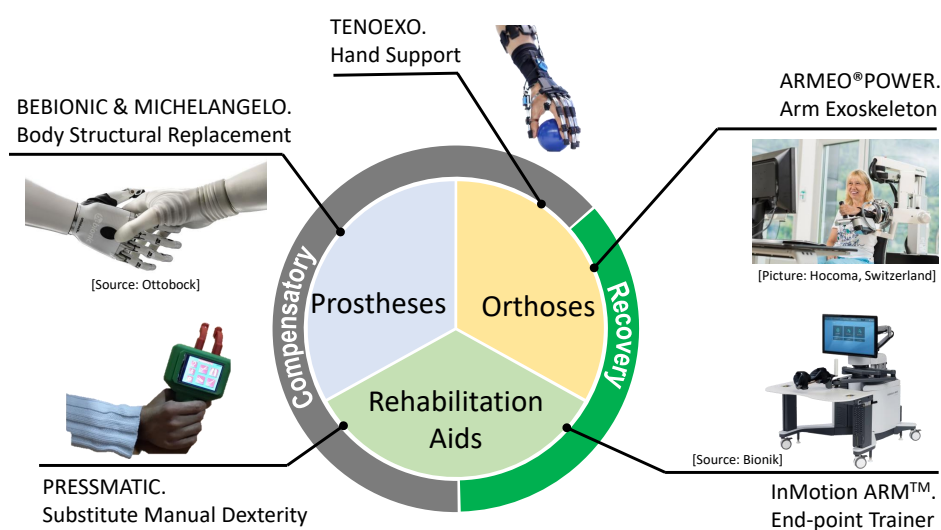
Additionally, focusing on the internal processes of individuals, movement emerges via the cooperative effort of many brain structures and processes [26]. The term “motor” control in itself is somewhat misleading since movement arises from the interaction of multiple processes, including those that are related to perception (integration of sensory information), cognition (organization to achieve intentions), and action (the context of motion performing).

On account of the above, it is not clear whether the current robot-mediated treatments are able to stimulate all the factors (individual, task, and environment) that compose the nature of the movement properly. Hence, a complete rehabilitation framework might consider the processes within the individual to generate proper stimuli, the attributes of the exercise (task), and the context (environment) in which motion is performed. Proper addressing of such factors (correct stimulation of an individual’s capacity to meet the interacting task and environmental demands) could help to increase the effectiveness of robot-based treatments, making the adoption of this technology in clinical settings closer. The following section presents an overview of the robotic application in healthcare in general, and for rehabilitation purposes in particular.

### 3. Robotics in Healthcare: Rehabilitation Domain

Development of robotic technology for healthcare purposes can be sorted into three domains: medical, assistive, and rehabilitation robotics. [29]. The medical robotics domain includes robotic systems that provide support in medical processes of healing (surgery) and care (diagnosis). Likely, medical robots for surgery are the most adopted systems in clinical settings. The domain associated with assistive robotics covers systems that provide assistance in task-related healthcare processes, either to carers or to patients, in care facilities. This assistance involves logistic tasks, surveillance, bed transfers, etc. Finally, the rehabilitation robotics domain covers a range of different forms of post-operative or post-injury care where direct physical interaction with a robot system will either enhance recovery or act as a replacement for lost function.

Figure 1 depicts systems related to the rehabilitation robotics domain, which are numerous and different. They can be organized from into two perspectives: the level of physical contact (morphology) or the role of the device (recovery or compensatory). On one side, the rehabilitation robotics domain according to physical contact can be divided into distinct sub-sectors: prostheses, orthoses, and rehabilitation aids.



**Figure 1.** Rehabilitation robotics domain according to device morphology and expected role it plays.

Prostheses are defined as external devices that partially or totally replace a limb. This definition includes any device placed within the body for structural or functional purposes [30]. In general, this definition includes classical external devices that are intended to substitute amputations. In the case of upper limbs, modern alternatives are robotic hands such as the Bebionic robotic hand or the Michelangelo prostheses hand manufactured by Ottobock [31]. In addition to the amputation replacement, robotic hand technology allows the patient to control with great dexterity some hand functions like grasping. Additionally, the development of internal body devices (artificial organs) clearly applies to this subsection. This type of device that has been inspired by biological systems is referred to as a bio-robotics system [32]. Another example is a neuronal prosthesis that aims to restore the damage from neurological injuries. Neuronal prostheses are brain-machine interfaces that register the neuronal activity of the brain and decode the cellular activity in control signals. Then, these control signals can be used to operate a device [33–35]. The development of implantable neural prosthesis is a proposal to treat conditions such as stroke, traumatic brain injury, or neurodegenerative diseases [36].

Orthoses are the external devices that are used to modify the structural and functional characteristics of the neuromuscular and skeletal system [30]. They do not replace a body part or an organ, but replace or reinforce its functionality. The presence of robotics in the development of orthoses is through the so-called active orthoses or exoskeletons. An active orthosis applies forces to the limb of a person through the actuators of the device. Contrarily, a passive orthosis is defined as a device for which the patient is required to apply force to move. There are some potential applications for active orthoses in healthcare. One of these is a therapeutic and diagnostic device for physiotherapy or an assistive device for physical human capacity augmentation (therapist or patient). An example is the Tenoexo hand exoskeleton [37] to assist patients in grasping tasks during physiotherapy and in ADL such as eating or grooming. Another example is the rehabilitation suite for upper limb developed by Hocoma [38]. Overall, there is a variety of actuation mechanisms for upper limb exoskeletons, such as electric engines [39,40], springs [41], electro-pneumatic actuators [42], hydraulic actuators (4-DOF) [43], or shape memory alloy (SMA) fibers [44,45].

Rehabilitation aids include systems or devices that not are covered within prostheses' and orthoses' definitions; namely, systems with a moderate level of physical contact (neither fixed to the body structure nor wearables). An example of rehabilitation aids is end-point robots that are partially in contact (usually hand-held) with the patient when training, such as the InMotion system [46]. Another example is a non-wearable electromechanical device that the user must grab to employ, such as Pressmatic [47].

On the other side, devices included in the rehabilitation robotics domain could also be categorized from the perspective of the expected role they play. That is, the same robotic device could be used for different purposes in healthcare, depending on the patient's prognosis. An example is a device for giving support to a person with reduced hand functionality, specifically problems when grasping. In the case that such a limitation of grasping functionality is due to the effects of a stroke, the purpose of the device is helping to functional recovery. Contrarily, if the limitation is an effect of a spinal cord injury, the purpose of the device is to compensate for the permanent lack of hand function. Hence, from the perspective of the role they play, the rehabilitation robotics domain could be divided into devices for recovery or compensatory purposes.

In the case of recovery purposes, the role of the robotic device is defined as giving back the capability of the individual to perform a task using mechanisms previously used. This is the case for some exoskeletons (orthoses) and end-point robots (rehabilitation aids). Examples are the ARMEO®POWER and InMotion ARM<sup>TM</sup> systems, respectively. They are used to support extremity mobilization for motor training.

