Multimedia Contents

64. Rehabilitation and Health Care Robotics

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The field of rehabilitation robotics considers robotic systems that 1) provide therapy for persons seeking to recover their physical, social, communication, or cognitive function, and/or that 2) assist persons who have a chronic disability to accomplish activities of daily living. This chapter will discuss these two main domains and provide descriptions of the major achievements of the field over its short history and chart out the challenges to come. Specifically, after providing background information on demographics (Sect. 64.1.2) and history (Sect. 64.1.3) of the field, Sect. 64.2 describes physical therapy and exercise training robots, and Sect. 64.3 describes robotic aids for people with disabilities. Section 64.4 then presents recent advances in smart prostheses and orthoses that are related to rehabilitation robotics. Finally, Sect. 64.5 provides an overview of recent work in diagnosis and monitoring for rehabilitation as well as other health-care issues. The reader is referred to Chap. 73 for cognitive rehabilitation robotics and to Chap. 65 for robotic smart home technologies, which are often considered assistive technologies for persons with disabilities. At the conclusion of the present chapter, the reader will be familiar with the history of rehabilitation robotics and its primary accomplishments, and will understand the challenges the field may face in the future as it seeks to improve health care and the well being of persons with disabilities.

64.1 **Overview** ... 1686
  64.1.1 Taxonomy of Rehabilitation Robotics ... 1686
  64.1.2 World Demographics ... 1687
  64.1.3 Short History of Rehabilitation Robotics ... 1688
64.2 **Rehabilitation Therapy and Training Robots** ... 1692
  64.2.1 Grand Challenges and Roadblocks ... 1692
  64.2.2 Movement Therapy After Neurologic Injury ... 1694
  64.2.3 Robotic Therapy for the Upper Extremity ... 1695
  64.2.4 Robotic Therapy for Walking ... 1699
64.3 **Aids for People with Disabilities** ... 1703
  64.3.1 Grand Challenges and Enabling Technologies ... 1703
  64.3.2 Types and Examples of Assistive Rehabilitation Robots ... 1705
64.4 **Smart Prostheses and Orthoses** ... 1711
  64.4.1 Grand Challenges and Roadblocks ... 1711
  64.4.2 Targeted Re-Innervation ... 1711
  64.4.3 Neural Interfaces for Limb Prosthetic Devices ... 1712
  64.4.4 Advances in Neural Stimulation ... 1713
  64.4.5 Embedded Intelligence ... 1713
64.5 **Augmentation for Diagnosis and Monitoring** ... 1713
  64.5.1 Grand Challenges and Enabling Technologies ... 1714
  64.5.2 Smart Homes for Health Care Monitoring and Care ... 1714
  64.5.3 Home-Based Rehabilitation Monitoring and Therapy Systems ... 1714
  64.5.4 Wearable Monitoring Devices ... 1715
64.6 **Safety, Ethics, Access and Economics** ... 1715
64.7 **Conclusions and Further Readings** ... 1716
Video-References ... 1717
References ... 1718

64.1 Overview

In this chapter, we discuss an application of robotics that will likely touch many of us in an acutely personal way at some point in our lives. When, through injury or disease, we become unable to interact physically with our immediate environment as we desire to achieve our personal goals, or when one of our family members, friends, or neighbors is in this situation, technology-based solutions will likely be a major component in the treatment interventions that therapists prescribe to assist us in re-learning how to complete our activities of daily living (ADL), or to assist us in actually doing them if we are unable to recover lost function. While human therapists and attendants can indeed shoulder the types of assistance required, the projected short-term demographics of many countries, including China, Japan, and the Scandinavian countries, show a growing shortage of working-age adults. Age-related disabilities will soon substantially impact the service sector job market, put many older and disabled people at risk, and increase the need for institutionalization when there is no viable home-based solution. National programs to develop personal robots, robotic therapy, smart prostheses, smart beds, smart homes, and tele-rehabilitation services have accelerated in the past 20 years and will need to continue apace with the ever increasing ability of health care to allow people to live longer through the repression of disease and improvement in surgical and medication interventions. Rehabilitation robotics, although only a 50 year old discipline [64.1–3], is projected to have a fast-growing future in the coming decades. Within the past 10 years, the field has seen significant strides in the commercialization of rehabilitation robotics due to an increasing acceptance of the validity of this approach by clinical care providers, as well as the cost reductions in sensors and actuators. We have also witnessed the expansion of applications from the social robotics research domain into rehabilitation, increasing the range of persons whose impairments can be targeted by robotic technologies in the years to come.

64.1.1 Taxonomy of Rehabilitation Robotics

The field of rehabilitation robotics is generally divided between the categories of *therapy* and *assistance* robots, although some devices can serve both purposes. In addition, rehabilitation robotics includes aspects of artificial limb (prosthetics) development, functional neural stimulation (FNS) and technology for diagnosis and monitoring of people during activities of daily living.

Therapy robots generally have at least two main users simultaneously, the person with a disability who is receiving the therapy and the therapist who sets up and monitors the interaction with the robot. As this type of therapy is moving into the home, a third user group has also become prominent: the disabled person's caregivers and family.

The Types of therapies that have benefited from robotic assistance are upper- and lower-extremity movement therapy, communication-enabling for children with autism and exploration-enabling (education) for children with cerebral palsy (CP) or other developmental disabilities (Chap. 73). A robot may be a good alternative to a physical or occupational therapist for the actual hands-on intervention for several reasons:

1. Once properly set up by a therapist – an essential role – an automated exercise machine can consistently apply therapy over long periods of time without tiring.
2. The robot's sensors can measure the work performed by the patient and quantify, to an extent not detectable by standard clinical scales, any recovery of function that may have occurred, which may be highly motivating for a person to continue in the therapy.
3. The robot may be able to engage the patient in types of therapy exercises that a therapist cannot do, such as computer game-based therapy or magnifying movement errors to provoke adaptation [64.4, 5].

One way to classify robotic solutions for application to rehabilitation therapy is by how they contact the patient [64.6].

Operational Therapy Robots (or End-Effector-Based Therapy Robots)

For these machines, the trajectories of the robot end-effector and that of the human end-effector, e.g., the hand or the foot, are physically coupled in operational space. In joint space, the trajectories of the robot joints and of the human joints can significantly differ. Main advantages of operational therapy robots are that: (a) they can be designed by using off-the-shelf components or robots; (b) they can be easily programmed in Cartesian space by nonexpert users. Main limitations are that: (a) they are not able to assist each single human joint independently; (b) patients using these robots are supposed to feature a minimum level of residual motor synergies in order to coordinate their own multijoint movement, producing the configurations of the affected limb required by the therapy exercise.

Wearable Therapy Robots (or Exoskeleton-Based Therapy Robots)

For these machines, a larger portion of the human body (typically the whole affected limb) is in continuous physical contact with the robot. In most cases, a biomimetic exoskeleton kinematic structure is selected. In this case, not only are the trajectories of the robot and human end-effectors the same in operational space, but the trajectories of the robot joints approximate those of the human joints in joint space. The main advantage of wearable therapy robots is the possibility of sensing the configuration and assisting each human joint independently. The main drawbacks of these systems are additional design considerations needed to avoid misalignments between robot and human joints, and to minimize the invasiveness for the patient in terms of weight, dimensions, and overall wearability (Sect. 64.2.4).

Non-Contact Therapy Robots (or Socially Assistive Robotics)

Robotic devices are also being developed for rehabilitation therapy that do not physically contact the patient, but instead monitor and coach the patient during therapy [64.7]. A key concept of this approach is that humans are wired to respond to embodied agents in ways that are important for motivation in rehabilitation therapy (see Chap. 73 for a detailed discussion of socially assistive robotics). One of the earliest robotic therapy devices, developed by Erlandson, can be classified as a socially assistive robot, as it provided reaching targets for patients rather than physically assisting movement [64.8] (see later). The main advantage of noncontact therapy robots is that of being intrinsically safe, since they are not supposed to physically interact with the patient, although this could limit significantly the scope of their clinical application.

From a design perspective, it is important to understand that therapy robots are tools typically intended for temporary use (i. e., the duration of the therapy at home or at the clinic), and are designed to maximize the objective clinical effectiveness of the therapy as well as the outcome and the efficiency of the entire clinical process.

Assistive robots, instead, are solutions for promoting independent living of disabled and elderly citizens. They need to be designed to be usable in a lifelong perspective in real-life scenarios, and thus, designers need to take into account (at a much more serious level than in the case of therapy robots) the end-user subjective preferences, and human factors, in general, in order to maximize their overall, long-term acceptability [64.6]. Whereas limited usability, some level of discomfort, or bad aesthetics might be tolerated by the patients experiencing the application of a therapeutic tool used in a gym or at home, these same factors are unacceptable for disabled or elderly persons who are supposed to depend upon an assistive robot for activities of daily living in a variety of social contexts for the rest of their lives.

Assistive robots can be grouped on the basis of their focus on manipulation, mobility, or cognition. Manipulation aids can further be classified into fixed-platform and portable-platform and mobile-autonomous types. Fixed-platform robots perform functions in the kitchen, on the desktop, or by the bed. Portable types are manipulator arms attached to an electric wheelchair to hold and move objects and to interact with other devices and equipment, as in opening a door. Mobile-autonomous robots can be controlled by voice or other means to do manipulation and other errands in the home or workplace. Mobility aids are divided into electric wheelchairs with navigation systems and mobile robots that act as smart, motorized walkers, allowing people with mobility impairment to lean on them for fall-prevention and stability. The third main type, cognitive aids, assists people who have dementia, autism, or other disorders that affect communication and physical well-being.

The fields of prosthetics, orthotics, and functional electrical stimulation (FES) are closely allied with rehabilitation robotics. Prostheses are artificial hands, arms, legs and feet that are worn by the user to replace amputated limbs. Prostheses are increasingly incorporating robotic features [64.9, 10]. Robotic orthoses are actuated braces that can assist a person in walking or moving the arms or hands. FES systems seek to reanimate limb movements of people who are weak or paralyzed by electrically stimulating nerve and muscle. FES control systems are analogous to robotic control systems, except that the actuators being controlled are human muscles. Another related field is technology for monitoring and diagnosing health care issues as a person performs activities of daily living.

