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Preface

The volume CCIS 1488 contains the refereed proceedings of the International Conference on Optimization, Learning Algorithms and Applications (OL2A 2021), an event that, due to the COVID-19 pandemic, was held online.

OL2A 2021 provided a space for the research community on optimization and learning to get together and share the latest developments, trends, and techniques as well as develop new paths and collaborations. OL2A 2021 had more than 400 participants in an online environment throughout the three days of the conference (July 19–21, 2021), discussing topics associated to areas such as optimization and learning and state-of-the-art applications related to multi-objective optimization, optimization for machine learning, robotics, health informatics, data analysis, optimization and learning under uncertainty, and the Fourth Industrial Revolution.

Four special sessions were organized under the following topics: Trends in Engineering Education, Optimization in Control Systems Design, Data Visualization and Virtual Reality, and Measurements with the Internet of Things. The event had 52 accepted papers, among which 39 were full papers. All papers were carefully reviewed and selected from 134 submissions. All the reviews were carefully carried out by a Scientific Committee of 61 PhD researchers from 18 countries.

July 2021 Ana I. Pereira

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Overview of Robotic Based System for Rehabilitation and Healthcare

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Abstract. As in many other fields, robots are increasingly being used in the healthcare sector, particularly for hospital logistics support, surgery and rehabilitation. Rehabilitation is a concern for millions of people around the world, and because of this, there has been a constant progress over the last decade in the rehabilitation robotics field, with the use of new technologies aimed at overcoming the different challenges faced in this field. In this sense, this paper reviews the main applications developed in the last ten years of rehabilitation robotics, as well as the different challenges that still need to be addressed in order to achieve the design of a prototype that is easy to use, small, safe, less costly and brings real added value to this field. Much of the efforts of the researchers in this topics is focused on providing as many DOF and ROM as possible, and also on the designing of new robots control algorithms.

Keywords: Rehabilitation robots · Review · Gait rehabilitation · Upper limb rehabilitation · Learning algorithms

1 Introduction

As described by the World Health Organisation (WHO), rehabilitation is a set of measures aimed at helping people who have lost function to regain their physical and cognitive functions through therapy and repetitive exercises, and achieve optimal interaction with their environment [1]. Rehabilitation is usually carried out by therapists, rehabilitation workers and technical assistants.

Rehabilitation strategies may differ, but they all aim to improve the patient's health status throughout the rehabilitation process. They have in common a series of steps, which belong to what is called the rehabilitation cycle [1]. This cycle involves first identifying a person's problems and needs, then linking the problems to relevant factors, after which it is necessary to define the objectives of rehabilitation, followed by planning and implementing measures and finally evaluating the effects. These steps are illustrated in Fig. 1.

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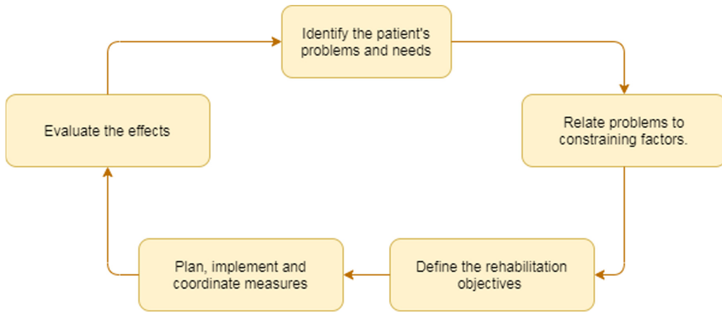

Fig. 1. The rehabilitation cycle [1]

However, traditional face-to-face manual training has resulted in some disadvantages such as: high labour intensity, lack of scientific and effective follow-up data and feedback. Also, the field of rehabilitation is becoming increasingly overburdened, mainly due to the fact that about one billion of people, equivalent to 15% of the world's population, suffers from a disability whether acquired at birth or as a result of an accident [2]. This constantly rising number will increase the shortage of this service in some countries with emerging economies or a high population growth, which will therefore not be able to provide sufficient rehabilitation training for every patient. Lack of access to rehabilitation services can worsen the effects of disabilities. To illustrate, for patients who have survived a first stroke, rehabilitation during the first six months after the stroke is considered to be the most beneficial and effective; after this period, the patient's chances of recovering their previous abilities are significantly reduced [3]. In addition, the extra costs due to the personal and medical support make patients with disabilities more likely to be poorer than non-disabled persons.