In the case of compensatory purposes, the role of the robotic device can be described as atypical approaches to meet the requirements of the task using alternative mechanisms not typically used. For example, the restoration of fine grasping function can be addressed via a wearable device (orthosis) or an electromechanical device (rehabilitation aid) that the user must hold. In both cases, the robotic

system is compensating the lack of grasping ability by assisting the fingers' movement [48,49] or automatically generating the movement [47], respectively. Compensatory strategies can also reflect modifications to the environment that simplify the demands of the task itself.

On account of the above, this paper focuses on reviewing robotic systems developed for upper limbs with the target role of motor function recovery. This field includes end-point robots and exoskeletons for supporting the clinicians in therapeutic interventions. For recovery, different modalities of physical human–robot interaction can be used in motor training [21]. The following section presents an overview of the interaction methods between the patient and the robotic system in robot-mediated training of upper extremities.

#### 4. Robot-Aided Modalities for Upper Limb Training

Most of the robotic devices oriented toward clinical practice for UE recovery offer the possibility of choosing among different training modalities. Three main blocks for physical human–robot interaction (pHRI) in robot-aided interventions have been defined: assistive, active, and passive. These terms relate to conventional therapy modes used in clinical practice and refer to the subject's status during the interaction. In the assistive block, the voluntary activity of the patient is required throughout the movement in therapy at all times, while the robot can provide help to complete the task, either through weight or forces. In this case, both subject and robot work together in the movement performance. In the active block, the robot is used as a device to measure movement. The performance arises only from the patient's contribution. Finally, in the passive block, the robot executes all the work independently of the patient's response.

In the assistive block, two modalities can be defined: the basic “assistive” and the “gravity compensation” methods. In the basic assistive method, the robot can be helping constantly or not. This help will depend on the strategy of the therapy. The tremor suppression system is an example. The gravity compensation method only cancels the gravity force, so that the patient is focused on the purpose of the movement. In this case, the forces are oriented towards weight support when the movement is against gravity.

In the active block, three modalities can be defined: the basic “active”, the “active-assisted”, and the “resistive” method. The basic active method only measures the evolution of the movement. The system never provides power to the patient's limb. In the active-assisted method, assistance to complete the task is provided only when the patient is not capable of performing actively. It is like triggered assistance. The robot observes continuous performance. If the task is not completed, the robot intervenes, taking full control. In this stage, the subject experiences a passive movement of the limb. In the resistance method, the robot provides opposing force to the movement. The device opposes movements through an elastic or damped force that attempts to return to the initial position.

In the passive block, also three modalities can be defined: the basic “passive”, the “bilateral”, and the “guided” method. In the basic passive method, the system takes care of all movements independently of the patient's activity. The bilateral method (also called passive-mirrored) is applied to bimanual robots when the unimpaired limb is used as an input to control the passive movement of the affected side. Finally, in the guided method, the robot aims to lead the subject when he/she deviates from the predefined path. In this method, tunnels are usually used. These devices produce haptic feedback only if the error exceeds a threshold. This error indicator device is related to corrective strategies.

In summary, eight modalities for physical human–robot interaction in rehabilitation of upper limb motor function have been defined. These modalities are: assistive (AS), gravity compensation (GC), active (A), active-assisted (AA), resistive (R), passive (P), bilateral (B), and guided (G). This classification is sufficient to describe the type of pHRI of all the systems that are evaluated in this article. However, a more specific categorization of methods of robot-mediated therapy was presented in a recent literature review [21]. These abbreviations will help to simplify and understand better the table shown in the next section. Besides, it is important to consider that the different robotics systems can be focused on



one or more modalities and even have a combination of these modalities. This feature depends on the purpose of the system, the kind of therapy, its morphology, etc.

## 5. Literature Review Summary

Robots have emerged as a useful tool to enhance the recovery process of motor function in neurological treatments. Robot-based systems participate actively in training and help the therapist to perform a better rehabilitation process. However, it is not clear to what extent robotic systems provide this help according to the rehabilitation principles. The most important is to improve the quality of help provided and to make the adoption of this technology in clinical settings easier. Therefore, the technical barriers and clinical limitations to be overcome must be identified.

In the following section, this review will highlight the particular aspects of the robot-aided approaches focused on recovering the upper extremity motor function with the assistance of a robotic system.

### 5.1. Materials and Methods

**Search methods:** The authors undertook a literature search in February 2019 for robot-assisted systems for dealing with motor function problems of upper limbs caused by neurological deficits, using as keywords: robot, neurological, rehabilitation, motor, function, upper, limb, extremity, arm, hand, neurorehabilitation, intervention, assisted therapy, treatment design, and various combinations. The databases were Brain, Science Direct, PubMed/Medline, and IEEE. Only papers written in English were considered, and the search was extended to the whole database.

Studies were included when: (1) systems for upper limb training (uni- and bilateral) were used; (2) systems were based on end-point or exoskeleton devices (commercially available or not); (3) the clinical intervention with real patients was conducted; and (4) the effects of robot-aided therapy on health outcomes were formally analyzed. Additionally, in the case of systems for which two versions of the same device were available, the newest version only was included in this study.

**Limitations:** This review is not without its limitations. Our study was limited to robotic rehabilitation systems for upper extremities in general, and motor function treatment in particular. Formal appraisal of the literature using quality-scoring tools was not carried out; instead, more practical aspects of the robot-based systems in neurological rehabilitation have been considered. This was intended to enhance the usability of the report for clinicians.

### 5.2. Robot-Aided Rehabilitation of Upper Limb Motor Function

Table 1 summarizes the collected information from several studies of 28 robot-aided systems for the motor training of upper extremities. The selected studies were organized according to the system used for the intervention. All of the systems selected have been used in clinical trials with various patients with motor deficits derived from different neurological disorders. The effect of robot-mediated treatment on UE motor function was explored through traditional outcome measures, such as the Action Research Arm Test (ARAT), Fugl-Meyer Assessment (FMA), etc. A comprehensive reading was done to identify how the robotic systems support the clinician during therapy in terms of data analysis capability, level of patient- and therapist-robot interaction, safety strategies, and options for treatment personalization.

According to the classification of the rehabilitation robotics domain presented in the previous Section 3, all of the systems included in Table 1 aimed to recover motor functionality. Systems are listed by end-point and exoskeletons. Furthermore, some information about the actuators and degrees of freedom (DoF) of the devices are included.