This chapter is organized according to this taxonomy. After providing background information on demographics (Sect. 64.1.2) and history (Sect. 64.1.3) of the field, Sect. 64.2 describes rehabilitation therapy and training robots, and Sect. 64.3 describes robotic aids for people with disabilities. Section 64.4 then reviews recent advances in smart prostheses and orthoses that are related to rehabilitation robotics. Finally, Sect. 64.5 provides an overview of recent work in diagnosis and monitoring for rehabilitation as well as other healthcare issues.

64.1.2 World Demographics

Different areas of rehabilitation robotics focus on different user populations, but a linking characteristic of these populations is that they have a disability. Disability is defined in the US with the Disabilities Act as *A physical or mental impairment that substantially limits one or more of the major life activities*. Worldwide disability, based on survey results from the WHO ranges from about 10 to 40% of the population, depending on gender, age, wealth, and residence, with an overall prevalence of about 16% (Table 64.1). Prevalence is the proportion of a population who have (or had) a specific characteristic in a given time period. In medicine, typically this characteristic is an illness or impairment. Prevalence is usually expressed as a percentage (e.g., 5%,), or as the number of cases per 10 000 or 100 000 people, depending on how common the illness or risk factor is in the population. Across all other parameters, there is approximately a 4 : 1 disparity in disability rates in the elderly population (>60 years) over working-class adults. In addition, lower birth rates and life-extending health care are the dominant factors contributing to the aging of the population and concomitant rise in disability overall. Other factors, such as China's population control policies of the 1970s, have created a lack of working-age adults to support the world economy. These and other factors make it clear that rehabilitation robotics developers will be faced with users who, as a demographic group, have generally lower levels of sensory and motor capability, and may have impaired cognition as well. The urgency of making advances in this field is increasing in line with the demographics.

64.1.3 Short History of Rehabilitation Robotics

The history of rehabilitation robotics is almost as old as that of robotics itself, although emanating from very different sources. Several book chapters and papers have been written on the history of rehabilitation robotics in more detail than this section [64.1, 19, 20], and numerous papers in the proceedings of the IEEE International Conference on Rehabilitation Robotics also provide more grounding for historical perspective. The chronology below pays particular attention to early work and to projects with notable clinical and/or commercial impact.

Early robotics, starting in the late 1950s, focused on large manipulators to replace workers in factories for dirty, dangerous, and undesirable tasks. The earliest rehabilitation robots came from the field of prosthetics and orthotics (P&O). Both the Case Western University Arm (1960s) and the Rancho Los Amigos *Golden Arm* (early 1970s) (reviewed in [64.19]) were adaptations of replacement mechanical arms meant as powered orthoses [64.1]. The user drove the Golden Arm with a set of tongue-operated switches, joint-by-joint, an arduous means of endpoint control. In the mid-1970s, the Department of Veterans Affairs began funding a group at the Applied Physics Lab under the guidance of *Seamone* and *Schmeisser* to computerize an orthosis mounted on a workstation to perform activities of daily living (ADL) tasks such as feeding a person and turning pages [64.21]. For the first time, a rehabilitation robot had a command-type interface, not just a joint-by-joint motion controller.

The 1970s also saw the French Spartacus system being developed, guided by the vision of Vertut, for use by people with high-level spinal cord injury (SCI) as well as children with CP [64.22]. This system did not emerge from the P&O field but was developed by the French Atomic Energy Commission (CEA), which used large tele-manipulators for nuclear fuel rod handling. One of these was adapted so that people with movement impairment could control it using a joystick for pick-and-place tasks. A decade later, one of the researchers on the Spartacus project, *Kwee*, began the Dutch MANUS Project [64.23] a dedicated effort to develop the first wheelchair-mounted manipulator de-

Table 64.1 Prevalence of disability and aging in selected countries (after [64.18])

Country	Number people with disabilities	Percentage of population with disabilities	Number of elderly people	Percentage of population that is elderly
France	5 146 000	8.3	12 151 000	19.6
USA	52 591 000	20.0	35 000 000	12.4
Great Britain	4 453 000	7.3	12 200 000	29.5
Netherlands	1 432 000	9.5	2 118 808	13.4
Spain	3 528 220	8.9	6 936 000	17.6
Japan	5 136 000	4.3	44 982 000	35.7
Korea	3 195 000	7.1	16 300 000	36.0
Italy	2 609 000	4.8 [64.11]	12 302 000	20.3 [64.12]
Germany	7 101 682	8.7	16 844 300	21.0 [64.13]
China	84 600 000	6.5 [64.14]	122 880 000	9.1 [64.15]
India	21 000 000	1.8 [64.16]	67 117 826	5.6 [64.17]

signed expressly as a rehabilitation robot, not adapted from a design from another field.

In between, several other major programs were begun. In 1978, at Stanford University, and then with decades-long funding from the US Department of Veterans Affairs, Leifer started the Vocational Assistant Robot program, culminating in several clinically tested versions of the Desktop robot, DeVAR [64.3, 24, 25], the mobile version, MoVAR [64.26], and finally a Professional version, ProVAR, developed by *Van der Loos* et al., which had the advanced ability for the user to program tasks in an easy-to-use browser-type environment [64.27]. Although DeVAR briefly made it onto the market in the early 1990s, multisite user testing revealed this industrial-arm-based approach to assistive robotics was still too costly for the low level of functionality achieved, even with ProVAR's advanced interface.

In the mid-1980s, from observations on the unsuitability of existing industrial, educational and orthosis-derived manipulators for rehabilitation applications, Tim Jones at Universal Machine Intelligence (later Oxford Intelligent Machines: OxIM) in the UK began an intensive effort to provide the rehabilitation robotics community with its first workhorse system especially designed from the ground up for human service tasks. Over 10 years, a series of systems, starting with the RTX model, were used in numerous research labs and clinics around the world. The most extensive effort to use the OxIM arm was in France, and a suite of research projects, funded by the French government and the European Research Commission, starting as RAID, then as MASTER [64.28], developed and clinically tested workstation-based assistive systems based on the RTX and subsequent OxIM arms. When OxIM ceased building its arms, the French company Afma Robotics [64.29] took over efforts to commercialize the MASTER system, although it has also stopped production.

The UK witnessed the first commercially available feeding robot, Handy-I, an inexpensive and well-received device first designed by *Topping* and then commercialized by Rehabilitation Robotics, Ltd. in the 1990s [64.30]. Primarily for people with CP to achieve a measure of independence in feeding themselves, task environments later also included face washing and applying cosmetics, areas of high demand identified by its users.

The history of mobile manipulator applications began in the 1980s with adaptations of educational and industrial robots, and achieved a boost with the funding of the US National Institute on Disability and Rehabilitation Research (NIDRR) for a Rehabilitation Engineering Research Center on Rehabilitation Robotics (RERC) at the AI duPont Hospital in Delaware from 1993 to 1997. With its ability to fund dozens of research projects in parallel, it also formed a partnership with a local company, Applied Resources, Corp. (ARC), which developed and marketed several rehabilitation technology products. One of the RERC researchers, *Mahoney*, moved to ARC and was instrumental in extending the company's repertoire to the RAPTOR wheelchair-mounted arm [64.31].

In Europe, the most significant mobile manipulator project was the MANUS Project [64.23] mentioned earlier. With much of the work done under the direction of Kwee at the iRV (Rehabilitation R&D Center) in the Netherlands, the project culminated in a robot specifically designed for wheelchair mounting, with user control through a joystick and feedback by a small display on the arm itself. This project led to numerous follow-on research projects, and, most significantly, to the commercialization of the system by Exact Dynamics, BV, in the Netherlands. The company's current product, called the iARM, is provided on physician prescription by the Dutch Government to qualified people with a disability, such as CP or tetraplegia from an SCI.

Realizing a potential growth in this market niche, the Canadian company, Kinova Robotics, in 2009 began commercializing a competing product, called the Jaco Arm [64.32], with a different design approach. Using carbon fiber segments and lightweight actuator and control components, the payload specifications and control options are approximately the same as for the iARM, but achieved at a lower arm weight.

Autonomous navigation systems on electric wheelchairs began in the 1980s also, benefiting initially from the development by Polaroid Corp. of range finders for its cameras using ultrasonic sensors. They were inexpensive, and small enough, at 30 mm in diameter, that dozens of them could be placed around the periphery of a wheelchair to aid medium-range navigation (≈10–500 cm). In the 1990s and early 2000s, with the advent of vision-based servoing and laser-range scanners, algorithms for faster, smarter, less-error prone navigation and obstacle avoidance dominated research advances in this sector. In Korea, for example, *Bien* et al., at the KAIST Human Welfare Robotics Center began developing the KARES line of wheelchair-based navigation systems in the late 1990s [64.33] and the NavChair project at the University of Michigan was the start of a development line that led to the commercialized Hephaestus system at the University of Pittsburgh [64.34, 35].

Therapy robots had a later start than assistive robots. Research on upper extremity therapy robots started in the mid-1980s with early exercise devices, such as the BioDex [64.36] a first step in programmable, force-controlled, albeit single-axis devices. The first multiaxis concept was published by *Khalili* and *Zomlefer* [64.37], and the first tested system by *Erlandson* et al. at Wayne State University emerged in the mid-1980s as well [64.8]. The RTX manipulator had a touch-sensitive pad as an end-effector, presenting targets at different locations for patients with upper extremity weakness (e.g., following a stroke) to hit after the screen gave a visual signal. Software logged response times, thereby providing a score that was tallied and compared to previous sessions. Later robots used advanced force-based control, which required significantly more computer power. The early-1990s saw the start of the MIT-MANUS Project with Hogan and Krebs, simple robotic devices designed for bimanual therapy after stroke designed by *Lum* et al. at U.C. Berkeley [64.38, 39], followed a few years later by the Palo Alto VA MIME (mirror image motion enabler) Project [64.40] and its derivative, Driver's SEAT [64.41], with Burgar, Van der Loos and Lum, as well as the Rehabilitation Institute of Chicago ARM Guide Project with *Reinkensmeyer* et al. [64.42]. Each had a different philosophy on upper extremity stroke therapy and each was able to demonstrate clinical effectiveness in a different way. Several of these programs, now two decades later, have made significant technical advances, and all the investigators are still active in the field. Current work is described in subsequent sections of this chapter.

