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The Present and Future of Robotic Technology in Rehabilitation

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Abstract

Robotic technology designed to assist rehabilitation can potentially increase the efficiency of and accessibility to therapy by assisting therapists to provide consistent training for extended periods of time, and collecting data to assess progress. Automatization of therapy may enable many patients to be treated simultaneously and possibly even remotely, in the comfort of their own homes, through telerehabilitation. The data collected can be used to objectively assess performance and document compliance as well as progress. All of these characteristics can make therapists more efficient in treating larger numbers of patients. Most importantly for the patient, it can increase access to therapy which is often in high demand and rationed severely in today's fiscal climate. In recent years, many consumer grade low-cost and off-the-shelf devices have been adopted for use in therapy sessions and methods for increasing motivation and engagement have been integrated with them. This review paper outlines the effort devoted to the development and integration of robotic technology for rehabilitation.

Keywords

medical devices; gaming; patient adherence; rehabilitation; rehabilitation engineering; robotics; stroke; telerehabilitation

Introduction

Disability from neurologic conditions can greatly increase health-care costs [1]. Such costs stem from inpatient care, medication cost, long-term care, and rehabilitation. Rehabilitation is critical to reduce future morbidity from immobility, depression, loss of autonomy and reduced functional independence [2], and inadequate provision of rehabilitation services, can further increase disability, leading to a vicious cycle of increasing costs [3]. Motor

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Conflict of Interest
Jeffrey Laut, Maurizio Porfiri, and Preeti Raghavan declare that they have no conflict of interest.

Compliance with Ethics Guidelines
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impairment, in particular, restricts mobility and function contributing significantly to disability and escalating costs [4] both due to the cost of long-term therapy services and that of caregiving, which are human resource intensive. While motor impairment after stroke is one of the most common reasons for rehabilitation, impairments resulting from cerebral palsy, multiple sclerosis, spinal cord injury, and Parkinson's disease require similar interventions to improve motor function [5].

The process of rehabilitation typically involves four steps [6]. First, the patient needs to be assessed to evaluate the type and extent of impairment. Second, the therapist must set goals to direct the treatment and plan an intervention to meet the goals. Third, the intervention must be implemented, which often requires repeated assisted practice of specific movements. Finally, the patient must be reassessed after the intervention, and the next set of goals set. The potential for robotics to support and facilitate the process of rehabilitation was recognized decades ago [7]. Robots can be used to enhance each of the four processes that therapists must perform. They can be used to assess performance before, after and during an intervention, and also provide targeted intervention consistently and repetitively depending on the extent of impairment. Actuators integral to the system can move a user's limb to assist or resist movement to varying degrees, while the sensors used for feedback to control the robotic mechanism also record the user's performance. An early study that investigated the use of an industrial robotic arm as a therapy aid demonstrated its safety and acceptance both by patients and therapists [8]. The advantage of robotics-based rehabilitation, when compared to conventional therapy, is that it enables consistent training of the prescribed intensity for extended periods of time [9]. Robotic devices also offer flexibility in their operation, as feedback of the user's performance based on the data from the sensors can be used to provide appropriate movements and forces during training [10, 11].

The first robotic device designed specifically for rehabilitation, the MIT-Manus, was built in 1992 and offered two degree-of-freedom motion of the shoulder and elbow in the horizontal plane, while guiding the motion of the user's arm along a trajectory with varying degrees of firmness [12]. The use of robots in rehabilitation has since grown substantially [13–16], and it has been verified that robotics-based regimens have outcomes similar to or better than those of traditional therapy [17]. However, several challenges, including cost, safety, efficacy, and ease of use for both the user and therapist, remain to be addressed to make robotic therapies more user-friendly and widely accessible. Significant research effort has also been devoted to adapting low-cost systems for rehabilitation, and assessing their ability to provide meaningful data for remote assessment in order to increase the accessibility to such devices [18]. The purpose of this review article is to describe the different types of robotic devices used for rehabilitation, how they are used to assess performance, and how the accessibility to such devices can be increased through telerehabilitation, virtual environments and the addition of gaming elements to increase adherence to the prescribed training regimens.

