Rehabilitation Robotics

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Abstract

Robotic rehabilitation devices have become increasingly important and popular in clinical and rehabilitation environments to facilitate prolonged duration of training, increased number of repetitions of movements, improved patient safety, less strenuous operation by therapists, and eventually, to improve the therapeutic outcome. Novel assistive technologies are becoming available as wearable devices that allow transferring the therapeutic training into home and work environments or assist the patient in day-to-day activities. This monograph summarizes the rationale for robot-assisted therapy and presents the technological steps in the evolution of the design and development of lower and upper extremity rehabilitation robots. After presenting the basic mechanisms of natural and artificial movement restoration, and the rationale of robot-aided movement therapy, this monograph shows several design criteria that are relevant for the development of effective and safe rehabilitation robots. The robotic design depends on the kind of application (i.e., therapeutic or assistive), and varies with respect to different kinds of actuation and patient interaction principles, robotic complexities, and kinematic approaches. Several examples of gait and arm rehabilitation robots are presented that are in developmental status or already commercially available. Novel patient-cooperative strategies are presented, such as impedance control, assistance-as-needed control and tunnel (path) control. Such patient-cooperative strategies can increase movement variability and patient activity; both can have a positive effect on the therapeutic outcome. Special bio-cooperative control strategies and biofeedback methods are introduced that increase engagement and motivation during the therapy session. Standardized assessment tools implemented in robotic devices have shown to be a convenient and accurate method to evaluate the rehabilitation process of individual patients and entire patient groups, which can allow therapists and researchers to perform better intra and inter-subject comparisons. This monograph, which in several parts has an emphasis on the work from the author’s laboratory, finishes with a short overview about existing clinical trials that have been performed.
showing that the application of rehabilitation devices is at least as effective as the application of conventional therapies. It concludes with the finding that further clinical studies are required to find predictors for the success of a robot-aided treatment.
1

Introduction

1.1 Sociomedical need and motivation

Loss of the abilities to walk and grasp represents a major disability for millions of individuals worldwide, and a major expense for health care and social support systems. More than 700,000 people in the U.S. suffer from a stroke each year; 60–75% of these individuals will live beyond one year after the incident, resulting in a stroke survivor population of about 3 million people \[190, 370\]. Almost two-thirds of all stroke survivors have no functional ability and cannot move without assistance in the acute phase following the incident \[176\]. Similarly, for many of the 10,000 Americans who are affected by a traumatic spinal cord injury (SCI) per year, the most visible lingering disability is the lost or limited ability to walk \[362\].

One major goal in the rehabilitation of patients suffering from a movement disorder, such as stroke or SCI, is retraining locomotor and upper extremity function. The approach to stroke physiotherapy is diverse, as are the theoretical bases assumed by the physiotherapists who provide the therapy \[76, 82, 225, 249, 277, 282\]. Traditional methodology includes neuro-developmental training (NDT) \[26\], the
motor relearning program [49], proprioceptive neuromuscular facilitation [198], and the Rood approach [332].

The effects of the different kinds of training on gait have been shown to be modest, irrespective of the exact type of training [219]. NDT is particularly prevalent [21, 76, 225, 305], with the best known stream being the Bobath concept. Better outcomes in gait rehabilitation have been elicited from the more direct approach of body weight supported treadmill training [13, 86, 141, 148, 221, 237, 289, 340, 365, 366], where the patient walks on a treadmill with the body weight partially supported, and two or more therapists support the patient and guide their limbs where required. This type of therapy has the advantages of being task specific and repetitive but is often very physically intensive [282]. As a result, the training duration can be limited by the fitness of the therapists themselves.

Restoration of arm and hand function is essential to resuming daily-living tasks and regaining independence in life. Plenty of studies show that sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients (see [15, 93, 288] to mention just a few).