Research on lower extremity therapy robots began with the work of Scherb in 1919 who proposed an approach called *mechanotherapy* [64.43]. He also developed a prototype, depicted in Fig. 64.1, of a cable-driven machine for assisting the motion of the lower limbs for bedridden patients. In 1976, the use of a master/slave exoskeleton system for lower limb therapy was introduced by the French physicians *Bel* and *Rabischong* [64.44], who developed a pneumatically actuated wearable robot to be used for assisted therapy of paraplegic patients (Fig. 64.2). The robot movements were remotely controlled by a therapist who wore a master device capable of sensing and recording the configuration of her/his lower limbs.

About 20 years later, the Lokomat project for the development of a stand-alone, programmable wearable robot for lower extremity was launched and originated the establishment of the Hocoma company by Colombo and Hostettler. The first prototype of the Lokomat system [64.45] was developed in close cooperation with the Balgrist University Hospital in Zurich and initially applied to patients who had had spinal cord injuries (Fig. 64.3b). During the same time, *Hesse* and *Uhlenbroch* developed the Gait Trainer [64.46], (Fig. 64.3a), which allowed training without the use of a treadmill by controlling the center of mass (COM) in both in the vertical and horizontal directions.

In the last decade the growth in rehabilitation robotics has been characterized by the development of new devices (as explained above) as well as by new investigation methods aimed at understanding brain changes induced by rehabilitation. A recent clinical study [64.50] confirms that high-intensity, repetitive, and task-oriented training yields a faster learning and recovery time. Robots are also a key-enabling technology for labor-intensive and patient-tailored training as well as for accurately imposing spatial and temporal constraints within interactive scenarios so as to augment patient involvement [64.51]. A recent international online survey, distributed through professional organizations to therapists, has set out a set of important robotic rehabilitation device requirements [64.52], such as variety of arm movements, biofeedback to patients, adjustable resistance, and need for virtual activities. Robots offer the advantage of providing ob-

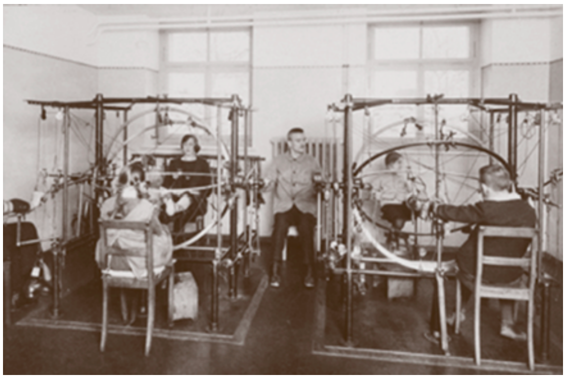

Fig. 64.1 The meridian. A universal machine for applying passive motion to any joint (after [64.43])

Fig. 64.2 This machine developed by Professor Rabischong allows the patient in rehabilitation to maintain her balance while inciting her muscles to move (after [64.47])

Fig.64.3a–e Gait-training robotic systems in use in clinics; **(a)** the gait trainer GT-I, developed by Hesse's group and commercialized by Reha-Stim (Germany), **(b)** the Lokomat, developed by Colombo and colleagues and commercialized by Hocoma AG (Switzerland), **(c)** AutoAmbulator, developed by the HealthSouth Corp. (USA), **(d)** LokoStation with Lokohelp (Darkov Spa, Czech Republic; after [64.48]), **(e)** G-EO Evolution (Panos Th. Skoutas S.A., Greece; after [64.49])

jective measures of user performance, thus enabling the development of quantitative kinematic and dynamic metrics [64.53–56]. The analysis of brain reorganization and associated clinical outcomes induced by robot-aided therapy in chronic stroke patients have shown that motor performance improvement is correlated with changes in inter-hemispheric connectivity between primary somatosensory areas: for those patients the connectivity returns to nearly *physiological levels* [64.57].

Protocols based on monitoring patient performance, strength, endurance, and emotional state are being investigated. Anticipating patient movement intentions and modeling internal states lead to adaptive patient–robot interaction control. This approach paves the way to a new generation of robotic therapy devices using *bio-cooperative* controllers, where *psychophysiological* and biomechanical information is used as feedback for updating robot control [64.58–60]. First examples of biocooperative controllers can be found in the robotic platforms developed within the European projects ECHORD/MAAT [64.56] (multimodal interfaces to improve therapeutic outcomes in robot-assisted rehabilitation) (Fig. 64.4) and MIMICS (multimodal immersive motion rehabilitation with interactive cognitive systems). Other bio-cooperative controllers have been developed by *Riener* and *Munih* [64.58], who developed new control strategies applied to lower limb

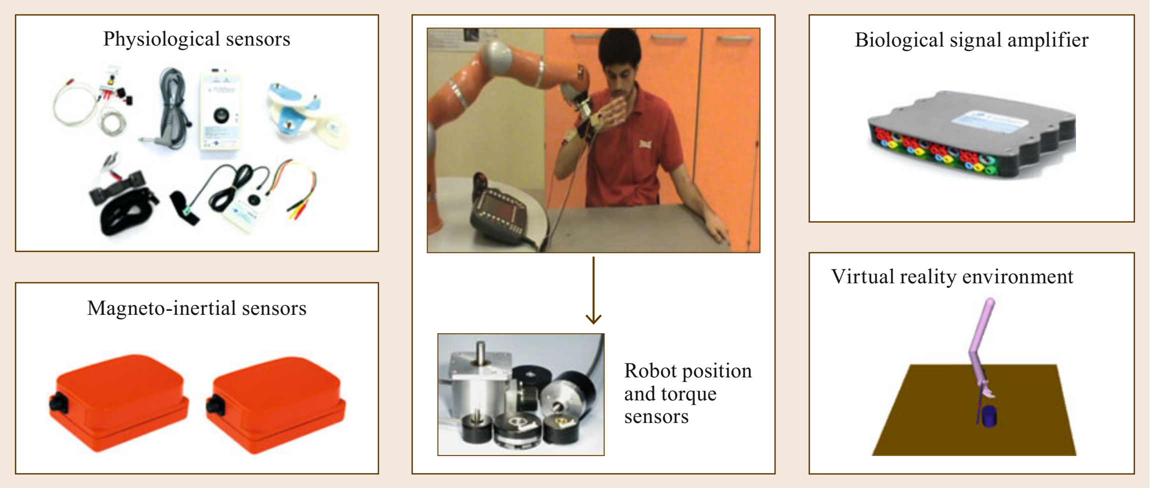

Fig. 64.4 Set up of the MAAT platform (after [64.61])

Fig. 64.5 PARO, an advanced interactive robot developed by AIST (after [64.62])

rehabilitation protocols that promote active participation of patients during training.

Cognitive robotics had started in the early 1980s to aid children with communication disorders and physical impairment to achieve a measure of control of their physical space. Using mostly educational manipulators, several demonstration systems were developed.

In the early 2000s, Latham of Anthrotronix, Inc. commercialized small robot systems to enable children with physical disabilities to play games with simple interfaces. A bit later, small mobile robots were used in clinics by *Dautenhahn* and *Werry* [64.63] with children who had autism, since robots have such simple interfaces that they appear not to be that challenging as communication with other humans. The early 2000s also saw the advent of pet robots, such as the Paro seal robot developed by *Shibata* et al. [64.64] (Fig. 64.5), as companions for both children and the elderly who are confined to clinics and have limited real companionship. This topic is further elaborated in Chap. 73.

The applications for robotics continues to increase in number as advances in materials, control software, higher robustness, and the diminishing size of sensors and actuators allow designers to attempt new ways of using mechatronics technology to further the well-being of people with disabilities.

64.2 Rehabilitation Therapy and Training Robots

The human neuromuscular system exhibits use-dependent plasticity, which is to say that use alters the properties of muscles and neurons, including the pattern of their connectivity, and thus their function [64.65–67]. For a detailed description of patient populations expected to benefit from robot-assisted therapy and the most common impairments to be treated, which include incoordination, abnormal synergies, spasticity and weakness, please see [64.50, 68–70].

64.2.1 Grand Challenges and Roadblocks

The process of neurorehabilitation seeks to exploit use-dependent plasticity in order to help people to relearn how to move following neuromuscular injuries or diseases. Neurorehabilitation is typically provided by skilled therapists, including physical, occupational, and speech therapists. This process is time-consuming, involving daily, intensive movement practice over many weeks. It is also labor-intensive, requiring hands-on assistance from therapists. For some tasks, such as teaching a person with poor balance and weak legs to walk, this hands-on assistance requires that the therapists have substantial strength and agility to provide safe and effective interventions.

Because neurorehabilitation is time and labor intensive, in recent years healthcare players have put limits on the amount of therapy that they will reimburse in an effort to contain spiraling healthcare costs. Ironically, at the same time, there has been increasing scientific evidence that more therapy can in many cases increase movement recovery via use-dependent plasticity [64.71]. As robotics and rehabilitation researchers began to recognize beginning in the late 1980s, neurorehabilitation is a logical target for automation because of its labor-intensive, mechanical nature, and because the amount of recovery is linked with the amount of repetition. Robots could deliver at least the repetitive parts of movement therapy at lower cost than human therapists, allowing patients to receive more therapy, recover more function, remain independent longer, and reduce downstream healthcare expenses.

The grand challenge for automating movement therapy is determining how to optimize use-dependent plasticity. That is, researchers in this field must determine what the robot should do in cooperation with the patient's own movement attempts in order to maximally improve movement ability, all the while engaging the patient. Meeting this challenge involves solving two key problems: determining appropriate movement tasks (what movements should patients practice and what feedback should they receive about their performance), and determining an appropriate pattern of mechanical input to the patient during these movement tasks (in other words, at what magnitude, how often, and in which directions, should the robot apply forces to the patient's limb to provoke increased plasticity). The prescription of movement tasks and mechanical input fundamentally constrains the mechanical and control design of the robotic therapy device.