**Table 1.** Robot-aided systems for upper limb neurorehabilitation.

<i>System</i>	<i>Market Available</i> †	<i>Type of Device</i>	<i>Data Analysis Capability</i>	<i>Methods for Therapy Adaptability</i>	<i>Focus of Rehabilitation</i>	<i>Type of pHRI</i> ‡	<i>Safety Strategy</i>	<i>Channel For Presenting Tasks (Environment)</i>	<i>User Feedback</i>
ACT-3D (2007) [50–52]	✗	End-point; 2 DoF; electrical engines	Low	Variation (progressive) of abduction loading therapy	Shoulder; elbow	A	Software limits in force	2D-VR (flat screen) showing an arm avatar	Haptic; audio
ARM-GUIDE (1999) [53–55]	✗	End-point; 3 DoF; electrical engines	High (tone, spasticity, incoordination)	Modification of targets for reaching task	Shoulder; elbow	P; AA; R	Back stops; software limits in force	2D-VR (flat screen) showing the target point	Haptic (off-axis force generation)
BRACCIO DI FERRO (2006) [56,57]	✗	End-point; 2 DoF; electrical engines	High (performance evaluator)	Adaptive controller to set the force loading automatically based on user's performance	Shoulder; elbow	AA; R; GC	Back stops; emergency push button	2D-VR (flat screen) displaying a path to follow	Visual; haptic (attractive force field)
GENTLE/A (2012) [58,59]	✗	End-point; 3 DoF; magnetic mechanism	High (lead-lag performance)	Self-adaptation of duration to execute movements according to the user's performance; definition of exercise path	Shoulder; elbow	P; AA; A; G	Software limits in force	3D-VR (flat screen) showing several ping-pong balls in a 3D configuration	Visual; haptic; audio
INMOTION-ARM™ (2010) [60,61]	✓	End-point; 6 DoF; electrical engines	High (software specific)	Adaptive therapy protocols; selection of exercise (games); progress measurement to determine medical necessity;	Shoulder; elbow	P; AA; R; GC	Backdrivable hardware; software limits in force	2D-VR (flat screen) with a variety of games/task	Visual; haptic; audio
IPAM MkII (2011) [62,63]	✗	End-point; 6 DoF; pneumatic engines	High (specific software)	Automatic generation of exercises (automated tasks)	Shoulder; elbow	P; R; A	Compliance control; emergency push button; software limits in force	2D-VR (flat screen) 4 scenarios: beach, gym, city, or countryside	Visual; audio; haptic
MEMOS (2006) [64–66]	✗	End-point; 2 DoF; electrical engines	Moderate	Variable gain of force loading	Shoulder; elbow	P; R; A	Emergency push button	2D-VR (flat screen) displaying the target points	Visual; audio; haptic
MIME (2006) [67,68]	✗	End-point; 6 DoF; electrical engines	Low	Variety of therapeutic modalities	Shoulder; elbow	P; AA; R; B	Back stops; emergency push button	Physical (real physical objects) promoting 3D reaching tasks	Visual (direct visualization of targets); haptic

Table 1. Cont.

<i>System</i>	<i>Market Available †</i>	<i>Type of Device</i>	<i>Data Analysis Capability</i>	<i>Methods for Therapy Adaptability</i>	<i>Focus of Rehabilitation</i>	<i>Type of pHRI ‡</i>	<i>Safety Strategy</i>	<i>Channel For Presenting Tasks (Environment)</i>	<i>User Feedback</i>
NEREBOT (2007) [69–72]	✗	End-point; 3 DoF; cable driven	Moderate	Exercise customization (via-points and setting of robot parameters)	Shoulder; elbow; forearm	P	Backdrivable hardware; back stops (magnetic attachment)	No user interface (hands-on movements)	Visual (direct visualization of movements)
REHAROB v2 (2017) [73]	✗	End-point; 7 DoF; electrical engines	Moderate	Exercise programming available via a graphical user interface (includes a program simulation interface)	Shoulder; elbow; forearm	P	Emergency push button; software limits in ROM	No user interface (hands-on movements)	Visual; haptic
AMADEO® (2012) [74–76]	✓	End-point; 5 DoF; electrical engines	High	Adjustable therapy and assessment modes	Hand (fingers)	P; AA; A	Software limits in force, speed and ROM; back stops (magnetic attachment)	2D-VR (flat screen) with serious gaming in one- and two-dimensional movements	Visual (video games); haptic
BI-MANU-TRACK (2003) [77–79]	✗	End-point; 2 DoF; electrical engines	Low	Selection of (two) operation modes	Forearm; wrist	A; B	Emergency push button; software limits in force (mechanical breaks)	Digital display showing the number of cycles	Visual (direct visualization of movements)
HWARD (2005) [80,81]	✗	End-point; 3 DoF; pneumatic engines	Moderate	Selection of standardized training protocols	Wrist; hand	P; AA; R	Backdrivable hardware; emergency push button; software limits of force; software shutdown	2D-VR (flat screen)	Visual; audio; haptic
ReoGo™-J (2008) [82]	✓	End-point; 3 DoF; electrical engines	High	Library with several exercises and games	Shoulder; elbow; wrist; hand	P; A; G	N/A	2D-VR (flat screen) presenting several real scenarios	Visual; audio; haptic
DIEGO® (2017) [83–85]	✓	End-point; 4 DoF; cable driven	High	Selection of therapy games. Intelligent gravity compensation (IGC); cooperative sequences of movement	Shoulder; elbow	P; B; AS; A; GC	Backdrivable hardware	3D-VR (fully immersive) with interactive games	Visual; audio; haptic (training with objects)
ADLER (2006) [86–88]	✗	End-point; 6 DoF; electrical engines	High (specific software)	Selection of training modes.; movement programming available via pre-defined trajectories	Forearm; Wrist	A; AA; R	Backdrivable hardware; emergency push button; software limits in force	2D-VR (Flat screen) displaying the target points	Visual; haptic



Table 1. Cont.

<i>System</i>	<i>Market Available</i> †	<i>Type of Device</i>	<i>Data Analysis Capability</i>	<i>Methods for Therapy Adaptability</i>	<i>Focus of Rehabilitation</i>	<i>Type of pHRI</i> ‡	<i>Safety Strategy</i>	<i>Channel For Presenting Tasks (Environment)</i>	<i>User Feedback</i>
L-EXOS (2007) [89–91]	✗	Exoskeleton; 5 DoF; cable driven	Low	Selection of different trajectories in the same virtual environment	Shoulder; elbow	A; AA; GC	Compliance control; back stops	3D-VR (flat screen)	Visual (physical objects)
MYOPRO (2006) [92–94]	✓	Exoskeleton; 2 DoF; electrical engines	Low	Distributed control mode for training different muscles	Elbow	AA	Software limits in forces	Physical (quotidian environments due to its portability)	Visual; haptic (physical objects); EMG
WREX (2004) [95,96]	✓	Exoskeleton; 4 DoF; elastic bands	Low	Variation (manual) of force loadings	Shoulder; elbow	AA; GC	Compliance control	Physical (quotidian environments due to its portability)	Visual; haptic (physical objects); EMG
ARMEO®SPRING (2006) [97–99]	✓	Exoskeleton; 5 DoF; electrical engines	High	Selection of therapy games; self-directed therapy option	Shoulder; elbow; forearm; wrist; hand	P; GC	Software limits in forces	3D-VR (flat screen)	Visual; audio; haptic
Mentor Pro™ (2004) [100–102]	✓	Exoskeleton; 1 DoF; pneumatic engines	Low	Selection of difficult/comfort levels; selection of (three) control modes	Wrist; hand; fingers	A	Compliance control; back stops	Physical (for increasing ROM in a real scenario)	Haptic, EMG
HEXORR (2010) [103–105]	✗	Exoskeleton; 2 DoF; electrical engines	Low	Selection of multiple exercises	Hand	P; AA; A; GC	Software limits in velocities; back stops	2D-VR (flat screen) with basic graphics	Haptic
RUTGERS-MASTER-II (2002) [106–108]	✗	Exoskeleton; 20DoF; pneumatic engines	Moderate	Selection of exercises and setting of parameters	Hand (fingers)	P; AA; R	Compliance control; software limits in forces; back stops	3D-VR (flat screen) training with games	Audio; visual; haptic
SUPINATOR-EXTENDER (2011) [109]	✗	Exoskeleton; 2 DoF; pneumatic engines	Low	N/A	Forearm; wrist	AA	Compliance control; emergency push button	N/A	Haptic
WOTAS (2005) [110]	✗	Exoskeleton; 3 DoF; Electrical engines	Low	Selection of assistance modes	Elbow; forearm; wrist	AS	Software limits in forces; back stops	Physical (keeping a target in a real scenario)	Haptic

Table 1. Cont.