1.2 Natural and artificial mechanisms of movement restoration

Motion impairments resulting from neural and musculoskeletal lesions can be restored by natural and artificial mechanisms. The central nervous system is characterized by three basic natural mechanisms that can enable partial or complete restoration of sensor and motor functions. First, lost motor functions can be adapted or compensated by other existing functions not being affected by the lesion. Second, tasks of injured brain regions can be transferred to other non-affected brain regions by generation of new synaptic connections. This property is known as “plasticity” of the central nervous system. And third, damaged brain regions can partly recover via different regeneration principles. These mechanisms can be enhanced and accelerated by pharmaceutical, physiotherapeutic, or surgical treatments.

However, the recovery of the central nervous system is limited due to the presence of inhibiting factors. These inhibiting factors are missing
in the peripheral nervous system. Therefore, minor nerve damages (neuropathies) can heal without any additional treatment. After full nerve transection, an artificial nerve graft can be surgically inserted to support nerve growth.

Natural restoration of the musculoskeletal system is limited to healing effects of muscles and bones, e.g., after muscle fiber lesions or bone fracture, whereas any kind of amputations cannot be restored by natural mechanisms (such as in certain animals).

If the impairment of the nervous or musculoskeletal system cannot be restored by natural mechanisms, artificial technical support is required. Totally lost functions can be substituted by prostheses, whereas orthoses are used to support remaining (but impaired) body functions. A mechanical orthosis is an orthopedic apparatus used to stabilize, support, and guide body limbs during movements. Typical examples for mechanical orthoses are crutches, shells, and gait and stance orthoses. Orthotic devices for upper and lower extremities can be applied in two different ways: first, as therapy devices, usually in clinical settings that aim at restoring movement function based on intensive training, and second, as assistive devices that support activities of daily living (ADL) tasks in home and work environments, and at leisure. Also assistive devices can have a therapeutic effect on the patient.

1.3 Rationale for movement therapy

Task-oriented repetitive movements can improve muscular strength and movement coordination in patients with impairments due to neurological or orthopedic problems. A typical repetitive movement is the human gait. Treadmill training has been shown to improve gait and lower limb motor function in patients with locomotor disorders. Manually assisted treadmill training was first used approximately 20 years ago as a regular therapy for patients with SCI or stroke. Currently, treadmill training is well-established at most large neuro-rehabilitation centers, and its use is steadily increasing. Numerous clinical studies support the effectiveness of the training, particularly in SCI and stroke patients [12, 86, 141].
Introduction

Similarly, arm therapy is used for patients with paralyzed upper extremities after stroke or SCI. Several studies prove that arm therapy has positive effects on the rehabilitation progress of stroke patients (see [288], for review). Besides recovering of motor function and improving movement coordination, arm therapy serves also to learn new motion strategies, so-called “trick movements” or “compensatory movements”, to better cope with different ADL tasks.

Lower and upper extremity movement therapy serves also to prevent secondary complications such as muscle atrophy, osteoporosis, and spasticity. It was observed that longer training sessions and a longer total training duration have a positive effect on the motor function. In a meta-analysis comprising nine controlled studies with 1051 stroke patients Kwakkel et al. [212] showed that increased training intensity yields positive effects on neuromuscular function and ADL. This study did not distinguish between upper and lower extremities. The finding that the rehabilitation progress depends on the training intensity motivates the application of robot-aided arm therapy.