These pervasive constraints in the sector, make it all the more urgent to make major advances in this area and the use of robots for rehabilitation purposes offers a promising future and an attractive alternative in the field of physiotherapy, given the benefits they can offer; it is worth mentioning that the development of these devices has attracted an increasing interest over the last three decades. These robotic devices offer an alternative to reduce the limitations of manual physical therapy by providing more intensive and personalised therapy sessions, relieving therapists of laborious repetitive tasks while making rehabilitation centers less crowded.

The purpose of this document is to provide an up-to-date summary of the progress made over the last ten years in the field of robot-based rehabilitation, discussing the latest advances in the field and including some of the control algorithms used. The rest of this paper is organised as follows. Section 2 presents a review of different robotic devices, mainly under development for the upper and lower limbs and then, in Sect. 3, we discuss the future challenges that robots have to face in order to make devices that work safely and achieve effective results during rehabilitation sessions. Finally, Sect. 4 presents a conclusion.

2 History of Rehabilitation in Robotics

Robot-assisted physical therapy is most often used for people with neurological injuries (stroke or severe paralysis) and for people who have suffered an accident [10,25]. These robots focus mainly on the upper part of the human body (shoulder, elbow, forearm, etc.) and on the lower limbs (ankle, feet). At present, the robots developed so far are not totally independent from human intervention, as they usually require a therapist to set initial parameters for the robot and ensure a smoothly running session. Nevertheless, these robots still represents a good alternative to traditional methods as:

– Robots are very good at performing repetitive movements and with adjustable speed;
– The sensors assess forces and movement of the patient which allows the monitoring of the patient's performance and progress throughout the sessions;
– The use of robots allows the combination of several technologies, such as interactive games, making the session more appealling especially for young patients.

The robots used in the rehabilitation are often associated to the "assistive devices" category [4], multiple studies have been able to show the applicability of these robots and have indicated a significant benefit in terms of therapy outcomes [8,27,37]. Also, the development and advancement of flexible materials such as elastomer, fabric and cables as well as more advanced development of actuators, have enabled the development of lighter and more comfortable rehabilitation robots.

2.1 Robotics Therapy for the Upper Limb

MIT-MANUS represents the reference followed in the design of various prototypes developed to date, this being due to the extensive clinical testing carried out by the research team. The robot was first designed specifically for use in shoulder and elbow rehabilitation for stroke patients, and its further development made it the first project to introduce whole arm robotic therapy [5,6]. This method is based on the use of visual and auditory stimuli, thus, the patients feel like they are playing a video game, while the robotic arm assists the patient's movement by providing a precise degree of force in the same movement direction. Papers [7,8] describe the results of clinical tests performed to 158 subjects, 26 patients were assigned to usual rehabilitative care, half of the remaining patients were assigned to intensive comparison therapy and the other half to robot-assisted therapy only; it is highlighted that the group of patients receiving an robot-based therapy shows significant improvement relative to the patients' abilities in contrast with other groups receiving usual care and without adverse events reported.

NTUH-ARM, is a 7 Degrees of Freedom (DOF) exoskeleton robot controlled by an Assist as Needed (AAN) strategy. The AAN controller is a strategy that allows to support the patients' arm and keep it in the defined trajectory and with an adequate force. The purpose of this controller is to provide the patient's arm with spatial freedom by building a virtual channel surrounding the predetermined motion trajectory, in order to help the patient exercise their muscles to the maximum of their ability [26,48]. It is also possible to manually set the torque generated by the robot. A clinical test was carried out on six patients with positive results [27]. A more advanced prototype, called *NTUH-II*, was developed some years later. It is similar to its predecessor in that both prototypes are computer based with their control algorithm set up on LabVIEW, allows rehabilitation movements in passive, active and assistive modes and have a fairly identical hardware configuration. However, the latest version has some major improvements [28], it offers an additional degree of freedom, bringing the total number to 8 DOF, and is capable of delivering a larger range of motion (ROM) to stroke patients and frozen shoulder patients [29]. Over the years, the control algorithm has been improved in subsequent studies [29–31] and aims to achieve better accuracy of the given torque using observers and improved synchronisation between the exoskeleton's robotic arm and the human arm using deep learning algorithm.