<i>System</i>	<i>Market Available</i> <sup>†</sup>	<i>Type of Device</i>	<i>Data Analysis Capability</i>	<i>Methods for Therapy Adaptability</i>	<i>Focus of Rehabilitation</i>	<i>Type of pHRI</i> <sup>‡</sup>	<i>Safety Strategy</i>	<i>Channel For Presenting Tasks (Environment)</i>	<i>User Feedback</i>
ARMEO®POWER (2008) [111–113]	✓	Exoskeleton; 6 DoF; electrical engines	High	Selection of several VR therapy tasks	Shoulder; elbow; forearm; wrist; hand	A; P; AA; R; GC	Backdrivable hardware; software limits in forces and loads	3D-VR (flat screen) training with games	Audio; visual; haptic
GENTLE/G (2007) [114,115]	✗	Exoskeleton; 9 DoF; cable driven	Moderate	Distributed control for training arm and/or hand; grasp therapy option	Shoulder; elbow; hand	P; AA; A; G	Compliance control; software limits in forces	3D-VR (flat screen) showing tasks in real environments	Audio; visual; haptic; scoreboard; rewards
RUPERT (2008) [116,117]	✗	Exoskeleton; 5 DoF; pneumatic engines	Low	Progressively challenging tasks	Shoulder; elbow; forearm; wrist	P; AA; A	Backdrivable hardware; compliance control	3D-VR (flat screen) showing the target point	Visual

<sup>†</sup> Commercially available (✓ = Yes; ✗ = No); <sup>‡</sup> abbreviations for pHRI: assistive (AS), gravity compensation (GC), active (A), active-assisted (AA), resistive (R), passive (P), bilateral (B), and guided (G).

Note that the newest version of some systems is listed in the table. That is the case for systems, such as GENTLE/A (GENTLE/S (2003) [118,119]), InMotion ARM<sup>TM</sup> (MIT-MANUS (1998) [120,121]), IPAM MkII (IPAM (2007) [122]), REHAROB V2 (REHAROB (2005) [123,124]), ARMEO<sup>®</sup>SPRING (T-WREX (2004) [125,126]), ARMEO<sup>®</sup>POWER (ARMin (2006) [127–129]), and ReoGo<sup>TM</sup>-J (ReoGo<sup>TM</sup> (2008) [130]).

### 5.2.1. Data Analysis Capability

One of the most significant advantages of using robot-based devices is the data acquisition capability, which is objective, reliable, and automatically stored. In agreement with that, the reviewed systems offered the possibility of analyzing the user's performance based on the metrics gathered by the robotic devices themselves. This data analysis can be performed during the therapy session or when it is finished (post analysis). In other words, it can be in an online or offline mode, respectively. In this way, we identify the data analysis capability of the robotic systems themselves rather than the post analysis using stored data. In this regard, three levels of data analysis capability of robotic systems have been defined: low, moderate, and high. Systems with a low level of analysis capability are those that only stored the patient scores and sensors measurements. In this category, we have included end-point systems such as ACT-3D, MIME, and BI-MANU-TRACK and exoskeleton systems such as L-EXOS, MYOPRO, WREX, Mentor Pro<sup>TM</sup>, HEXORR, SUPINATOR-EXTENDER, WOTAS, and RUPERT. A moderate level of analysis capability is denoted for those systems that provided the therapist with a rapid report about the user's performance. Thus, it we obtain an overview of the patient's evolution. This report is generated in online mode, and it is based on the outcome comparison between the current therapy session and the previous one. End-point systems such as MEMOS, NEREBOT, REHAROB, or HWARD and exoskeleton systems such as RUTGERS MASTER or GENTLE/G are included in this category. Finally, a high level of analysis capability is defined for those systems that can provide extended metrics. Besides, they can provide additional information by online analysis of the raw data of the sensors. A total of ten systems (eight end-point: ARM-GUIDE, BRACCIO DI FERRO, GENTLE/A, InMotion ARM<sup>TM</sup>, AMADEO<sup>®</sup>, ReoGo<sup>TM</sup>, DIEGO<sup>®</sup>, and ADLER; and two exoskeletons: ARMEO<sup>®</sup>SPRING and ARMEO<sup>®</sup>POWER) were classified as high level.

The storage and sharing of big data from patients, and in an efficient way, comprise two of the most important issues for the ongoing digital healthcare era. In this way, the properties of robotic rehabilitation systems could contribute to enhancing the management of a large amount of information. This fact could make the integration of robotic technology into a digital healthcare framework easier.

### 5.2.2. Adaptability of Treatments

The systems included in this review make available to the therapist different methods for adapting the treatment to the patient necessities. A wide variety of options for therapy customization are available for therapists. According to this adaptability, two categories of systems were identified. These systems are manually adapted and self-adaptive. The first category denotes for those systems that offer the clinician options to customize the therapy. For personalizing, the options are the selection among operation modes, exercises, or games (InMotion ARM<sup>TM</sup>, MIME, AMADEO<sup>®</sup>, BI-MANU TRACK, HWARD, ReoGo<sup>TM</sup>, ADLER, L-EXOS, HEXORR, RUTGERS MASTER, WOTAS, ARMEO<sup>®</sup>POWER, GENTLE/G, MYOPRO, Mentor Pro<sup>TM</sup>), tuning of robot parameters to modify the workspace (ARM-GUIDE), or the training intensity (ACT-3D, MEMOS, NEREBOT, RUPERT, WREX), and even creating new exercises (REHAROB). The second category denotes for those systems that automatically set the therapy parameters or the tasks, based on the user's performance. This one requires more advanced control and data analysis capabilities. This approach is covered by systems such as BRACCIO DI FERRO to fit the loading force, GENTLE/A to modify the task duration, DIEGO<sup>®</sup> and ARMEO<sup>®</sup>SPRING to adapt the support level, and iPAM to vary the movement range.

A well-known feature of robotic systems, in general, is the capability to perform repetitive and controlled movements, keeping a high level of accuracy. Such a feature is also beneficial in the

particular case of robot-aided systems for rehabilitation. Nevertheless, control strategies regarding the automatic modeling of the patient–robot interaction or the autonomy of therapy have not been fully explored. Note that in the manually-adapted systems, the customization depends on the clinician criteria, and thereby, an autonomous and unsupervised therapy would be not possible. In this regard, cutting-edge systems are considering new strategies for allowing cooperative treatments (DIEGO<sup>®</sup>) or even self-directed therapies (ARMEO<sup>®</sup>SPRING). Noteworthy as well is the RECUPERA system [131], a lightweight dual-arm exoskeleton with a high level of modularity (the system can be used as a wheel chair-mounted system or as a full-body system) and multi-therapy options. This system is promising for enabling mobile support, as well as for self-training during a hospital stay or at home. Overall, it can be seen that a trend towards more autonomous robot-based recovery procedures is arising.