1.4 Neuronal basis underlying movement training

Stroke and traumatic brain or spinal cord injury result in neurological disorders associated with impaired or total loss of locomotion, hand function, and other body functions. Basic research studies in the animal model including the cat have shown that repetitive execution of the movement (supported by any external help) can improve motor function of the affected limbs, especially during locomotion [13]. These improvements seem to be based on neuroplasticity of the central nervous system at many levels and result in compensation for the loss of lesioned brain or spinal cord areas [70, 88, 246]. In SCI, the supraspinal control over the neural circuitry in the spinal cord is impaired, while the spinal and supraspinal neural centers underlying locomotion remain intact. Evidence for the existence of a human spinal pattern generator is indicated by the observation of spontaneously occurring step-like movements [46] and myoclonus [43] as well as from late flexion
reflexes \[43\] and from locomotor movements induced in body-weight supported paraplegic patients walking on a treadmill \[85, 86\]. Other studies have shown that a locomotor pattern may be induced and trained even in completely paraplegic patients when leg movements are assisted externally and an appropriate afferent input to the spinal cord is provided \[84, 85, 86, 87, 92\]. Nevertheless, the amplitude of leg muscle electromyographic (EMG) activity in these patients is small when compared with healthy subjects but increases during locomotor training sessions \[86\]. These studies provide indirect but sufficient evidence for the existence of a Central Pattern Generator (CPG) in human subjects. The spinal pattern generator and an appropriate proprioceptive feedback can be implemented in a training system to target neural circuits to induce plastic changes. Body un-loading and re-loading are considered to be of crucial importance to induce training effects upon the neurological locomotor centers because the afferent input from receptors signaling contact forces during the stance phase is essential for the activation of spinal locomotor centers \[136\]. Therefore, this cyclic loading is considered to be important for achieving training effects in cat \[280\] and man \[83, 90\]. Because the available muscle force is not sufficient to support the body weight during walking, partial body weight unloading is necessary in order to allow for stable and safe locomotor training. Recent findings demonstrated that following an acute, incomplete SCI in humans, an improvement of locomotor function was observed and was specifically attributed to the functional locomotor training \[88, 373\] in addition to the spontaneous recovery of spinal cord function that can occur over several months following SCI \[72, 73, 74, 184\].

1.5 Rationale for robot-aided training

Manually assisted movement training has several major limitations. Treatment for stroke, SCI, and other neurological diseases is very costly and accounts for a large percentage of health care budgets \[305\]. The training is labor-intensive, and, therefore, training duration is usually
Introduction

limited by personnel shortage and fatigue of the therapist, not by that of the patient. During treadmill training, therapists often suffer from back pain, because the training has to be performed in an ergonomically unfavorable posture. During upper extremity training, the therapist has to lift the arm of the patient, thus, carrying the complete weight of the upper limb or a portion of it. The disadvantageous consequence is that the training sessions are shorter than required to gain an optimal therapeutic outcome. Finally, manually-assisted movement training lacks repeatability and objective measures of patient performance and progress.

In contrast, with automated, i.e., robot-assisted, gait and arm training the duration and number of training sessions can be increased, while reducing the number of therapists required per patient. Long-term automated therapy can be an efficient way to make intensive movement training affordable for clinical use. One therapist may be able to train two or more patients at a time. Thus, personnel costs can be significantly reduced and more patients can be treated satisfying the need for a higher treatment capacity due to the increasing number of age-related neurological patients.

Furthermore, the robot provides quantitative measures, thus, allowing the observation and quantitative assessment of the rehabilitation process. Even more, some of the recorded data can be online-processed and displayed to the patient as “biofeedback” signals so that the patient immediately understands how she or he performs. This can help the patient to try to improve the movement pattern and performance during the robot-aided training sessions. This kind of feedback can be further exploited via the application of virtual reality (VR) technologies. Allowing the patient to perform a movement task within a virtual environment, does not only allow to instruct the patient in an easy, convenient, and very intuitive way, but it also increases the patient’s engagement during task execution and the general motivation to participate in the rehabilitation program.

These advantages of the use of robots as compared to conventional therapy are based on common wisdom and plausibility. Not many publications exist that prove these arguments yet.
1.6 Definition of “Rehabilitation Robotics” and scope

The term “Rehabilitation Robotics” has become popular in the early nineties of the last century, when the first assistive technologies, and a bit later, also rehabilitation training devices have been developed and become available for clinical use, some of them even on a commercial level. To better understand the meaning of the term “Rehabilitation Robotics” and to formulate a definition, it is worth to look into meaning of the two sub-terms “Robotics” and “Rehabilitation”.