Types of robotic devices for rehabilitation

Devices for rehabilitation may operate passively, where the limb under treatment is constrained to a certain range of motion with no assistance or resistance; actively, where the affected limb is guided along a trajectory through the use of actuators; or interactively, with forces provided in response to the movement of the affected limb to provide an optimal assistive strategy [19]. Most of robotic the devices used in clinical settings today are active or interactive, but may also act in a passive manner. Furthermore, based on the interface of the device with the user, the devices may be classified as end-effector devices or exoskeletal devices.

End-effector robotic devices

End-effector devices for the treatment of the upper limb interface with the user through a manipulandum that is held in the hand [20]; end-effector devices for gait training interface at the foot or feet [21]. The manipulandum is connected to a robotic arm, which provides the force supplied to the user and contains the sensors that measure performance. Since the forces and measurements occur at a single interface, this type of system can easily be adapted to users of various body sizes without major modification to the system. Given this advantage, end-effector systems are popular for rehabilitation of the upper limb and for gait training. However, since the interaction with the robot is only at a single interface, the movements at each joint cannot be independently adjusted.

The MIT-Manus is an end-effector type of robot for treating the post-stroke upper limb [10]. The manipulandum, and thus the movement of the hand, is constrained to the horizontal plane with some play along the vertical direction provided by springs. Sensory-motor training using this device uses simple video games, where the input is provided through the motion of the manipulandum. The goal of training is to move a point on the screen through interaction with the manipulandum, enabling the user to draw shapes or move along a path. If the user is unable to accomplish the task, assistive force is provided by the robot through the manipulandum. A series of studies using this technology support the potential of robotics to assist and enhance traditional rehabilitation [10], and improve rehabilitation outcomes [22, 23]. Importantly, research on the MIT-Manus also demonstrated that kinematic data collected by the robot as a result of the manipulandum's motion may be useful in gauging post-stroke motor recovery. By shifting from traditional human-assessed metrics to metrics based on kinematic data collected by the robot, one can achieve more reliable and objective information to guide training [10]. Passive end-effector type robots have also been used to train both arms together but separately [24, 25], or in a mirror-symmetric coupled manner [26–28].

End-effector robots are also used to improve lower limb function, which is typically easier to train compared to upper limb function due to the lower level of complexity associated with these movements compared with the upper limb. Hence, the development of devices for gait rehabilitation has received substantial attention, with positive results [21, 29]. The HapticWalker is an end-effector type robot that is able to simulate walking and stair-climbing [30]. Force and torque sensors allow for an interactive control strategy, while enabling data collection to gauge the user's progress and walking performance. The G-EO-System is a similar end-effector robot for gait training [31]. In a clinical study, users rated this system positively and experienced increased walking and stair-climbing ability when compared to a control group [32]. Such gait training robots allow for repetitive training with minimal effort from a physical therapist without increased risk of falling [32].

Exoskeletal devices

In contrast to the end-effector robots, the exoskeleton-type robots act directly upon specific joints of the user, and are often more difficult to design and construct as they must follow the design of the limb that is targeted, be adjustable to accommodate users of different anthropomorphic dimensions, and attach to the limb at multiple points. The forces at each joint can be adjusted using motors, but the joints are typically connected using rigid links attached to the arm (e.g. ARMin and MGA [33, 34]) or leg (e.g. AnkleBot [35] and LOPES [36]. Robotic devices for bimanual training have also been tested [37–39].

Current designs of exoskeletons for the upper limb use rigid links that add inertia to the segments of the human arm making it 4–6 times heavier, which invariably requires users to use compensatory non-physiological muscle strategies during movement. Approaches to reduce inertia of the exoskeleton are to place the motors away from the joints and drive the joints using cables and pulleys (e.g. L-exos, CADEN-7, and MEDARM [40–42]). The Cable Driven Upper Arm Exoskeleton, CAREX, is a novel robot which suspends the arm using a robot-controlled cable system, making it 10 times lighter [43]. In a preliminary study, the CAREX was found to promote near-physiological muscle patterns, similar to those observed during movements without CAREX [44]. The upper limb exoskeleton robots offer: (1) assist-as-needed force fields to keep the upper limb within the desired path of motion, referred to as path-assistance, to promote higher movement accuracy, and (2) adjustable weight support to eliminate the effect of gravity, both of which can potentially assist with motor learning after a stroke. It has been shown that elimination of gravity using partial weight support can reduce abnormal motor synergies in the upper limb after stroke and improve range of motion and function [45–47]. Studies have also shown that subjects exhibit higher movement accuracy along the desired path with assist-as-needed force fields [43]. What is not clear is what aspects of robotic function should be applied to a given user, and how the therapeutic protocols should be adjusted for individuals with different levels of impairment.