### 5.2.3. Intervention and Safety Strategies

Therapists use a variety of techniques to help the upper extremity to gain better motor functionality. Some of these techniques involve physical contact between the therapist's hands and the patient's body, and they are referred to as hands-on treatments [132]. These types of treatments primarily use manual techniques for limb mobilization. The idea is to increase the range of motion (ROM), facilitating movement, and improving function. Therefore, this type of therapy is such that robot-aided systems aim to support or complement it. Besides, the close physical interplay between the patient and the robotic device require that safety must be granted.

On one side, the interaction in robot-aided interventions involves partial or full contact between the patient's extremity and the links of the robotic device. Usually, this kind of interaction is denoted as physical human–robot interaction (pHRI). As described in the previous Section 4, we considered eight types of pHRI strategies in robot-aided interventions. In Table 1, the abbreviations of the pHRI strategy that the selected robotic systems can implement are summarized. Note that the same robotic system could be able to perform various pHRI strategies.

It can be seen that seven systems (ACT-3D, NEREBOT, REHAROB, MYOPRO, Mentor Pro<sup>TM</sup>, SUPINATOR-EXTENDER, and WOTAS) used a single pHRI strategy. On the opposite side, only two systems were able to perform up to five pHRI strategies. This is the case of both the DIEGO<sup>®</sup> (passive, bilateral, assisted, active, gravity compensation) and ARMEO<sup>®</sup>POWER systems (active, passive, active-assisted, resistive, and gravity compensation). The remaining systems implemented a number of pHRI strategies between two and four, both inclusive.

On the other side, the inherent physical contact in the mobilization of the patient's extremities implies that the robotic rehabilitation systems must implement safety strategies to ensure patient well-being. In this regard, unlike with human beings, the interaction with a robot could provide a safest, predictive, and reliable environment. This is possible because such an interaction can be controlled and progressively modified.

Hence, the patient's safety may be ensured via different strategies, primarily hardware or software related. In the mechanical part, there are three different strategies. The easiest strategy to implement is the emergency stop button (emergency push button). This type of system helps to block the robotic system. Usually, the therapist is in charge of the activation of this button in case the robot fails or the rehabilitation task is out of control. There are some cases like the robotic systems MIME or HWARD, which adjust the intensity of the control or the task when the button is pushed. This kind of strategy is typical of end-point robots (BRACCIO DI FERRO, IPAM MKII, MEMOS, MIME, REHAROB, BI-MANU-TRACK, HWARD, or ADLER). The second system is back-stops. These systems are based on the mechanical limitation of the range of motion of the robotic system to avoid damage to the patient. A curious example is the AMADEO<sup>®</sup> or NEREBOT system, which have a magnetic attachment system. This strategy allows the patient to be released quickly from the end-effector robot if critical forces are reached. A mechanical limitation is one of the most common strategies, and we have included end-point systems such as ARM GUIDE, MIME, BRACCIO DI FERRO, NEREBOT, or AMADEO<sup>®</sup> and exoskeleton systems such as L-EXOS, Mentor Pro<sup>TM</sup>, HEXORR, RUTGERS MASTER, or WOTAS.

The third system is called mechanical compliance. This system is related to the form of mechanical design. In this case, the implementation of the robot is associated with soft and light characteristics, providing impedance movements. Patient safety is assured because the robot will absorb excessive movements of the patient and return to the task. Systems that use backdrivable actuators are included in this group. Because it is more difficult to implement, only the systems InMotion ARM<sup>TM</sup>, NEREBOT, HWARD, DIEGO<sup>®</sup>, ADLER, ARMEO<sup>®</sup>POWER, and RUPERT had this strategy.

In the software part, there are also three different strategies. The easiest strategy to implement is the shutdown button. This type of system deactivates the robotic system. These systems are used in extreme cases because the therapist has not pressed the emergency button in time for the therapist's slip or malfunction of the robot. We only have included the HWARD system in this category. The second system is the software limits. These systems are based on limiting system properties to avoid damage to the patient. The most typical parameters that are handled are the forces, speeds, or loads. An unusual example is the BI-MANU-TRACK system, which controls the maximum force by activating mechanical brakes. This is the most used strategy via software for both types of robotics systems. We have included end-point systems such as ACT-3D, ARM GUIDE, GENTLE/A, InMotion ARM<sup>TM</sup>, IPAM MKII, REHAROB, AMADEO<sup>®</sup>, HWARD, or ADLER and exoskeleton systems such as MYOPRO, ARMEO<sup>®</sup>SPRING, HEXORR, RUTGERS MASTER, WOTAS, ARMEO<sup>®</sup>POWER, or GENTLE/G. The third system is the control compliance. This system is related to the way of controlling the robotic system. In this case, the implementation of the controller is associated with the dynamics of the movements, allowing smoother movements for the patient (without sudden movements). This kind of controller is easier to implement in a system with pneumatic engines or a cable drive, and also, this kind of strategy is typical of exoskeleton robots (L-EXOS, WREX, Mentor Pro<sup>TM</sup>, RUTGERS MASTER, SUPINATOR-EXTENDER, GENTLE/G, RUPERT).

#### 5.2.4. Focus of Treatment

The human arm is a complex chain of bones and muscles. It can be divided into the upper arm, which extends from the shoulder to the elbow, the forearm, which extends from the elbow to the hand, and the hand. The arm model can be simplified into a model of two links (upper arm and forearm) or seven DoF. In this definition, the fingers' joints are not considered.

It can be seen that regardless of the type of robot, a common approach is focused on the rehabilitation of the shoulder and elbow joints. Forty percent of the reviewed systems (primarily end-point systems) covered the training of such joints. However, 27% of systems extended its primary use for shoulder and elbow training to cover other arm parts such as forearm, wrist, or hand. Besides, another portion is focused on specific movements of forearm and wrist (BI-MANU-TRACK, SUPINATOR-EXTENDER, WOTAS, ADLER), only elbow (MYOPRO), or hand and fingers. It must be noted that regarding hand training, it can be with (AMADEO<sup>®</sup>, RUTGERS MASTER) or without (HWARD, Mentor Pro<sup>TM</sup>, HEXORR) fingers' dissociation.

Different advantages and drawbacks could arise depending on the morphology of the robotic device. For example, due to the condition of exoskeletons as a wearable device, it allows for aligning the joints of the patient with the exoskeletons'. In this case, the therapist has better control of the patient's movements. However, one of the main drawbacks of exoskeleton-type systems is the risk of joint misalignment in arm mobilization. Modern developments are promising to obtain exoskeletons with a natural and wide range of motions [133].

In the case of end-point robots, the mobilization is performed with the user's arm partially attached to the device. This feature implies a good trajectory control for the joints attached to the robotic device. However, there is a loss of control on the non-attached joints. Hence, compensatory movements can be performed, reducing the effectiveness of the treatment. The use of external systems for monitoring the user's movements could help to detect these abnormal actions.