There are three main roadblocks to achieving the grand challenge. The first is a scientific roadblock: neither the optimal movement tasks nor the optimal mechanical inputs are known. The scientific basis for neurorehabilitation remains ill-defined, with competing schools of thought. The number of large, randomized, controlled trials that have rigorously compared different therapy techniques is still small, in part because these trials are expensive and difficult to control well. Therefore, the first problem that a robotics engineer will encounter when setting out to build a robotic therapy device is that there is still substantial uncertainty as to what exactly the device should do.

This uncertainty corresponds to an opportunity to use robotic therapy devices as scientific tools themselves. Robotic therapy devices have the potential to help identify what exactly provokes plasticity during movement rehabilitation, because they can provide well-controlled patterns of therapy. They can also simultaneously measure the results of that therapy. Better control over therapy delivery and improved quantitative assessment of patient improvement are two desirable features for clinical trials that have often been lacking in the past. Recent work with robotic movement training devices is leading, for example, to the characterization of computations that underlie motor adaptation, and then to strategies for enhancing adaptation based on optimization approaches [64.5, 72, 73]. Early work at UBC on the characterization of human balance in quiet standing will lead to the ability to use robotics clinically to develop new therapies to prevent falls for stroke survivors and others with balance impairment [64.74, 75].

The second roadblock is a technological one: robotic therapy devices often have as their goal to assist in therapy of many-body degrees of freedom (e.g., the arms and torso for reaching, or the pelvis and legs for walking). The devices also require a wide dynamic bandwidth such that they can, for example, impose a desired movement on a patient who is paralyzed, but also *fade-to-nothing* as the patient recovers. Further, making the devices lightweight enough to be wearable is desirable, so that the patient can participate in rehabilitation in a natural setting (for example, by walking over ground or working at a counter in a kitchen), or even throughout the course of normal activities of daily living. The development of high degree-of-freedom, wearable, high-bandwidth robotic exoskeletons is an unsolved problem in robotics, although much progress has been made toward this goal in the last 10 years, as described below. Still, no device at present comes close to matching the flexibility of a human therapist, in terms of assisting in moving different body degrees of freedom in a variety of settings (e.g., walking, reaching, grasping, neck movement), or the intelligence of a human therapist, in terms of providing different forms of mechanical input (e.g., stretching, assisting, resisting, perturbing) based on a real-time assessment of the patient's response.

The third roadblock is maintaining the motivation and engagement of the patient through the tens of thousands of repetitions required to achieve meaningful increases in function [64.50] that will carry over to performing actual ADLs. Rehabilitation can be compared to the exercise required by an athlete to compete at an elite competition level. By necessity, therapy at this intensity will have to move largely to the home setting to be economically viable, and therefore motivation becomes the key ingredient of success. Current work focuses on developing adaptive therapy through robotics and feedback, embedding therapy in computer games, music, and sport, and applying motor-learning theories, for example, the *Challenge Point* [64.76] model of keeping people at a desirable difficulty level, to maximize effectiveness and minimize frustration over the long term [64.76]. Meeting the grand challenge of robotic therapy therefore will require substantial, inter-related advances in clinical neuroscience, robot engineering, and kinesiology.

64.2.2 Movement Therapy After Neurologic Injury

Modern, evidence-based medicine relies on objective evaluation and quantitative comparative analysis of the impact of different therapeutic approaches. Robotics technology has the potential to boost evidence-based neurorehabilitation: therapy robots provide precise and sensitive tools for assessing and modeling human behavior, well beyond the capability of a human observer. This is of paramount importance for enabling appropriate initial diagnosis, early adoption of corrective clinical strategies, and for identifying verifiable milestones as well as prognostic indicators of the recovery process.

Bosecker et al. [64.77] tried to evaluate clinical scores during upper limb therapy by means of robot-based metrics; *Zollo* et al. [64.54, 78] evaluated robotic therapy exploiting robotic outcome; thus providing quantitative measure of biomechanical and motion planning features of arm motor control following upper limb rehabilitation. A recent study carried out by *Krebs* et al. showed that robotic measurements of arm movements after upper limb, robot-aided therapy may establish biomarkers for motor recovery [64.79]. Similarly, *Domingo* and *Lam* [64.80] tried to apply robot-based assessment to the lower limb by using the Lokomat system and customized software.

Another important advantage of therapy robots is the possibility that a single operator can effectively supervise multiple patients, locally or even remotely, i. e., in a telerehabilitation scenario [64.81]. Therapy robots can potentially improve patients' access to rehabilitation by providing the opportunity to increase the duration and the frequency of their therapy experience, with limitations mainly depending on clinical considerations rather than on other organizational or economic constraints.

At present, much of the activity in physical therapy and training robots has been focused on retraining movement ability for individuals who have had a stroke or SCI, or are affected by CP. The main reasons for this emphasis are that there are a relatively large number of patients with these conditions, the rehabilitation costs associated with them are high, and because these patients can sometimes experience large gains with intensive rehabilitation because of use-dependent plasticity.

A stroke refers to an obstruction or breakage of a blood vessel supplying oxygen and nutrients to the brain. Approximately 800 000 people suffer a stroke each year in the United States, and about 80% of these people experience acute movement deficits [64.82]. In Europe, 1 100 000 people suffered a stroke in 2000, and they are expected to increase up to 1 500 000 in 2025. There are over 3 000 000 survivors of stroke in the United States [64.83], with over half of these individuals experiencing persistent, disabling, movement impairments. Data are similar to those of Europe, where it has been estimated that between half and two-thirds of people survive stroke. Of these, half do not recover fully, and a quarter need assistance in daily living. While most of the survivors of stroke are elderly persons, motor impairment from a stroke affects 3000 of the 10 000 children born with CP each year [64.83]. While this is a small proportion of all stroke survivors, the motor function impairment will persist throughout the person's entire life, so the impact on independence is disproportionately large.

The number of people who have experienced and survived a stroke is expected to increase substantially in the United States and other industrialized countries in the next two decades, mostly because age is a risk factor for stroke and the mean age of people in industrialized countries is rapidly increasing due to the baby boom of the 1950s, but also because improved acute treatments will allow more people to survive a stroke, albeit perhaps with impairment.

The number of people who experience an SCI in the United States each year is relatively smaller – about 15 000, with about 200 000 people alive who have survived an SCI – but the consequences can be even more costly than stroke [64.82]. In Europe, there are about 11 000 new cases of SCI per year, and about 330 000 have survived an SCI [64.84]. The most common causes of SCI are automobile accidents and falls. These accidents crush the spinal column and contuse the spinal cord, damaging, or destroying neurons within the spinal cord. Lower limb robotic therapy has demonstrated promising results when applied to SCI patients with incomplete lesions [64.85] although large, systematic, and randomized controlled trials are still missing. It is important to note that SCI patients are typically younger than stroke patients, which may affect their familiarity with and acceptance of technical aids.

64.2.3 Robotic Therapy for the Upper Extremity

This section first describes early, clinically tested upper limb therapy robot systems (Fig. 64.6a–e), then more recent systems.

MIT-MANUS

The first robotic therapy device to undergo extensive clinical testing, and, now, to achieve some commercial success, is the MIT-MANUS, sold as the InMotion2 by Interactive Motion, Inc. [64.86]. MIT-MANUS is a planar two-joint arm that makes use of the SCARA configuration, allowing two large, mechanically grounded motors to drive a lightweight linkage. The patient sits across from the device, with the weaker hand attached to the end-effector, and the arm supported on a table with a low-friction support. By virtue of the use of the SCARA configuration, the MIT-MANUS is perhaps the simplest possible mechanical design that allows planar movements while also allowing a large range of forces to be applied to the arm without requiring force feedback control.

MIT-MANUS assists the patient in moving the arm across the table-top as the patient plays simple video games, such as moving a cursor into a target that changes locations on a computer screen. Assistance is achieved using a position controller with an adjustable impedance. Additional modules have been developed for the device for allowing vertical motion [64.87], wrist motion [64.88], and hand grasp [64.89]. Software has been developed for providing graded resistance as well as assistance to movement [64.90], and for varying the firmness and timing of assistance based on real-time measurements of the patient's performance on the video games [64.91].

MIT-MANUS has undergone extensive clinical testing in several studies, summarized as follows. The first clinical test of the device compared the motor recovery of acute stroke patients who received an additional dose of robot therapy on top of their conventional therapy, to that of a control group, who received con-

Fig.64.6a–e Arm-therapy robotic systems that have undergone extensive clinical testing; **(a)** MIT-MANUS, developed by Hogan, Krebs, and colleagues at the Massachusetts Institute of Technology (USA), **(b)** MIME, developed at the Department of Veterans Affairs in Palo Alto in collaboration with Stanford University (USA), **(c)** GENTLE/s developed in the EU, **(d)** ARM-Guide, developed at the Rehabilitation Institute of Chicago and the University of California, Irvine (USA), and **(e)** Bi-Manu-Track, developed by Reha-Stim (Germany)

ventional therapy and a brief, sham exposure to the robot [64.92]. The robot group patients received the additional robotic therapy for an hour each day, five days per week, for several weeks. The robot group recovered more arm movement ability than the control group according to clinical scales, without any increase in adverse effects such as shoulder pain. The improvements might subjectively be characterized as *small but somewhat meaningful to the patient*. The improvements were sustained at a three-year follow-up.

This first study with MIT-MANUS demonstrated that acute stroke patients who received more therapy recover better, and that this extra therapy can be delivered by a robotic device. It did not answer the question as to whether the robotic features of the robotic device were necessary. In other words, it may have been that patients would have also improved their movement ability if they had practiced additional movements with MIT-MANUS with the motor's off (thus making it equivalent to a computer mouse), simply by virtue of the increased dose of movement practice stimulating use-dependent plasticity. Thus, while this study indicated the promise of robots for rehabilitation therapy, it did not close the gap of knowledge as to how external mechanical forces provoke use-dependent plasticity.