According to Wikipedia a “Robot” can be defined as “a mechanical or virtual agent, usually an electro-mechanical machine that is guided by a computer program or electronic circuitry. Robots can be autonomous or semi-autonomous and range from humanoids [...] to industrial robots [...].” According to Oxford Dictionaries (2011) and Wikipedia, the term “Robotics” can be defined as “the branch of technology that deals with the design, construction, operation, and application of robots as well as computer systems for their control, sensory feedback, and information processing. These technologies deal with automated machines that can take the place of humans in dangerous environments or manufacturing processes, or resemble humans in appearance, behavior, and/or cognition.”

W. Reich from Uppsala University, Sweden, once described a robot as “an artificial, physically embodied ‘agent tool’” (Robots Podcast & Community, March 12, 2010, www.robotspodcast.com). According to his definition, a robot is a physical object, which has been constructed by someone and fulfills a function for someone, which makes it a ‘tool’, etc. Similarly, K. Makice defines a robot as “a physical machine manipulated to automatically perform an undesirable work function that supports a desired human outcome” and P. Agius claims that “A robot is an intelligent machine that moves, reacts and interacts with its environment in an autonomous manner” (Robots Podcast & Community, March 12, 2010, www.robotspodcast.com).

Many further definitions exist that are similar or deviate from above-mentioned descriptions. Robots applied to the field of rehabilitation can be considered as “service robots”, which have been defined as
“those robotics systems that assist people in their daily lives at work, in their houses, for leisure, and as part of assistance to the handicapped and elderly. [...] service robotics’ tasks are performed in spaces occupied by humans and typically in direct collaboration with people” [64].

The term “Rehabilitation” has its original meaning from the Latin term “habilitare” (to enable). State lawyer, physician, and politician Franz Josef Ritter von Buss was one of the first, who gave the term “Rehabilitation” its current meaning already in 1844. According to unconfirmed sources, he said that the “invalid person should rise up from the position he was descended”, and that “he should regain his/her feeling of dignity and with it a new life”. He already considers rehabilitation has a recovery of function to improve quality of life rather than (only) a healing of body structures.

A more modern definition was presented by C. Robinson, who defined rehabilitation as “the (re-)integration of an individual with a disability into society. This can be done either by enhancing existing capabilities or by providing alternative means to perform various functions or to substitute for specific sensations” [313]. His definition comprises two important aspects of rehabilitation. First, he mentions “enhancement of existing capabilities”, which can be achieved through therapy and training. And second, he speaks about “alternative means” to perform functions or to substitute sensations, which can be reached by the application of assistive technologies. Both meanings are relevant to reintegrate disabled people into society so that they can regain their dignity and reach a satisfactory quality of life, even if an impaired body structure cannot be completely restored (i.e., healed), such as limb amputation or spinal cord injury.

From the above-mentioned definitions, one could derive the following most generous definition:

**Rehabilitation Robotics is the application of robotic methods to train or assist an individual with a disability, supporting this individual to get (re-)integrated into society.**

This broad definition includes a variety of different mechatronic machines that support gait and arm therapy in a clinical setting,
1.6. Definition of “Rehabilitation Robotics” and scope

powered orthotics for use in daily life environments, actuated exo-
prosthetics, ranging even to intelligent wheelchairs that have some
autonomous function of mobility. Also devices supporting human
sensory and vegetative functions can be included, when the technol-
ogy is based on robotic methods.

This monograph focuses on robotic devices that provide a technical
support to the impaired human motor system. A large overview of
different technologies and approaches is presented that can be used for
the therapeutic training or daily assistance of mainly neurologically
impaired patients. Therefore, prosthetic technologies as well as sensory
restoration systems were excluded. Also wheelchair technologies have
not been treated in this overview. Several parts of this monograph
have an emphasis on the work from the author’s laboratory, thus this
monograph is not a complete, though a broad review of the field.
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