ANYexo is a 6 DOF upper limb rehabilitation robot, it features an optimized design covering a wide range of motion and operation by six elastic actuators in series. This robot is intended to be used as a development platform, facilitating the future design of more efficient control algorithms and allows the validation of a wide variety of hardware designs in order to identify the recommended compromises for the upcoming generation of rehabilitation robots [32,34]. Two cameras record the position of the patient and the exoskeleton to avoid any collision between them [33], increasing the safety of the device. As the project is still ongoing and the research team is focusing on the control algorithm to ensure a safer usage of this prototype, no clinical test has been performed yet.

Harmony is a 7 DOF upper-limb rehabilitation exoskeleton using series elastic actuators, this robot can offer a wide ROM with a great kinematic compatibility with the human body and is able to exercise both hands at the same time [36]. As with the prototypes presented above, this robot is also intended to be used as a development platform for the design and validation of control strategies and the realization of clinical studies [35]. So far, there have been no clinical tests of this prototype reported in the literature.

Physiotherabot/WF is the prototype proposed by Atlihan *et al.* [41]. It is a PC-based 3 DOF robotic arm manipulator designed specifically for the forearm and wrist. Hybrid Impedance control is implemented to perform passive, active-assistive and resistive therapeutic exercises, three servo motors are used to perform the action. To ensure the safe use of this device, the limit angle of the robot's movement is the same as that of a human arm and the algorithm also includes some limitation of the robot's movement and force; as in many solutions proposed by different research teams, an emergency button is also included

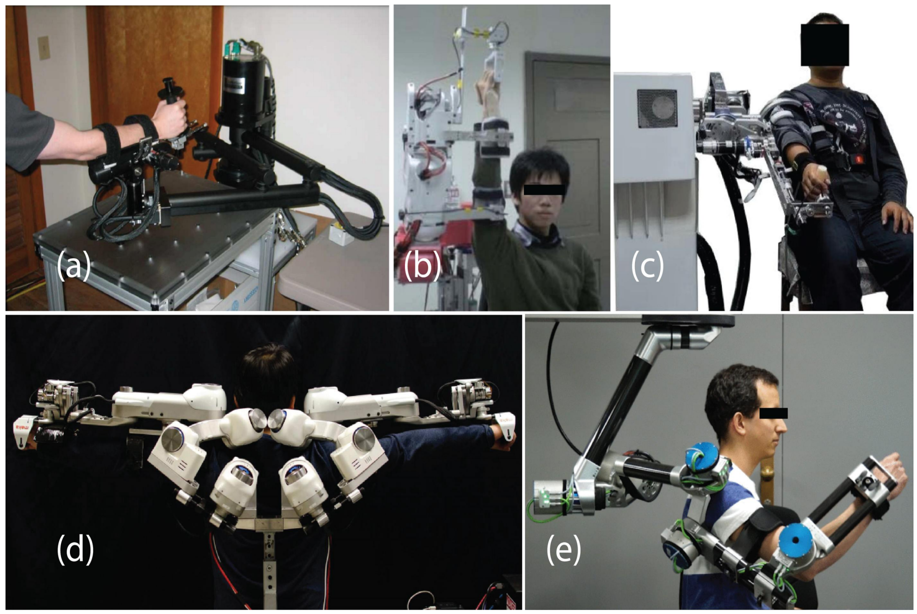

Fig. 2. Upper limb robotic rehabilitation systems; (a) MIT-MANUS developed by Krebs *et al.* at the Massachusetts Institute of Technology (USA) [7]. (b) NUTH-ARM [26] and (c) NUTH-II [28] developed by Chen *et al.* at the National Taiwan University Hospital (Taiwan). (d) Harmony developed by Kim and Deshpande (USA) [36]. (e) ANYexo developed by Zimmermann *et al.* (Switzerland) [32].

in the design [40]. Clinical tests were carried out on 7 subjects (3 healthy and 4 patients), these preliminary tests showed that the prototype offered positive results to the recovery process

E2Rebot, it is a robotic planner platform with 2 DOF that actively engage the patient through a game displayed in front of him, two DC motors are used to move the end-effector. The platform is fully adjustable, allowing it to be used standing or sitting in a wheelchair, the control algorithm is based on an ANN strategy [38]. This prototype is the successor of a first prototype realized a few years ago and named *SOFTROBOT* [39], which was actively used in a medical institution, the data acquired after more than two years of tests are the basis for the realization of E2Rebot. Currently, a clinical test for E2Robot is still underway, but no results have been reported.