For the lower limb, the AnkleBot is a two degree-of-freedom exoskeleton robot that directly actuates the ankle, and is capable of detecting deficiencies in gait and actively applying corrective forces to train a paretic ankle and improve both balance and walking after stroke [48]. This robot can also serve as a clinical measurement device by estimating the stiffness of the ankle joint, which can be used as a measure of rehabilitation progress [49]. Similarly, LOPES is an eight degree-of-freedom exoskeleton device for the legs designed to actuate the leg for gait training, or act passively as a measurement device [36].

Assessing performance with robotic devices

Beyond the development of interventions for rehabilitation, both the kinetic and kinematic data collected by the sensors embedded in the devices can be extremely informative. While clinical indices assessed by a therapist are based on movements that are performed only for assessment, kinematic data collected by the various sensors during a robotic intervention can inform how motor learning occurs. For example, in a path following task, movement accuracy can be scored by taking the mean of the absolute values of the distance of each point in the path generated by the user from the ideal path to be followed [20]. In such a scenario, as the user's performance improves, the metric will decrease. Examples of performance metrics extend beyond precision of the movements and can also include movement smoothness [50], range of motion [20, 51], and inter-limb coordination [52], with the last metric being used in bi-manual training involving both the affected and unaffected limbs [53].

In the case of end-effector type robots which interface at a single location, assessment of individual joint function is not possible [54]. For example, using an end-effector robot one can assess the range of motion of the hand, but not how much the user is moving the shoulder or the elbow during the task. This issue is minimized when using an exoskeleton type robot, where each joint of the limb that is being actuated can be assessed. However, for complex movements with many degrees of freedom, the movements with the robot must be compared with the movements performed without the robot to know if the robot-facilitated movements are physiologic and use patterns of muscle activity that are typical of healthy individuals. A comprehensive review on the use of kinematic data for movement assessment in stroke using robotic devices and how they tie in to rehabilitation progress is presented in [54].

Robot-Assisted Telerehabilitation

In contrast to traditional assessments that require one-on-one interaction with a therapist, objective assessment of motor function using data collected by rehabilitation robots can enable consistent, reliable and automatic assessment of motor function free of subjective bias from a treating therapist. Furthermore, by pairing rehabilitation devices with information technology and delivering assessment and performance data over the internet to the therapist, treatment can be moved out of specialized facilities and into patient's homes with remote supervision by a therapist. This can allow a single therapist to treat multiple patients simultaneously greatly increasing the numbers of patients treated and increasing the efficiency of the therapist. Making this shift, from the hospital to a home-based rehabilitation program has the potential to decrease costs of the program while also making rehabilitation more accessible [55, 56].

In general, telerehabilitation leverages telecommunications, computing technology, and remote sensing to enable both the delivery and assessment of rehabilitation services from a distance. While traditional telerehabilitation often requires a one-on-one interaction with a therapist [57], albeit from a distance, a robotics-based approach allows for a more flexible interaction. Research in robot-mediated telerehabilitation has been gaining traction, yielding a spectrum of reliable services [58–61]. These programs enable a trained professional to remotely verify that tasks are executed with the necessary intensity, level of precision, and posture, while supervising multiple robots and patients simultaneously and remotely [62, 63]. A comprehensive review of this area from its inception up to 2010 has been conducted in [64].

Challenges to Adoption and Accessibility to Robot-Assisted Rehabilitation

Although robotics-based rehabilitation and telerehabilitation have both been widely demonstrated to be effective, they are not yet part of routine treatment in most settings. This is primarily due to the fact that most studies include ad-hoc robotic devices that are not mass-produced, and although commercially-available rehabilitation robots are becoming more common, their cost remains high. Coupled with the need to provide outpatient rehabilitation to greater numbers of patients [65], a considerable effort is now geared towards the development and adoption of low-cost devices that mitigate direct supervision from a therapist.