Subsequent studies with MIT-MANUS have confirmed that robotic therapy can also benefit chronic stroke patients [64.93]. The device has been used to analyze different types of therapies, for example, to compare assisting movement versus resisting movement in chronic stroke subjects, but with inconclusive results: both types of therapies produced benefits [64.90]. The device has also been used to compare assistive robot therapy with another technological approach to rehabilitation – electrical stimulation of finger and wrist muscles [64.94]. Again, significant benefits were found for both therapies, and those benefits were specific to the movements practiced, but the benefits were not significantly different between therapies. We note that the lack of a significant difference in these studies may simply be due to the limited number of patients who participated in these studies (i. e., inadequate study power), rather than a close similarity of the effectiveness of the therapies.

As mentioned above, the MIT-MANUS device was recently tested in a multisite clinical trial funded by the Department of Veterans Affairs in the United States [64.50]. This study compared clinical outcomes in chronic stroke survivors who were randomized to three groups: usual care, robot-assisted therapy with arm, wrist, and hand modules, and one-on-one therapy with a rehabilitation therapist that was dose matched to the robotic therapy in terms of the number of movements achieved per therapy session. The robot-assisted therapy group improved their movement ability more than the usual care, and about the same as the dose-matched group. This is an important finding for the field, as it demonstrated with the highest scientific rigor that robotic therapy was about as effective as an intense, therapist-delivered therapy.

A cost-benefit analysis of this study suggested that although both robotic and intense, therapist-based therapies were more expensive to deliver than usual care, it reduced long-term follow-up costs, so that the total cost of care of the patients was the same over the duration of the study [64.95]. Thus, as the cost of robotic therapy devices decreases, it should be possible to provide patients with improved outcomes while reducing the cost of therapy – another important finding.

MIME

Another early system to undergo clinical testing was the MIME (mirror-image movement enhancer) system, which used a Puma-560 robot arm to assist in movement of the patient's arm [64.96]. The device is attached to the hand through a customized splint and a connector that is designed to break away if interaction forces become too large. Compared to MIT-MANUS, the device allows more naturalistic motion of the arm because of its six degrees of freedom (DOF), but must rely on force feedback so that the patient can drive the robot arm. Four control modes were developed for MIME. In the passive mode, the patient relaxes and the robot moves the arm through a desired pattern. In the active assist mode, the patient initiates a reach toward a target, indicated by physical cones on a table top, which then triggers a smooth movement of the robot toward the target. In the active-constrained mode, the device acts as a sort of virtual ratchet, allowing movement toward the target, but preventing the patient from moving away from the target. Finally, in the mirror-image mode, the motion of the patient's less impaired arm is measured with a digitizing linkage, and the impaired arm is controlled to follow along in a mirror-symmetric path. The initial clinical test of MIME found that chronic stroke patients who received therapy with the device improved their movement ability about as much as patients who received conventional table-top exercises with an occupational therapist [64.96]. The robot group even surpassed the gains from human-delivered therapy for the outcome measures of reaching the range of motion and strength at key joints of the arm. A follow-on study attempted to elucidate which of the control modes or what combination of MIME exercises caused the gains, but was inconclusive [64.97]. A multisite randomized control of MIME again funded by the Department of Veterans Affairs compared the effect of a high-dose (30 h) of additional therapy with MIME, to a lower dose (15 h), to 15 h of additional conventional therapy in 54 acute stroke patients [64.98]. Gains in the primary outcome measure, the Fugl-Meyer assessment, were not significantly different between the groups at the 6-month follow-up, although there the actual dose of robotic therapy patients received predicted their recovery.

ARM Guide

The question of the effect of robot forces on movement recovery was also left unresolved by a study with another device, the ARM Guide, which is a trombone-like device that can be oriented then locked in different directions, and can assist people in reaching in a straight line. Chronic stroke patients who received assistance during reaching with the robot improved their movement ability [64.99]. However, they improved about as much as a control group that simply practiced a matched number of reaches without assistance from the robot. This suggests that movement effort by the patient is a key factor for recovery, although the small sample size of this study limited the ability to resolve the size of the difference between guided and unguided therapies.

Bi-Manu-Track

Perhaps the most striking clinical results generated so far have come from one of the simplest devices built. Similar to a design proposed previously by *Lum* et al. [64.39], the Bi-Manu-Track uses two motors, one for each hand, to allow bimanual wrist-flexion extension [64.100]. The device can also assist in forearm pronation/supination if it is tilted downward and the handles are changed. In an extensive clinical test of the device, 22 subacute patients (i. e., 4–6 weeks after stroke) practiced 800 movements with the device for 20 minutes per day, five days per week for six weeks [64.100]. For half the movements, the device drove both arms, and for the other half, the patient's stronger arm drove the motion of the more impaired arm. A control group received a matched duration of electrical stimulation (ES) of their wrist extensor muscles, with the stimulation triggered by voluntary activation of their muscles when possible, as measured by electromyography (EMG). The number of movements performed with EMG-triggered ES was 60–80 per session. The robot-trained group improved by 15 points more on the Fugl-Meyer scale, a standard clinical scale of movement ability with a range from 0 to 66 points in upper extremity function. It assigns a score of 0 (cannot complete), 1 (completes partially), or 2 (completes normally) for 33 test movements, such as lifting the arm without flexing the elbow. For comparison, reported gains in Fugl-Meyer score after therapy with the MIT-MANUS and MIME devices ranged from 0 to 5points [64.101].

Other Early Devices to Undergo Clinical Testing

Other early devices to undergo clinical testing are as follows. The GENTLE/s system uses a commercial robot, the HapticMaster, to assist in patient movement as the patient plays video games. The HapticMaster allows four degrees of freedom of movement and achieves a high bandwidth of force control using force feedback. Chronic stroke patients who exercised with GENTLE/s improved their movement ability [64.102, 103]. The Rutgers ARM robotic device uses low-friction pneumatic cylinders to help extend or flex the fingers, and has been shown to improve hand movement ability of chronic stroke subjects [64.104]. Simple force-feedback controlled devices, including a 1-DOF wrist manipulator and a 2-DOF elbow–shoulder manipulator, were also recently shown to improve movement ability of chronic stroke subjects who exercised with the devices [64.105]. A passive exoskeleton, the T-WREX arm orthosis, provides support to the arm against gravity using elastic bands, while still allowing a large range of motion of the arm [64.106]. By incorporating a simple hand-grasp sensor, this device allows substantially weakened patients to practice simple virtual reality exercises that simulate functional tasks such as shopping and cooking. Chronic stroke patients who practiced exercising with this nonrobotic device recovered significant amounts of movement ability, comparable with the Fugl-Meyer gains seen with MIT-MANUS and MIME. A randomized controlled trial of T-WREX in 28 chronic stroke subjects compared therapy with the device to conventional, table-top therapy [64.107] and found that the device was slightly more effective in improving patient's motor ability at the six-month follow-up according to the primary outcome measure, the Fugl-Meyer score, and that patients strongly preferred exercising with the device. T-WREX has been commercialized as the Armeo Spring upper extremity training device by Hocoma, and was in use in over 500 clinics as of early 2014, with published reports studying its use for individuals with multiple sclerosis [64.108], SCI [64.109], and proximal humeral fracture [64.110]. NeReBot is a 3-DOF wire-based robot that can slowly move a stroke patient's arm in spatial paths. Acute stroke patients who received additional movement therapy beyond their conventional rehabilitation therapy with NeReBot recovered significantly more movement ability than patients who received just conventional rehabilitation therapy [64.111]. RehaRob uses an industrial robot arm to mobilize patients' arms along arbitrary trajectories following stroke [64.112].

Further Research and Developments on Robotic Therapy for the Upper Extremity

One recent trend in the field is to develop devices that can provide therapy for a larger number of degrees of freedom of the arm. For example, at the high end of cost and complexity are the ARMin [64.113], Pneu-WREX [64.114], and BONES [64.115], which are exoskeletons that accommodate nearly naturalistic movement of the arm while still achieving a wide range of force control. A system that couples a immersive virtual reality display with a haptic robot arm is described in [64.116]. A wearable exoskeleton driven by pneumatic muscles is described in [64.117]. Several other exoskeletal machines have been proposed to jointly train arm and wrist, such as the CADEN-7, an anthropometric 7-DOF powered exoskeleton system [64.118]; the SUEFEL-7, which exploits EMG signals to adjust impedance parameters [64.119]; a lightweight exoskeleton described in [64.120], and the highly redundant 9-DOFs machine introduced in [64.121].

Another area of active development in robotic therapy devices for the upper extremity is to devices that can be used at home or in rank-and-filed clinics. For example, at the lower end of cost/complexity are devices that use force feedback joysticks and steering wheels with a view toward implementation in the home [64.114–125]. In 2008, a planar machine for upper limb rehabilitation designed for delivering at-home neurorehabilitation, namely CBM MOTUS, was developed and patented [64.126] (Fig. 64.7). Such a device has low inertia and highly isotropic behavior. Recently, a passive module has been developed to be installed on the CBM-MOTUS, able to further reduce robot perceived inertia when the machine is moved by the patient, while being highly rigid when the machine assists the patient's movements.

As far as wearable robotic systems for the upper limb are concerned, Hocoma engineered and commercialized the ARMEO power system, and also the ArmeoSpring and ArmeoBoom machines [64.108].

A third area in robotic therapy devices for the upper extremity that has received increased attention is to develop devices for hand rehabilitation, since hand movement ability is essential for functional recovery. Examples of recent, novel robotic devices for the hand are the Haptic Knob for grasping and wrist pronation/supination [64.128]; the HandCARE, a cable-actuated rehabilitation system [64.129]; a device for repeating controlled passive movements of paralyzed fingers given in [64.130]; the exoskeletal machines HWARD [64.131], and HEXORR [64.132] to help open and close the hand; the 18-DOFs highly redundant Gifu Haptic Interface [64.133], able to produce adduction–abduction and flexion–extension finger movements. Other devices are presented in [64.134–138], and a review of robotic therapy of the hand is given in [64.139]. One robotic therapy system for the hand incorporates the idea of using visual feedback distortion to enhance motivation of patients during movement therapy [64.140]. A few commercial machines are available, such as the Reha-Digit, Amadeo, and ManovoSpring.

Based on the availability of modular hand, wrist, and shoulder–elbow therapeutic robotic devices, some recent studies tried to tackle the fundamental question of whether proximal or distal treatment differentially affect the recovery of arm/hand function. For more information of these preliminary studies, see references [64.100, 141, 142].