### 5.2.5. Interaction Channel and Feedback for the User

Regarding the interaction channel, virtual reality (VR) is used for a vast portion (67%) of the systems included in this paper. Within systems that use VR, 55% of systems (ACT-3D, ARM-GUIDE, BRACCIO DI FERRO, InMotion ARM<sup>TM</sup>, IPAM, MEMOS, AMADEO<sup>®</sup>, HWARD, ReoGo<sup>TM</sup>, ADLER, HEXORR) implement a two-dimensional environment, and 45% of systems (GENTLE/A, DIEGO<sup>®</sup>, L-EXOS, ARMEO<sup>®</sup>SPRING, RUTGERS MASTERS, ARMEO<sup>®</sup>POWER, GENTLE/G, RUPERT) implement a three-dimensional environment. All these systems (except for DIEGO<sup>®</sup>) display their environments on a flat screen. It must be highlighted that the DIEGO<sup>®</sup> system uses a VR headset for running the game-like interface. This VR headset allows a fully-immersive experience for the user.

Opposite, the remaining systems (23%) have not implemented a graphical interface. This is the case of the NEREBOT and REHAROB systems, for which it is the therapist who must interact with the patient in the traditional way, but having support in limb mobilization. Besides, other systems were identified (MIME, MYOPRO, WREX, Mentor Pro<sup>TM</sup>, WOTAS) with a lack of graphical interface to interact, but they promoted training with real (physical) objects. This approach is focused on optimizing the assimilation of motor gains. In the exercise, the patient is in a scenario closer to a daily living one. Note that portability seems essential for such an approach considering the predominance of exoskeleton-type devices.

It can be seen that VR technology serves as a means of encouraging the patient and promoting task development in a friendly environment. Besides, gaming technology is useful for modeling more attractive (environment other than a hospital room) or challenging scenarios (with digital games) to perform the tasks.

Regarding the feedback given to the patient, it can be appreciated that the most used ways for stimulating the patient's senses are by visual and audio feedback. This contactless stimulation could be empowered with the use of virtual reality. However, tactile feedback is also vital in motor function recovery. Therefore, another common source of stimuli is haptic feedback. The reviewed systems provide direct haptic stimuli via control techniques (software) or in an indirect manner via strategies that imply the manipulation of physical objects.

## 6. Framework for Robot-Aided Systems in Clinical Practice

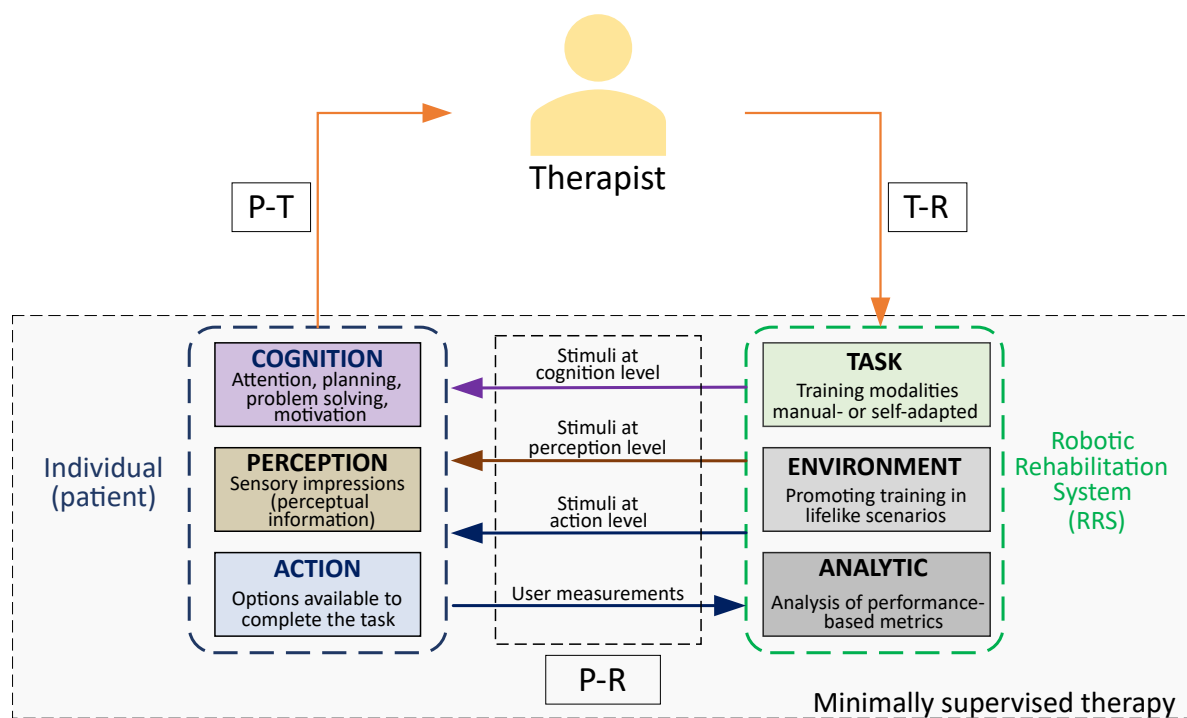
The research review carried out in this article shows that in spite of the great progress achieved, robotic rehabilitation systems (RRS) will confront important challenges in order to be successfully integrated into routine practice. Cost reduction is one of the most known concerns about the use of robot-aided systems. Nevertheless, at present, health providers are realizing that robotic technology could provide benefits in terms of shorter in-patient treatments, enhanced data administration, improved decision-making, and easier management of electronic health record (EHR). Thus, a clear example is the increasing use of surgical robots in hospitals to perform minimally-invasive procedures. These systems based on the accuracy of robot movements, image processing algorithms, and cognitive systems are able to execute autonomously simple surgical tasks. Thereby, automation of procedures seems to be a key point towards reducing expenses and enhancing traditional rehabilitation treatments.

This review has shown that the development of more autonomous systems is a rising trend in the field of rehabilitation robotics for the upper extremity. The increasing of automation and better exploiting of data analysis capabilities are aligned with the current digital health concepts. Therefore, it is expected to be progressively accepted in healthcare processes within the ongoing e-health framework. However, it is necessary to highlight the main technical requirements that should be addressed in the near future, in order to facilitate the adoption of robot-aided systems in healthcare.

In that sense, Figure 2 presents a framework for robot-aided rehabilitation, taking into account aspects such as the human–robot interactions (patient-robot and therapist-robot), proper exercise elaboration (task and environment) in order to optimize motor gains, and data analysis capabilities to increase the treatment autonomy. The following section aims to describe what, in the opinion of authors, are the needs that robotic rehabilitation systems must address towards increasing their



usability and autonomy in clinical practice. Strategies for improving the human–robot interaction, boosting and assimilation of motor gains, and obtaining more autonomous devices are presented.



**Figure 2.** Framework for robot-aided therapy in clinical practice. T, therapist; R, robot; P, patient.

### 6.1. Efficient Human–Robot Interactions

In the above-presented robot-aided framework, the three participants of the process can be appreciated: therapist, patient, and robotic device. Thereby, human–robot interaction can be considered from two perspectives: between therapist and robot (T-R) and between patient and robot (P-R). Enabling proper channels for such interactions is essential for increasing the effectiveness of therapy.

From the point of view of the patient, proper stimulation of factors such as cognition, perception, and action is quite important to promote movement recovery. These factors comprise the patient's capacity to meet interacting tasks and environmental demands [26]. Therefore, it is strongly related to the patient's autonomy in ADL performance.