RoboTherapy 2D is a 3 DOF robotic manipulator coupled to a computer and use Pneumatic Muscle actuators (PMA), similar in design to MIT-MANUS, which uses visual and auditory stimuli to motivate the patient [43]. Extensive clinical testing was conducted and a marketed version was released by Instead Technologies Inc. [42]. *HomeRehab*, represents the continuation of the first developed product, with the same performance and user experience [45], the newly developed prototype is a 3 DOF robotic manipulator coupled with a Computer intended to be used at home, it provides a compact design as all the actuators are concentrated in one box [44]. This prototype aims to implement the aspect of competition between patients and increasing the difficulty to further promote the patient's engagement in the rehabilitation session. Only tests on healthy subjects have been reported in the literature [46].

LIMPACT, is a hydraulically driven exoskeleton with a total mass of 8 kg (4 kg without motors), designed for use by stroke patients. Although it appears to be heavy, the authors consider it to be light, as it offers high torque for its weight and a large range of motion for most rehabilitation sessions [57].

Zhao *et al.* designed a new exoskelton robot structure with 7 DOF in [49]. The system uses a multi-sensor system (force, encoding, hearing, vision, myoelectric and proximity sensors), the principles of machine learning and deep learning are used by applying optimal and robust adaptive control based on Udwdia-Kalaba theory and fuzzy logic to ensure safe human-machine interaction [49]. The prototype designed will improve patient participation in training sessions through the use of virtual reality and game-based therapy sessions, help doctors build a good rehabilitation training programme and help hospitals manage patients in real time and summarise experiences. This design is only a proof of concept, therefore no prototype has been built yet.

Maqsood *et al.* proposed a 2 DOF robotic planner platform using an iterative trajectory learning algorithm and an impedance matching method to overcome the unknown user behavior and prevent patient deviation from the trajectory [50]. No knowledge of the patient's dynamics is required for the proposed approach to achieve algorithm convergence. Validation of this approach has been carried out, but no clinical tests have been recorded for this prototype, as the control algorithm is still being developed and improved.

In addition, several works focus only on the development of control algorithms without offering special consideration to hardware development and using already developed platforms. In [58], a Normal Optimal Iterative Learning Control algorithm (NOILC) and an Optimization-based Proportional Iterative Learning Control algorithm (OPILC) are proposed and applied on a KUKA iiwa robot. Tests performed showed that both algorithms are robust to slowly changing disturbances and can be applied for ANN-based therapy and can perform both linear and circular movements. No tests with real patients have been performed and reported for the NOILC and OPILC approaches. However, some reported studies [59,60] have examined the feasibility of Iterative Learning Control (ILC) for upper extremity rehabilitation through clinical testing on real patients.

A UR3 collabor ative robot, mainly intended for industrial use, is described by De Azevedo Fernandes *et al.* [24] as a shoulder rehabilitation robot, with the main aim of demonstrating the feasibility of this approach and shows how intuitive and versatile these robots can be. The robot provides a force in the opposite direction to the patient's movement, the force provided by the robot is variable depending on the force emitted by the patient and is self-controlled by an reinforcement learning based on Machine Learning (ML). By using this method it is only possible to use the robot on partially paralysed patients and, so far, no clinical tests have been performed by the research team of this prototype (Figs. 2, 3, 4 and 5).