Robotic devices have been demonstrated to be effective in therapeutic settings; however, in order for a treatment to be widely accessible, providing such systems in under-supervised environments outside of treatment centers will be necessary. A major challenge to implementing robot-assisted rehabilitation in such settings is that the patient must be willing to comply with the prescribed regimen(s) [66]. In rehabilitation, patient adherence to prescribed regimens is associated with both increased satisfaction [67] and improved outcome of treatment [68]. However, lack of motivation to perform the exercises is one of the main reasons for non-compliance with therapy [69–71]. Supplementing rehabilitation exercises with additional motivational elements could thus indirectly improve the effectiveness of rehabilitation interventions through increased compliance. For example, including gaming consoles has been shown to increase motivation and enjoyment during exercise [72, 73], and interactive computer play may be an effective means for bolstering engagement in children [74].

Most early robotic devices lacked engaging interfaces; however more recent efforts have begun to include interactivity and virtual reality elements in an effort to challenge patients and provide additional motivation. The GENTLE/s system, for example, provides feedback to the patient through visual, haptic, auditory, and performance cues [75]. In this system, the user sits in a chair, and the arm and wrist are suspended with support mechanisms. The wrist is connected to a haptic device via an orthosis, and the user is presented with an artificial environment selected by a therapist through a computer screen, which they navigate using the haptic device as input. The system also has several strategies for correcting the user’s motion while they move through the virtual environment, and clinical trials have demonstrated that the haptic and visual feedback provided by the system has a more positive treatment effect than treatment without feedback [76].

Java therapy is an early example of the use of a low-cost gaming device for rehabilitation of the arm and hand following stroke in an effort to increase accessibility to rehabilitation in home settings. It consists of a force-feedback joystick connected to a home computer with custom software. The system has been found to be feasible to provide therapeutic treatment over the internet and enable a therapist to assess progress [77]. Unmodified consumer grade off-the-shelf gaming systems have also been used to augment rehabilitation [78, 79]. For example, the Nintendo Wii is a popular gaming device used in rehabilitation, with 20% of surveyed therapists having used the device for upper-limb stroke rehabilitation [80]. The system consists of hand-held sensors to interact with the game which offer some haptic feedback, or a sensorized balance board. It however lacks assistive feedback which is present with most robotic devices [81]. Nevertheless, clinical trials with the system for patients undergoing stroke rehabilitation have reported that it is both enjoyable and beneficial [82], and both patients and caregivers have reported high use rates in a home setting [83]. The PlayStation EyeToy is a similar gaming console that uses a digital webcam to track interaction. It has also been shown to be suitable for rehabilitation, and was found to elicit higher intensities of movement than the Nintendo Wii [84].

While rehabilitation systems with gaming elements can enhance user motivation and engagement [79, 85], one major challenge lies in the nature of the video games that are commercially available. Games designed primarily for entertainment may be too fast-paced for sensorimotor-impaired individuals [86]. Serious games developed not purely for entertainment but specifically for rehabilitation [87, 88] hold more promise in this regard [89, 90]. These games should enable clinicians to tailor the game as rehabilitation progresses to ensure that the appropriate level of difficulty is maintained throughout the recovery process [91]. An important consideration in selecting games for rehabilitation is to examine if the games encourage or discourage the use of unwanted compensatory strategies. Structured gaming that uses available games but in a step-by-step guided manner may be one solution to using existing gaming consoles, such as the Wii [92]. Furthermore, rehabilitation games are now being designed to provide specific feedback regarding desirable and undesirable movements and forces through the use of sensors embedded in real-world objects [93] and instrumented clothing [94].

Rehabilitation gaming primarily leverages entertainment to increase engagement in exercises, but pairing participants in cooperative or competitive gameplay may serve as a means to further enhance participation in robot-mediated therapy. Such a concept was investigated using a pair of ARMin exoskeleton rehabilitation robots, where participants competed in a virtual air-hockey game in single-player competitive and cooperative gameplay conditions [95]. While subjects' personality traits roughly dictated which gameplay mode they preferred, the study indicated that multi-player gaming can improve the enjoyability and level of intensity of rehabilitation.