Firstly, at the cognitive level, current robot-aided treatments include methods (usually video games) for capturing the user's attention and promoting his/her motivation during therapy. The game-based methods offer also the possibility of training the planning and problem-solving capabilities of individuals by means of reaching goals in challenging scenarios. Indirectly, stimulus at this level is likely the most developed strategy of the RRS.

Secondly, at the perception level, the most commonly-used methods focus on stimulating the senses of vision, audio, and touch. Regarding visual and audio stimulus, digital games are also useful tools. However, the lack of tangible feedback is a clear limitation for gaming technology. Here, the use of haptic feedback covers such a limitation. In this way, the optimal solution in order to generate more effective stimulation at the perception level could combine the digital games with haptic feedback.

Finally, the action level is related to the context within the movement performed. Considering the degrees of freedom of the human arm, there are multiple ways a movement can be carried out. This is similar to finding the inverse kinematic solution for a robotic arm. This problem of choosing among equivalent solutions and then coordinating the many muscles and joints involved in a movement has been referred to as the “degrees of freedom problem” [26,134]. Most of the robot-based systems focus on repetition of tasks, but it is also relevant to provide the patient with several options of accomplishing a particular action. In the case of approaches based on end-point devices, the freedom to choose a

“solution” to perform a particular action is greater than in the case of exoskeleton-based approaches. Consequently, the control of patients’ movements is reduced in systems based on end-point devices, and compensatory movements can be used by the patient. Balancing of the benefits and drawbacks of systems based on end-point and exoskeleton devices is a big challenge. In the case of end-point systems, one solution could be the use of external systems to monitor the patient during the execution of tasks and detecting compensatory movements. Thus, compensatory movements are not prevented, but detected, leaving the interpretation of this being clinically meaningful to the therapist. Regarding exoskeleton-based systems, the high number of DoF that are necessary to get closer to the human arm motion is a big issue to solve. Hence, more redundant devices are required for allowing the user as many as possible joint configurations corresponding with reaching the same target position, which is fundamental in a rehabilitation context.

From the point of view of the interaction with the clinician, the common understanding in the robotics community is that the goal of robotic rehabilitation devices should be to assist therapists in performing the types of activities and exercises they believe give their patients the best chance of functional recovery. This fact implies that the robotic devices must implement proper methods for enabling the therapist to customize the intervention to the patient’s needs. As presented in Table 1, robot-based systems offer options such as the selection of exercises (game-based or not), the selection of operation modes (to perform different physical interactions with the patient), and also hands-on collaborative treatment (using physical objects). Additionally, tuning of robot parameters (to regulate the number of repetitions, the intensity, the workspace, the assistive or resistive loading, among others) and selection of training options are commonly available for the therapist via graphical user interfaces.

However, beyond the customization of interventions via a GUI, future developments may stress implementing friendly strategies for allowing the therapist to create new robot-based exercises or tasks. This issue was addressed by the REHAROB system, where the therapist can program new exercises and simulate them before execution. Note that this approach is also used by industrial robots. However, it must be considered that simple-to-use devices are more likely to be adopted by clinicians than those that have long setup times [135]. One way of enabling flexible and intuitive strategies to create new exercises could be robot programming by demonstration [136]. This way, therapist-robot interaction is moving from purely preprogrammed robots to very flexible user-based interfaces for training robots to perform a task.

On account of the above, it can be seen that it is not only important to empower the patient-robot interaction, but also the therapist-robot interaction. On one side, integration of movement and proprioception training in the same experimental paradigm is beneficial for motor learning. On the other side, the development of intuitive methods for adapting the therapy elements and, more importantly, for creating new robot-based exercises is required to increase the usability of the RRS.

## 6.2. Safety in Physical Human–Robot Interaction

Safety is one of the biggest concerns about the extended use of the RRS in clinical practice. The fear of an accident or injuries produced by a robotic device is understandable, considering that robots can be dangerous to humans if used without care. This concern is not only applied to rehabilitation robots, but also the ones used in the industry (likely its origins). However, the growth of robots in the industry has led to the development of effective methods to increase the protection of workers, even allowing them to work sharing the same workspace for the case of collaborative robots. The same result is expected for the rehabilitation robots, save the differences.

One of the unique aspects of the RRS is that they must enforce the safety of the patient as an object within the workspace, while also being able to treat the patient. This dichotomy creates the need for specific safety strategies that can allow the robot to interact with the patient, while also enforcing all necessary safety precautions [137]. The common hazards in robot-aided treatments include collisions (when a robot link hits the user), pinch injury (when a robot traps a body part), and interior factors (such as sudden spasms or twitches). It must be noted that the probability of a specific risk depends on

the type of robotic device. For example, it is more likely that a collision will happen when interacting with an end-point-type robot. Conversely, spasms or twitches may be more dangerous in the case of an exoskeleton, since the patients are basically encapsulated in the device.

As presented in the previous Section 5.2.3, safety strategies of the RRS may consider the hardware and software points of view. The security strategies mainly involve compliance control, backdrivable mechanisms, pneumatic actuators, stroke limits (hard stops or software-based), emergency stop button/handle, or force/speed limits. It is relevant to realize that safety is not an absolute concept. A system can only be built to reduce the risk of an accident to an acceptable level [137].

Notwithstanding all of the strategies aimed to reduce the risks of patient's damage in human-robot interactions, the broad variety of safety strategies requires measures to control reliability and safeguarding. Such a standardization could facilitate the use of the RRS in clinical settings. As an example, in the case of industrial robots, safety has been regulated by several standards to overcome technical barriers in international commerce and foster market growth. Unfortunately, there is no available industry-standard approach to design safety-critical robot systems for rehabilitation.

In this sense, considering the great amount of research in robots for healthcare-related applications, there are many standardization bodies currently dealing with the safety of human interaction with rehabilitation robots. The most influential ones are the International Organisation for Standardisation (ISO) and the American National Standards Institute (ANSI). As a result, dedicated standards for rehabilitation robotics devices are under development, such as the standard IEC/DIS 80601-2-78. It can be appreciated from the different standards that the most relevant functional requirements for safe robotic applications are related to limiting the forces, speed, and power of the robot [138]. This ongoing effort of standardization in rehabilitation robotics is promising in order to contribute to the acceptance of robot-aided procedures in clinical settings.

### 6.3. Scenarios for Boosting Motor Gain Assimilation

As presented in the previous Section 2, movement generation depends on the individual, the task, and the environment within which the motion is performed. It can be appreciated that the research community has been focused on developing intervention strategies [12]. This is primarily associated with task-related factors in movement generation. Complementary to this, VR technology has been used for modeling the patient-robot interaction in a friendly scenario (environment), in addition to motivational purposes.

The effects of robot-assisted therapy on the motor and functional recovery have been evaluated by different studies [9]. This demonstrates that robot-aided treatment improves motor function. Besides, the benefits of gaming technology for enhancing the mood of patients have also been proven. In spite of this, there is evidence that motor function improvements are often not transferred from robot-based therapy to the performance of ADL [8,139]. A possible reason for the limited transferring of motor gains to ADL could be that factors other than task-related ones that intervene in movement generation have not been addressed enough.