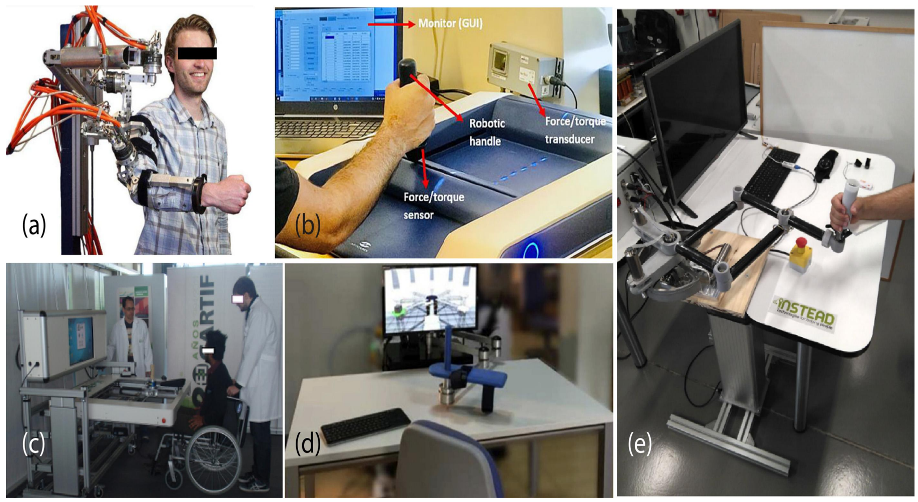

Fig. 3. Upper limb rehabilitation robotic systems (a) Limpact developed by Otten et *al.* [57] (Netherlands). (b) developed by Maqsood *et al.* (UK & China) [50]. (c) E2Rebot developed by Fraile *et al.* (Spain) [38]. (d) RoboTherapist 2D and (e) HomeRehab developed by Díaz *et al.* (Spain) [44].

During hand rehabilitation, limited recovery of the hand and wrist joints has been reported in stroke patients, and has always been a challenge for them [18]. Several research teams have focused on specific devices that can accomplish this task.

Ho *et al.* [18] proposed a portable exoskeleton robotic hand allowing patients to carry it around in their daily activities. A total of 30 subjects with chronic stroke were selected to evaluate the device throughout the years, all patients were involved in a similar training program lasting about 20 sessions, a positive feedback about the use of this robotic hand was reported in [19–21], showing an improvement of the finger muscle coordination, as well as reducing the excessive muscle activities in the biceps. A further development of this device is proposed in Heung *et al.* [16,17], which proposes a flexible and lightweight 3D printed robotic hand, with the dual purpose of helping patients rehabilitate their hands as well as assisting them in their daily activities, as the device is fully wearable. This device is twice as light as the previous one thanks to the use of a soft elastic composite as an actuator. As a test of the proposed solution, two stroke patients were enrolled to assess the effects of rehabilitation using the recently developed 3D-printed flexible robotic hand. The results after 20 sessions, each lasting 45 min, showed an improvement in hand function for both subjects.

RELab tenoexo is a fully wearable exoskeleton robotic hand that use a remote control system situated in a backpack to reduce the weight on the hand module; it aims to assist the users in activities of daily living (ADL) focusing mainly on grasping activities [22]. The prototype also seeks to maintain user motivation during training and improve residual hand function by offering an appealing appearance, an intuitive controller and provides visual feedback of muscle activity. A pediatric hand rehabilitation named *PEXO* has also been developed by the same research team. It is adapted from the adult's model and they both have the same architecture and the same objective but for 6–12 years old patient [23]. Both prototypes have been clinically tested and are fulfilling their objectives.

Yang *et al.* have proposed an approach that allows patients to experience more intuitive and authentic rehabilitation sessions than virtual reality and virtual systems-based stroke rehabilitation systems. The proposed prototype consists of two parts, a smart cuff that records sEMG signals and a five-fingered 3D printed robotic device called 'smart training equipment', driven by an offline trained ML algorithm. The real-time assistance of the robotic hand offered by this device allows users feedback on muscle activity and helps them strengthen their muscles, and demonstrates once again the feasibility of implementing robot-assisted active training for stroke patients. [47].

SAFE Glove, developed by Ben-Tzvi and Ma, is a sensorised exoskeleton prototype that analyses the movements made by the subject, learns common fingertip movements and release patterns, these can then be reproduced in a weakened hand to train it. It uses a dynamic time warping (DTW) method and a machine learning approach to perform the learning part. The glove is portable, wireless and adaptable to different hands with a large ROM. The prototype developed is lightweight with a mass of 430 g [51]. A digital twin is being developed alongside, in a 3D environment showing the kinematics of the hand. Only a test on healthy subjects has been performed and shared by the research team [52].

Chen *et al.* have proposed a pair of soft gloves that assist stroke patients in their rehabilitation therapy using a so-called "mirror therapy" and ensure synchronisation between a weakened and a stronger hand [54]. The first pair, called the "sensory glove", detects the movement of the hand and using an ML algorithm implemented on MATLAB Software, classifies the movement into one of 16 predefined gestures. The second pair, called the "motor glove", driven by micromotors and worn by the weakened hand, provides the disabled hand with assistive motor strength to perform the mirrored movement done by the other hand as a training exercises [53].