An important recent development in robotic therapy devices is the development of devices that can be used in conjunction with the instrumentation needed to measure neurophysiological signals, such as functional magnetic resonance imaging (fMRI)-compatible systems [64.143, 144] or, more generally, brain-imaging (BI)-compatible robotic systems that can be used in conjunction not only with fMRI but also with magne-

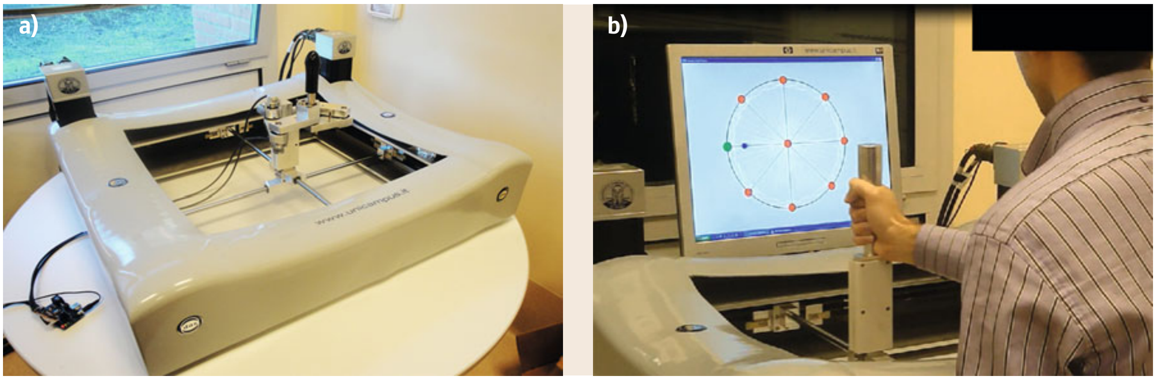

Fig.64.7a,b CBM Motus robot for upper limb rehabilitation (after [64.127])

toencephalography (MEG), transcranial magnetic stimulation (TMS), repetitive TMS (rTMS), transcranial direct current stimulation (tDCS), near infrared spectroscopy (NIRS) and other brain imaging and stimulation equipment. Such devices are notable because they will allow a systematic scientific study of neural recovery during robotic therapy. Developing these devices requires dealing with the problems of electromagnetic compatibility and interaction.

Recently, a few fMRI-compatible devices for hand rehabilitation have been designed to acquire functional imaging while performing therapeutic exercises, such as the exoskeletal machine in [64.145]; the pneumatic actuated 2-DOF device to help wrist pronation/supination and hand open/closure in [64.146]; machines driven by electro-rheological fluids, able to provide a variable resistance to patient motion [64.147]; the planar device to help move fingers described in [64.148]. A passive fMRI-compatible manipulandum morphologically similar to MIT-MANUS has been developed and tested to acquire functional imaging in [64.149]. Another study proposed the applications of a brain–computer interface (BCI) therapy approach on a cohort of stroke patients, [64.150]; a magnetoencephalography-based BCI system is used which in turn raised or lowered a screen cursor in the direction of a target. Results suggest that volitional control of neuromagnetic activity features recorded over central scalp regions can be achieved with BCI training after stroke.

Finally, the primary paradigm that has been tested so far with upper extremity robotics is to assist patients in moving, a strategy which may in some cases have the unintended affect of causing patients to *slack* [64.151]. In general, the field is still relatively undeveloped in its ability to identifying the most appropriate forms of robotic intervention given the nature of the impairment and the patient. For example, an approach opposite to physical assistance, which is using robotic force fields to amplify the kinematic errors of stroke patients during reaching, may provoke novel forms of the adaptation of those patterns [64.4, 152]. A major emphasis of the field in the next 10 years will be improving the mechanistic understanding of how robotic interaction influences brain plasticity.

64.2.4 Robotic Therapy for Walking

Scientific evidence that gait training improves the recovery of mobility after neurologic injury started to accumulate in the 1980s through studies with cats. Cats with SCI can be trained to step with their hind limbs on a treadmill with the partial support of body weight and assistance of leg movements [64.153, 154]. Following the animal studies, various laboratories developed a rehabilitation approach in which the patient steps on a treadmill with the body weight partially supported by an overhead harness and assistance from therapists [64.155–158]. Depending on the patient's impairment level, from one to three therapists are needed for BWSTT (body-weight supported treadmill training), with one therapist assisting in stabilizing and moving the pelvis, while two additional therapists sit next to the treadmill and assist the patient's legs in swing and stance. This type of training is based on the principle of generating normative, locomotor-like sensory input that promotes the functional reorganization and recovery of the injured neural circuitry [64.159]. In the 1990s, several independent studies indicated that BWSTT improves stepping in people with SCI or hemiplegia after stroke [64.155–157].

Gait training is particularly labor-intensive and strenuous for therapists, so it is an important target for automation. The efforts of roboticists have been especially focused on BWSTT rather than over-ground gait training because BWSTT is done on a stationary setup in a well-defined manner and thus can be more easily automated than over-ground gait training. Randomized, controlled clinical trials have shown that BWSTT is comparable in effectiveness to conventional physical therapy for various gait-impairing diseases [64.160–166]. These trials support the efforts toward the automation of BWSTT, as the working conditions of physical therapists will improve if the robots do much of the physical work, which, in the case of BWSTT, actually leads to occasional back injuries to therapists. Usually, only one therapist is needed in robot-assisted training, for the tasks of helping the patient into and out of the robot and monitoring the therapy. In the case of SCI patients, a small randomized, controlled trial [64.161] reported that robotic-assisted BWSTT with a first-generation robot required significantly less labor than both conventional overground training and therapist-assisted BWSTT, with no significant difference found in effectiveness.

Gait-Training Robots in Current Clinical Use

Some gait-training robot systems are commercially available and are used for therapy in several clinics worldwide, such as the gait trainer GT-I [64.46], the Lokomat [64.45] the ReoAmbulator, the Loko-Help [64.167], and the G-EO System [64.168] (Fig. 64.3a–e).

Of these robots, the GT-I (commercialized by Reha-Stim) is the one that departs most from therapist-assisted BWSTT, since it interacts with the patient's lower limbs through two footplates rather than acting on the shank as human therapists do. It also appears to depart more from natural walking because the footplate principle substantially alters the sensory cues of the foot impact with the ground or treadmill band. The GT-I footplates are driven by a singly actuated mechanism that moves the foot along a fixed gait-like trajectory with a doubled crank and rocker system [64.46]. The stride length can be adjusted between sessions by changing gears. The body weight is unloaded as needed by an overhead harness. The torso is moved sagittally in a phase-dependent manner by ropes attached to the harness and connected by another crank to the foot crank. The GT-I is currently installed in dozens of clinics, mainly in Europe. One randomized, controlled study has been reported that tested the GT-I with 30 subacute stroke patients [64.169]. The robot group improved their overground walking ability more than the control group, although differences were not significant at a 6-month follow-up. A total of 80% of the patients said they preferred training with the robot rather than the therapists because training with the robot was less demanding and more comfortable. The other 20% of patients stated that swinging of the paretic limb seemed less natural and thus less effective when training with the robot. Robot-assisted training required an average of one therapist per patient, while therapist-assisted training required two therapists per patient on average. A follow-up, randomized controlled study comparing conventional training plus robotic training with the GTI, to a time-matched amount of conventional training alone with subacute stroke patients, found that the group that received some robotic training recovery walking ability to a great extent [64.170]. More recent clinical tests with the GT I are reported in [64.171].

The Lokomat (commercialized by Hocoma) is a robotic exoskeleton worn by the patients during treadmill walking [64.45]. Four motorized joints (two per leg) move hip and knee. The actuators consist of ball screws connected to dc motors. The legs are driven in a gait-like pattern along a fixed position-controlled trajectory. The device attaches to the thighs and shanks through padded straps. A parallelogram mechanism allows the vertical translation of the patient's torso, restricting lateral translation. The patient's body weight is actively unloaded as needed through an overhead harness. The Lokomat is currently being used in over 100 clinics worldwide. In 2005, *Wirz* et al. [64.85] reported preliminary results of robot-assisted BWSTT with the Lokomat in 20 chronic incomplete SCI patients. The improvements in overground walking speed and endurance were statistically significant: approximately 50% gain on average in the 16 patients who were ambulatory before training. There were no significant changes in the requirement of walking aids, orthoses, or external physical assistance. The improvements appear to be comparable to those achieved by similar SCI patients who received therapist-assisted BWSTT [64.161, 172]). For the case of stroke patients, however, therapy with the Lokomat was beneficial but about half as effective as treadmill-based or therapist-based training in improving overground gait velocity and endurance [64.173, 174].

The ReoAmbulator (commercialized by Motorika and marketed in the United States as AutoAmbulator) consists of two robotic arms that assist patients to step on a treadmill with their body weight supported as needed. The interface to the patient's legs is through straps at the thigh and ankle. The ReoAmbulator is currently being used in at least 57 HealthSouth rehabilitation centers, all of them in the United States, but little data have been published concerning its use.

The LokoHelp (commercialized by LokoHelp Group) assists users' feet motion along physiological trajectories while walking on a treadmill, also providing body weight support. Clinical trials [64.167, 171, 175] show that therapeutic outcomes are similar to manual training with reduced therapist effort.

The G-EO system (commercialized by Reha Technology) is also based on the footplate principle as for the GT I system. Studies with stroke survivors [64.176], patients with SCI [64.177] and with Parkinson's disease [64.178] have recently shown the value of this particular device.

Further Research and Developments on Robotic Therapy for Walking

Several groups worldwide are working toward improving gait-training robotic technologies. A great deal of effort has been made to incorporate and investigate the ability to assist as needed [64.72, 179–183], that is, the ability of the robot to let the patients contribute to the locomotor efforts as much as they are able. This is likely essential for maximizing locomotor plasticity [64.184]. Some effort has also been directed toward adding more active DOFs, particularly for torso manipulation [64.182, 185]. These robotic tools are needed not only for their potential clinical use in therapy, but for studying what aspects of the assistance are important for effective gait training and how best to control and implement them with robotic devices.