The older population, which comprises the majority of patients with neurologic disability, may be more receptive to games that challenge their intellect in contrast to the typical action and reflex videogames. This population has been found to enjoy helping new players, solving puzzles, and participating in the social aspects of gaming [96]. In a departure from traditional gaming, the effect of science learning in a virtual environment has also been studied [97]. Here an off-the-shelf haptic joystick, the Novint Falcon, was used to navigate a virtual environment representing a zoo. Rather than presenting gaming or competitive elements, participants were presented with educational content about the zoo and some of its exhibits. Subjects controlled the movement of a cursor along a predefined trajectory superimposed on a map of New York City's Bronx Zoo to learn from the zoo-related content presented, and answer scientific questions. The task engaged the participants cognitively, and simultaneously enhanced visuomotor dexterity. The findings suggest that educational content may be used to increase the level of interest in the activity, time spent in rehabilitation, and can increase participant satisfaction. Building on this infrastructure, and shifting from passive scientific learning to active science participation, another study used citizen science to boost motivation in rehabilitation [98]. Here participants used a haptic joystick to tag images of a polluted environment and contribute to the analysis of data as part of an authentic environmental monitoring project [99]. The results suggested that users were more willing to repeat their exercises when they had an authentic citizen science task to perform as part of their therapy. The Novint Falcon used in these studies [97, 98] is a low-cost haptic device capable of both providing programmed force-feedback, and recording end-effector position data at a high rate. Importantly, it was demonstrated that performance metrics using data collected from the Novint Falcon can distinguish between participants without disabilities and those undergoing stroke rehabilitation [98], suggesting that it can measure progress during rehabilitation.

It may be reasonable to argue that rehabilitative exercises can be more easily, effectively, and routinely executed from the comfort of the home when compared to clinical environments. However substantial progress remains to be made to make robot-assisted home-based telerehabilitation an affordable reality. While some consumer grade low-cost and portable devices, such as the Novint Falcon or the Java therapy system, can easily be adopted in a confined home environment, they cannot be used to practice large shoulder and arm movements often needed during rehabilitation [100]. To address this issue, consumer motion capture systems have been adopted both for human motion analysis and rehabilitation [101]. For example, the Microsoft Kinect is a camera-based human motion tracking device that is able to estimate the coordinates of the joints of a human skeleton model in three dimensions [102]. Similar to the aforementioned gaming systems, it was originally intended to be used as an input device for videogames, but has been repurposed for use as a natural user interface [103], whereby the captured motion, often in the form of gestures [104], is used as input for human-computer applications [105]. This functionality has enabled the use of the Kinect in both human motion analysis [106] and rehabilitation [107, 108]. Adding to the versatility of the Kinect is its ability to be paired with a personal computer rather than a gaming console, making the development of custom rehabilitation interfaces and virtual environments more straightforward. Custom game-based rehabilitation software has been developed for the Kinect, which requires the user to perform therapeutic gestures to accomplish the goals of the game [107], with most participants reporting the experience to be both enjoyable and challenging. Importantly, the Kinect can estimate joint angles with accuracy comparable to professional-grade optoelectronic systems [109], suggesting that it can also be used to accurately gauge progress during rehabilitation. Most of the studies using the Kinect however focus on the upper limb [110].

Conclusions

The use of robotic technology has the potential to transform rehabilitation from a one-on-one human resource intensive treatment that can only be provided in specialized centers, to a technology driven, remotely-supervised and widely accessible enterprise. Given the increased costs associated with long-term rehabilitation and the difficulty in providing appropriate duration and intensity of rehabilitation services required to manage disability, cost-effective development of robotic rehabilitation is greatly warranted. Many new developments in the use of robotic technology include development of light-weight devices, use of off-the shelf devices, incorporation of motivational elements such as gaming, virtual reality, and educational and scientific tasks to provide user-friendly access to technology to empower therapists to provide rehabilitation more efficiently, and to empower patients to have greater access to rehabilitation. The true transformative potential of robotic rehabilitation will require the development of telerehabilitation that can be provided via low-cost devices to effectively and efficiently rehabilitate individuals in their own homes.

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