2.2 Robotics Therapy for Ankle and Foot

The ankle joint is a very complex part of the human body and it is essential to maintain the body balance. Several research groups are working in the development of a lower limb rehabilitation robot, in order to improve the outcomes of rehabilitation sessions. There are two main categories, the *portable robots* which are most appropriate for gait therapy, and the *robotic platforms*, which are more suitable for ankle exercise only [14].

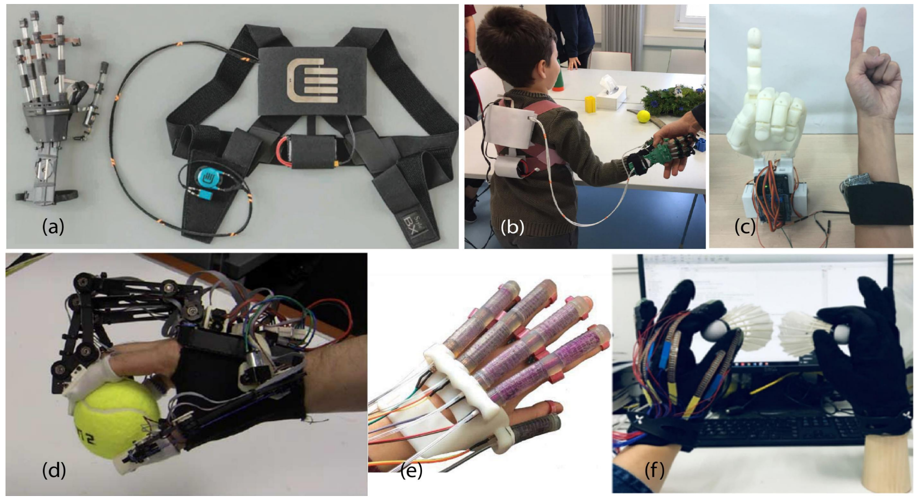

Fig. 4. (a) RELab tenoex [22] and (b) PEXO [23] developed by Bützer *et al.* at the Rehabilitation Engineering Laboratory (Switzerland). (c) developed by Yang *et al.* (China) [47]. (d) SAFE Glove developpped by Ben-Tzvi and Ma (USA) [52]. (e) developed by Heung *et al.* (Hong Kong) [16]. (f) developed by Chen *et al.* (USA & China) [53].

An adaptive, light weight and parallel ankle rehabilitation for sprained ankle treatment was addressed by Jamwal *et al.* in [9]. The robot is based on the use of pneumatic muscle actuators (PMA) placed in parallel of the patient's shinbone. The control strategy is based on a fuzzy controller associated with a fuzzy-based perturbation observer. The suggested strategy offers three degrees of freedom. An ANN based system to restore gait, has also been proposed by the same research team. The system is composed of a treadmill and a robotic orthosis actuated also by PMA. It adapts the assistance provided according to the patient's disability, in real time. It is based on an adaptive impedance control architecture using a boundary-layer-augmented sliding mode controller controls the PMA's angle [11,12]. Ten healthy and neurologically healthy subject have been tested and asked to walk on the treadmill without assistance and with assistance for 20 min [13].

Zhang *et al.* proposed a Compliant Ankle Rehabilitation Robot (CARR) with 3 DOF [15]. The control strategy is based on a so called adaptive patient cooperative control, making this device safer and more comfortable to use; this is achieved through real-time measurements of the joints position and torque [14]. Two neurologically injured subjects have been asked to test the device, but no improvement following the session has been stated.

Chen *et al.* have developed an Assist When Needed (AWN) control strategy, an extension of the ANN used in most of the proposed prototypes, where individual conditions are taken into account. The phases of walking are detected using sensors and a Hidden Markov Model (HMM), the assistance degree is variable depending on the patient's deviation [55]. So far, tests have been performed on one healthy subjects, no clinical tests of this control algorithm have been performed by the authors to show the real benefits for injured patients.

Meng *et al.* have developed a flexible 6 DOF robot, which aims to increase patient motivation by providing assistance when needed, using a motion recognition system based on EMG signals, which identifies the trajectory and rehabilitation factors based on real-time assessment and motion detection. Robot force and movements are usually controlled using an adaptive impedance control. [56]. The test on healthy subjects showed that the robot's movements were perfectly in line with the user's intention, as well as an increase in muscle activity.