The team responsible for the GT-1 has developed the Haptic Walker [64.179], which maintains the permanent foot/machine contact but allows the footplates to move along 3-DOF trajectories. In addition, it incorporates force feedback and compliance control, as well as haptic simulation of ground conditions (e.g., stair climbing).

An advanced version of the Lokomat integrates force sensors and automatic adaptation of gait patterns to allow for a reduction of the interaction effort between patient persons and machine [64.180]. It has been tested on unimpaired persons and SCI patients, who were able to influence the gait trajectories toward a more desired motion by means of their own motor activity [64.180, 186].

PAM is a 5-DOF robot for torso manipulation, and POGO is a leg robot with 2-DOF per leg. PAM's and POGO's actuators are pneumatic, which cost less than electric motors and have higher power-to-weight ratios [64.185]. The robots' ability to control forces and yield to patients and/or therapists has been tested with unimpaired and SCI participants [64.187]. Of particular note here is the development of an adaptive synchronization algorithm that allows these compliant robots to provide assistance at the right time as the participants varies the timing or size of steps.

Based on the string-puppet principle, the String-Man achieves weight bearing and compliant 6-DOF torso manipulation by means of seven wires and a force sensor on each wire [64.182]. In addition, a control scheme has been designed for the String-Man to control both the zero-moment-point location and the ground reaction force with help of foot force sensors.

Veneman et al. [64.189] developed the LOPES exoskeleton (lower extremity powered exoskeleton) visible in Fig. 64.8. In this system, two horizontal pelvis translations are actuated, while the vertical motion is left free and weight is compensated. Furthermore, the LOPES have three actuated rotational joints per leg: two at the hip and one at the knee. The actuation system for hip and knee flexion/extension [64.183] combines Bowden cables with series elastic actuation. The Bowden cables allow the motors to be mounted remotely in a fixed position, thus reducing the mass to be moved on the exoskeleton links. The spring element connecting the Bowden cables with the joint allows the closing of a torque feedback control loop with a position sensor that measures the spring elongation, a concept inspired from the series elastic actuators (SEAs) described by Pratt and coworkers [64.190].

Veneman et al.'s experimental results on LOPES SEAs show that adequate torque control bandwidth was achieved by the prototype of their Bowden-cable-based actuation design [64.183], so that the robot can execute both a stiff, position-dominated robot-in-charge mode and a compliant, low-impedance patient-in-charge mode. Some results on the testing of the LOPES exoskeleton are presented in [64.192–194].

The FET European project *Evolving Morphologies for Human–Robot Symbiotic Interaction* (EVRYON) investigated a novel approach for the design of wearable robots in which robot morphology and control are co-evolved in a physics-based simulation environment to achieve a symbiotic interaction, with useful behaviors (walking patterns) emerging from the dynamic interaction between the robot and the human body. To narrow the search space, an atlas of topologies of robot architectures assisting hip and knee flexion/extension was produced [64.195], showing that only ten topologies are capable of providing independent assistance to hip and knee if the number of robot links is not higher than 4 and only revolute joints are considered. The kinematic structures (morphologies) descending from such topologies do not require the alignment of robot and human joints (nonanthropomorphism), thus possibly shortening calibration time and limiting wearability issues. Among the abovementioned ten topologies, only

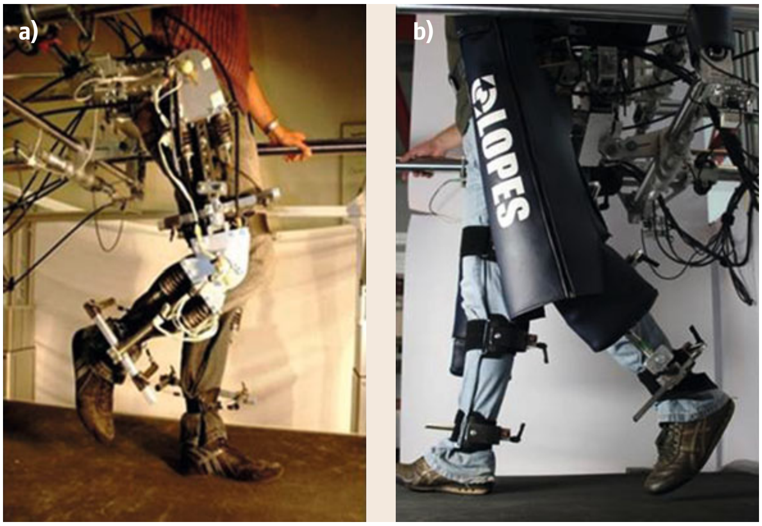

Fig.64.8a,b LOPES (lower-extremity powered exoskeleton) device for gait training and assessment of motor function in stroke survivors (after [64.188])

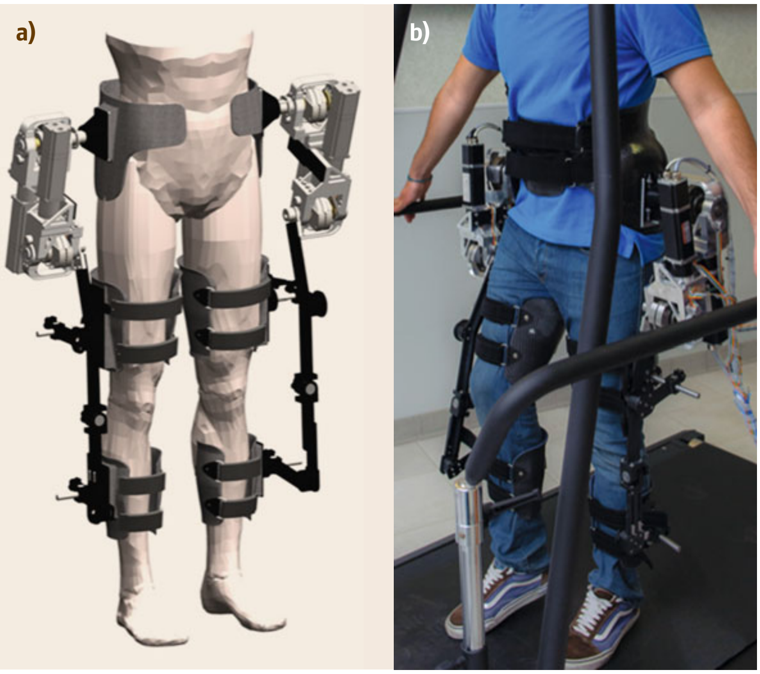

Fig. 64.9a,b EVRYON/LENAR. **(a)** Wearable robot to assist hip and **(b)** knee flexion/extension through series elastic actuators (after [64.191])

one allows us to mechanically (intrinsically) minimize unwanted shear forces while keeping encumbrance low. A morphology belonging to this topology class was optimized to minimize reaction forces on the human body [64.196] and to maximize wearability and backdrivability [64.197]. Based on this study, the lower extremity nonanthropomorphic robot (LENAR) [64.191] was developed (Fig. 64.9), incorporating custom-made series-elastic actuators for a robust interaction control [64.198].

A different approach to gait training was taken with the KineAssist device [64.199]. KineAssist (Fig. 64.10) is a motorized mobile platform that follows the patient and therapist as they move overground and incorporates a smart brace that compliantly supports the patient's trunk and pelvis. This smart support is designed to allow the therapist to adjust its stiffness from fully rigid down to fully compliant. Within a safety zone, the fully compliant mode allows patients to challenge the limits of their stability. A compliant virtual wall catches the patients when they lose balance. The location of this virtual wall is also adjustable. The body weight can be unloaded as needed. The main advantage of this system is the possibility for the therapist to work in close contact with the patient while cooperating with the robotic system, which deals with the crucial, basic task to keep the patient stable and safe. From this research platform, HDT Robotics began commercialization of the KineAssist-MX. Actuation and sensors allow interactive force-field environments so that a wide variety of challenging mobility experiences can be delivered to the user.

Other efforts include *Ferris* and coworkers [64.202], who are developing foot, ankle, knee, and hip orthoses actuated by artificial pneumatic muscles that may possibly be used to assist in gait training. The Rutgers Ankle is a 6-DOF pneumatic system based on a Stewart Platform that allows exercise of the ankle [64.203]. Also in the United States, Agrawal's group proposes the use of gravity-balancing leg orthoses for people with gait impairments to practice walking [64.204]. Their designs allow the orthoses to passively support the gravity torque required at the patient's joints. This approach would have the advantage of being safer than powerful robots for clinical use. They have also extended their design

Fig. 64.10 KINE ASSIST for unobtrusive support to patients, allowing them to walk on their own, or with variable levels of support (after [64.200])

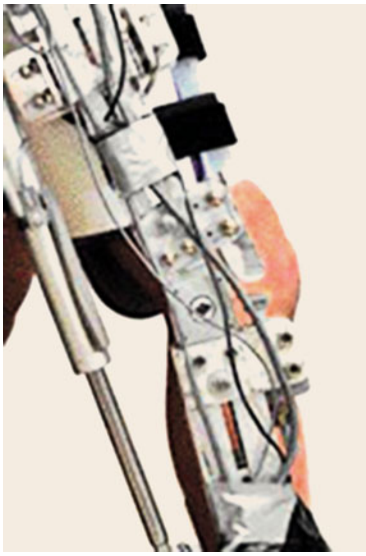

Fig. 64.11 Active leg exoskeleton (ALEX) to supplement traditional rehabilitation therapy (after [64.201])

to include actuators with reduced torque requirements [64.205]. A robot has been used to provide graded body weight support as a patient who cannot bear full body weight because of a medical problem walks in a circle [64.206]. *Banala* et al. developed the treadmill-based rehabilitation robot ALEX [64.207], as seen in Fig. 64.11. In this system, hip and knee joints are actuated in the sagittal plane while hip abduction/adduction and ankle motion are spring-loaded. More details and further examples of robotic systems for walking therapy are reported in [64.208].