In this sense, it is clear that gaming technology could contribute more to transfer motor gains from therapy to ADL. On one side, tasks are performed in a variety of environments in daily life. Functionality depends on consideration of environment attributes when planning task-specific movements [26]. On the other side, the literature shows that motor preparation is affected by the meaning of the action, even when the action is only virtual [140]. This fact suggests that performing of movements into a virtual scenario similar to a real one could be beneficial.

On this basis, VR technology could be a useful tool for creating environments as similar as possible to daily life ones and modeling the attributes of such environments towards increasing motor gains of patients. Current robot-aided systems are not tapping the full potential of VR. It can be seen that a high percentage of the systems included in this review used a VR-based environment running on a flat screen, even when a three-dimensional scenario was built. Despite the more realistic environment, the perception of the tasks was reduced due to lack of depth information. This limitation is currently

addressed by cutting-edge systems such as DIEGO®. This system used a three-dimensional therapeutic area with a fully-immersive VR-based environment. This aimed to enable the ideal transfer of what it has learned during therapy into everyday life.

Currently, serious games and VR technology are increasingly used for rehabilitation purposes and have been shown to be an effective alternative to traditional rehabilitation therapies [141,142]. However, methods purely based on gaming technology lack the feedback possibilities that robots can provide. Hence, the proper integration of both technologies could lead to more effective treatments. More immersive exercises that include biofeedback and gaming technology might be considered as deployable solutions for clinical settings. As previously argued, gaming technology is widely used as a channel for motivating the user and asking to perform specific tasks. However, flexibility for modeling life-like scenarios and the capability of measuring interaction have not been fully exploited.

#### 6.4. Towards More Autonomous Interventions: Self-Adaptive Versus Sizeable Systems

Therapeutic strategies that help the patient to relearn how to perform functional tasks, taking into consideration underlying impairments, are essential to optimize the recovery of functional independence. However, the selection of the more suitable tasks, the order, or even the moment for the intervention is an aspect that depends on the patient needs. When treating neurological disorders, patient needs are usually multi-dimensional and may be very complex. This fact highlights the importance of making adaptive systems available for neurological rehabilitation.

A good example of the necessity to adapt the intervention systems could be as follows. A patient who has just started the rehabilitation of a limb should start with passive exercises. In these exercises, the robot would perform all the movement to recover the mobility of the patient. Afterwards, a guided intervention system could be applied. At this point, the therapist wants exercises in which several joints collaborate with more complex tasks at the same time. The idea is to remember how the muscles should move. Then, the robotic system could assist with simple tasks, in such a way that the patient begins to be more active. Then, through more active methods, the patient would recover part of or all of his/her motor function. Finally, a method of resistive intervention could be applied to increase and consolidate everything learned. Obviously, if the robotic system is more adaptable to the needs of the patient and the therapist's suggestions, rehabilitation will be better.

A recent review of physical rehabilitation approaches for the recovery of function and mobility after stroke [143] suggested that the selection of treatment components is a key implication in practice. This customization-based approach has been considered by most of the robot-based systems included in this review. In this case, it is the clinician who manually adapts the parameters of the robot towards training a specific motor problem. Therefore, this type of system is denoted as manually adapted.

Beyond, the present review has shown that various robot-aided systems include high data analysis capabilities for interpreting the performance-based information. This information about the user's performance is automatically gathered by the robotic device itself. In the case of manually-adapted systems, the treatment selection is based on the assessment of the individual and the clinician's interpretation. Contrarily, more autonomous robot-based systems can tune the parameters of treatment based on the measurements from sensors about the user progress. Therefore, this type of robotic device is denoted as self-adaptive.

Personalizing robot therapy by means of self-adaptive interaction strategies seems to be practical and might be a crucial element for achieving optimal assistance [56]. Artificial intelligence (AI) could be a key component in order to obtain a better interpretation of performance-based data. AI also may play an important role in building appropriate healthy reference models. The benefits of self-adaptive robot-aided treatments is a research line that is yet to be fully discovered.

In summary, this study highlights that key factors for adoption of robot-aided systems in clinical practice are the capability of customization to the patient needs and the flexibility to administer different treatment techniques. Additionally, it was identified that robot-aided systems could include high data analysis capability in order to self-adapt the treatment to the patient needs. Self-adaptation of robot

assistance could be a relevant factor for overcoming the barrier between improvements in the control parameters and functional achievements in ADL.

## 7. Conclusions

Robotic rehabilitation systems comprises one of the fields that has been widely developed in recent decades. However, the adoption of these systems in clinical practice is less than expected. Aside from the well-known affordability issues, this review focused on identifying the technical requirements of robot-aided systems for facilitating their adoption in clinical practice.

One concern about robot-based interventions is that improvements are often not transferred to the performance of activities of daily living. A possible reason for this limited transference of motor gains to ADL is that the robot-aided systems have been mainly focused on developing mobilization techniques (task-related), but factors other than task-related and that also intervene in movement generation have not been sufficiently addressed. These other factors are those related to the patient (cognition, perception, action) and the context of the task (environment).

In regard to patient stimulation, gaming technology has been widely used in robot-aided systems. The primary purpose is to encourage the patient and modeling the interaction with the robotic device in a friendly way. In order to extend the cognitive and perceptual stimulation, challenging tasks using more sensorial channels are required. Combined exercises that include biofeedback and gaming technology might be considered for deployable solutions for clinical settings.

Regarding the context of tasks, better use of VR technology is required in order to promote a long-term recovery of motor function in terms of ADL performance. The principle is that aspects of motor preparation are affected by the meaning of the action, even when the action is only virtual. Based on that assumption, building fully-immersive VR-based environments as similar as possible to lifelike scenarios could promote the transference of motor achievements in robot-aided interventions to ADL.

Additionally, high adaptability of robotic systems to the patient needs would be beneficial in terms of the effectiveness of treatments. Adaptability can come from the mechanical level (hardware) or the software level (control).

At the hardware level, systems with a high level of compliance are necessary in order to provide the patient with several options of accomplishing a specific task. This is related to the “degrees-of-freedom” problem in neurological rehabilitation. However, it is also important to make available strategies (embedded or external) for detecting the compensatory movements and security. Since robot-aided therapy implies a high degree of physical human–robot interaction, it is very important to implement security systems that ensure patient well-being. For that purpose, the use of collaborative robots that are considered intrinsically safe systems could be a feasible alternative.

At the software level, an investment in better use of performance-based data for enhancing the therapy adaptability is necessary. Thus, more efficient treatments could be obtained via self-adaptation of robot parameters according to the rehabilitation needs. In this regard, integration of artificial intelligent agents into the software of robotic devices could lead to more intelligent interventions.

Finally, another significant issue to address is the development of reliable and effective strategies for guaranteeing the patient’s safety during robot-aided therapy. Thereby, international safety standards form part of the primary basis to facilitate the adoption of rehabilitation robots in clinical practice, paving the way toward the market for reliable and secure robotic products.

The framework presented in this paper suggest an ecosystem in which therapist can organize the rehabilitation session with a more effective support of robotic devices. This approach could be obtained via increasing the adaptability of robots, enhancing the human–robot interactions, and empowering the decision-making capability. Proper addressing of such aspects could lead to the sustainable transference of motor gains and better acceptance of robot-aided systems in clinical practice.

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