Fig. 5. (a) developed by Zhang *et al.* (UK & China) [14]. (b) developed by Meng *et al.* at the Key Laboratory of Fiber Optic Sensing Technology and Information Processing (China) [56]. (c) developed by Chen *et al.* (China) [55]. (d) [11] and (e) [9] developed by Jamwal *et al.* (New Zealand).

3 Upcoming Challenges for Robotics in Physical Therapy

Rehabilitation can assist to reduce poverty and improve the quality of life of the patients, by improving their abilities, activity level and participation in society [2], but the cost of rehabilitation can be a barrier for people with disabilities in both high and low income countries. In India, people with disabilities and their families buy more than half of the assistive devices directly, which represents a huge budget and makes them even poorer [1]. In addition to the cost of these strategies, whether for generalisation or use, it is also important to point out that many of the proposed solutions can only be used by a certain category of people and cannot be generalised [25]; sometimes even if two patients have the same pathologies, the same solution cannot work for them. Therefore, the first challenge of these new technologies is to make mass production of customisable products possible, making them more accessible to the poorest population.

In several studies, the robot does not completely match the human arm, one of the main obstacles is to make these prototypes lighter and smaller, with much more powerful actuators and a better power source. In addition, they need to be ergonomic, comfortable and visually appealing to the user and only a few devices have reached such criteria [22,23,36]. This makes patients more engaged and confident in using the devices during therapy sessions. Research teams also need to find ways to integrate their laboratory-based or PC-based prototypes into portable, stand-alone systems, which would facilitate home rehabilitation and the delivery of therapy in the post-accident period, which is crucial for successful rehabilitation.

Rehabilitation robots are designed to be powerful enough to interact with the user's environment, but they are also sufficiently powerful to harm the user and others in the surrounding area, especially as these products interact very closely with humans. Several safety criteria must be met to ensure safe interaction with patients. Both the actions of patients and robots must be coordinated and adapted to each other, as unexpected behaviour by either of them can lead to serious injury, this constraint is increasingly taken into account in the latest control algorithms using deep learning [31]. It is also necessary to ensure that robots do not exceed the physiological range of motion of human beings. Force and pressure applied to the human body are important factors to consider in the development of any device with contract with human users, inadequate application can results in problems such as fatigue [10].

Very few control strategies designed for these robots use artificial intelligence and machine learning, as the exercises are designed in advance and follow a predefined trajectory, while the difficulty is increased manually. However, the versatile behaviour of human users is unpredictable and vary a lot between persons. These predefined patterns are not the best to offer optimal rehabilitation therapy to patients and, therefore, the real challenge for the next generation of rehabilitation robots is to make full use of machine learning, which would allow the most ideal and beneficial exercise for the patient's condition to be offered, so that the movement data collected are not only used to monitor the improvement of the patient's abilities, but are also used effectively and precisely to improve their medical condition.

4 Conclusion

Various research groups around the world are actively researching and developing new prototype robots using the latest technologies to provide quality rehabilitation of the upper and lower limbs of the human body. This work focuses mainly on the advances made on the upper part of the human body, as the most significant advances are made on this type of robot, but it does not neglect some prototypes developed for the lower parts. Much of their effort, in addition to providing as many DOF and ROM as possible, is focused on designing new algorithms to control the robots. Several control approaches have been described and presented in published papers for the operation of end-effectors and exoskeletons based robots, some of which are beginning to include artificial intelligence and machine learning algorithms to provide the most effective therapy sessions. Machine learning-based approaches allows the patient to follow the trajectories, and have the potential then to offer the most appropriate exercise to allow optimal effectiveness, and are able to monitors the effort provided by these patients. This can be achieved by learn from the motion achieved from healthy patients, that can be provided by therapists, then reproduced for injured patients. This type of rehabilitation can promote telerehabilitation, and thus allow sessions to be conducted by patients at home, which is increasingly important, especially after the COVID-19 outbreak.

Rehabilitation using robots should not be an alternative to conventional physiotherapy, but rather a complementary approach. Indeed, the exclusive use of robots during rehabilitation sessions has so far shown no evidence of faster recovery and better quality sessions compared to traditional sessions with a physiotherapist, although in some of the studies discussed, the opposite is claimed, this is mainly due to the way the clinical tests was conducted, patients were subjected to a double dose of therapy (with and without robots) which biased the final result. It should be noted that there is converging evidence that more sessions may give better results.

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