Other Robotic Movement Therapy Approaches

As reviewed earlier, most of the work to date in robotic therapy devices has focused on robots that are attached to patients to assist them in practicing reaching or walking exercises. Other early proposals for using robots for movement therapy included using two planar robot arms to carefully control continuous passive motion of the knee following joint surgery [64.37], and using a multiaxis robot arm to place targets for patients doing reaching exercises [64.209]. An emerging approach toward robotic movement therapy is to provide the therapy at a distance, in a form of telerehabilitation, in order to improve accessibility to the therapy [64.81, 123, 210]. Non-contacting, socially assistive robots, as reviewed in Chap. 73, may play an important role in motivating and monitoring therapy.

64.3 Aids for People with Disabilities

Enabling technologies assist people with disabilities to achieve a quality of life on a par with able-bodied individuals through increased functional independence. The main issue with most such technologies is that disability has a highly individualized impact: a solution for one person will not work for someone else, even if their disabilities appear clinically similar.

64.3.1 Grand Challenges and Enabling Technologies

The more a disability impacts function, the more costly the technical intervention tends to be, since the consumer market cannot benefit from economies of scale if each solution must be individualized. As an extreme example, an electric wheelchair with individualized padding, motorized recliner, and customized joystick control costs as much as a mass-produced mid-sized automobile, but has a fraction of the electronics, robustness, and functions. A grand challenge for assistive, enabling technologies is to find a means to make mass-personalization possible, as it has been in the automotive industry, for example. One component is designer focus. If we can re-badge *assistive technology* as *design for well-being products*, the change in focus from *fixing* people to improving their quality of life will have the effect of mainstreaming disability itself so that manufacturers of consumer equipment tend to develop products that can explicitly accommodate a much wider range of functional abilities and therefore provide benefit to a larger, overall less-able, consumer base. As the average age of the baby boomers climbs into retirement years with significant disposable income, this segment will compel the market into providing better solutions to their well-being needs.

Another grand challenge is robotic autonomy. Especially for persons with reduced communication, physical and/or cognitive abilities, a rehabilitation robot will need to have sensory (e.g., vision, auditory) and motor capabilities, combined with its own software processing capabilities (also termed artificial intelligence), that make it a sufficiently safe and capable system to coexist with and benefit humans. This challenge will to some extent be dependent on continuing increases in computer-processing power, and also specifically dependent on the algorithmic developments that issue from the community of robotics researchers.

For instance, several advanced navigation assistive tools for blind and visually impaired persons have been developed by exploiting knowledge and technologies directly derived from research on autonomous robot navigation; as a sample, *Borenstein* and *Ulrich* in 1997 developed the GuideCane [64.211], an intelligent cane, based on ultrasound proximity sensor technology, which was designed to help blind or visually impaired travellers to navigate safely and quickly among obstacles and other hazards faced by blind pedestrians [64.212].

Research on robotic aids (namely *physically assistive robots* or, also, *contact assistive robots*) has so far primarily targeted persons with mobility and manipulation limitations, rather than children and adults with cognitive impairments [64.213, 214]. However, increases in the prevalence of cognitive impairments related to aging will make the latter focus increasingly important. *Socially assistive robots*, also named *contactless assistive robots*, are emerging assistive systems that focus on helping human users through social rather than physical interaction (see Chap. 73 for more details on socially assistive robots). Research has been limited to the mobility focus due to the difficulty of designing and developing intrinsically safe robots that can coexist with people and exhibit a certain amount of autonomy while performing useful work. Robots, therefore, today rely on user vigilance and explicit control to be safe. If the user does not have the cognitive capacity to evaluate a robot's safety situation or the ability to communicate efficiently, then the positive value of a function-enhancing robot is nullified by the harm that it could inflict on the user or bystanders. Coupled with the fact that the design of interfaces to personal robots is still in its infancy, a challenge for robotic aid developers is a significant improvement in intrinsic safety without a decrease in function (strength, speed, etc.) from what is typical today in industrial robotics.

To address some of these challenges, the US government, through NSF, NIH and other federal agencies, in 2011 issued a call for a $ 50 million per year, 5-year program called the National Robotics Initiative (NRI) [64.215]. The realization of co-robots acting in the direct support of individuals and groups. A substantial amount of this funding is focused on healthcare of the future.

Disabilities and Functional Limitations Served by Robotic Aids

Assistive robots have been designed for people who have become severely disabled as a result of, for example, muscular dystrophy or a high-level SCI, for children who have CP, and more generally for anyone who lacks the ability to manipulate household objects. A market research study conducted 10 years ago, specifically for rehabilitation robotics clients, conservatively projected a US market of 100 000 people [64.216]. With the incidence of disability increasing exponentially, and the niches that robots can fill in rehabilitation applications multiplying with advances in robotics and rehabilitation science, it is clear that the market for rehabilitation robotics can only continue to increase.

Human–Robot Interface Design for Assistive Robots

A fundamental difference between using industrial and assistive robots is the interface required to command, control, and ultimately benefit from them. An industrial robot commonly has a combination of a manual controller and a programming language interface to allow an operator to teach a robot where to go and to enter the specific motion, grasping, tool changing, and error-recovery steps it must follow repeatedly in its factory automation scenario. An assistive robot, on the other hand, typically has three main differences and challenges:

1. The operator is not by definition a roboticist or engineer, so the interface must make accessible all the functions of the robot to allow its user to complete the required tasks.
2. The user of a rehabilitation robot is, by definition, a person with a disability, which means that physical, sensory, communication, and/or cognitive limitations in accessing the commands and controls of a robot need to be handled on a systems level by the designers of robots and their interfaces, with critical attention to universal design principles, and
3. All rehabilitation robots require individualization of the interface to each user by the engineering and therapy professionals in charge of prescription and fitting, since disabilities vary considerably in how they restrict adaptability to standard configurations [64.217].

Interfaces of assistive robots consist of the software and hardware components conceived to enable a person with a disability to interact with an assistive device, thus tapping into residual communication capabilities of each user. For example, many people with tetraplegia retain the ability to move a hand, arm, foot, or the head in a repeatable, even if range-limited way, and possibly even in two axes, such as forward/backward and left/right. With a proper placement of pushbuttons, a joystick, or noncontact position measurement device, a rehabilitation engineer and therapist can develop a custom solution for each of their clients with disabilities to control a wheelchair computer and robot. In addition, adaptive hardware and software for controlling a computer, such as head-position cursor control, eye-trackers, speech recognition systems, trackballs and special keyboards, can be used to provide access to computer-based robot functionality.

Even more important than for able-bodied computer and robot users, redundancy in input modality is important for persons with disabilities to prevent a system from becoming inoperable due to a simple interface malfunction or calibration problem. Providing two means of creating a mouse-click action (for example, a separate button placed next to a cursor-control trackball, as well as dwell time on a software *button* on-screen), even if one is inherently slower than the other, allows continued and uninterrupted use of the computer without outside assistance even if one of the two fails.

For therapy robots, physical interfaces resemble those for physical and occupational therapy equipment, in general, and have a commonality with sports equipment interfaces as well, with adjustable hook-and-loop-type straps, heat-formable plastic cuffs, soft rubber, foam-based materials, and durable coverings for abrasion resistance and long wear. After a session or two for fitting and adaptation, a person using a therapy robot can often use the same interface for a long period of time.

In summary, the keys to interface design are customizability, individualization, functional redundancy, adaptability, and patience in getting the interface to a comfort and functional level appropriate for the effective use of the robot.

64.3.2 Types and Examples of Assistive Rehabilitation Robots

As mentioned in the Introduction, assistive robots can be divided into three main categories: manipulation aids, mobility aids, and cognitive aids. Each can be subdivided as follows. Manipulation aids are commonly divided into fixed, portable, and mobile subtypes. Mobility aids are divided into electric wheelchairs with autonomous navigation features and smart walkers. Cognitive aids are divided into communication aids such as pet robots and autonomous caretaker robots. These categories are introduced below, and representative systems that have undergone scientific user studies or are commercial products are presented (Fig. 64.12a–c). Other examples are mentioned in Sect. 64.1.3.

Manipulation Aids: Fixed-Base

Common robots of this type are ADL and vocational manipulation aids and kitchen robots. In the United States, the professional vocational assistive robot (ProVAR) is a research prototype based initially on a PUMA-260 robot arm mounted on a 1 m-transverse overhead track that allows the robot to manipulate objects and operate devices on side shelves and the table-top, bringing objects (like a drink of water or throat lozenge) to the robot's operator. The interface is via a JAVA/VRML plug-in to a common Internet browser, delivering high-level control to disabled office workers in a conventional pull-down menu and a control screen interface [64.27, 218]. This system and its predecessor DeVAR have been field tested by over 50 subjects at 5 rehabilitation clinics to assess feasibility and acceptability [64.219, 220]. At a cost of over US $ 100 000 currently, there are currently no plans for eventual product introduction.

Fig.64.12a–c Workstation-type robots: **(a)** AfMaster, developed by the French Muscular Dystrophy Association, **(b)** ProVAR, developed at the VA Palo Alto Rehabilitation R&D Center, and **(c)** Handy-1, developed by RehabRobotics, Ltd. (UK)

In the EU, following a development path parallel to ProVAR's, there is the AfMASTER/RAID workstation, whose concept, instead of being built into a workstation, includes a 2 m × 3 m robot work area in the user's office to store objects and place appliances, next to the user's own office space. The system has been developed over a 20-year span and was briefly in limited production [64.29] but is no longer offered for sale.

The kitchen robot, Giving-A-Hand, developed at the Scuola Superiore Sant'Anna in Pisa, Italy, is a low-degree-of-freedom device for mounting on the front rail of a kitchen counter and able to move food containers to and from appliances, such as refrigerators and ovens [64.221]. With an integrated control system, it can also make use of the internal controls of the devices to, for example, set cooking times and open doors.

The UK-developed Handy-1 is a domestic robot with 3-DOF designed for one-switch operation by persons with CP [64.30]. Originally designed to allow a person to eat a meal one bite at a time, its application areas have been extended to face hygiene and cosmetics. A commercial product selling for about US$ 6000, it has been a commercial success due to its simplicity and application focus. An even simpler feeding robot, the UK's electric Neater Eater [64.20] is for sale worldwide at about US$ 5000, and is designed for eating only.

In [64.222], an overview of manipulation robotic aids is provided. They are classified through five criteria, based on robotic arm usage scenarios and surveys. In particular, new assistive manipulators have recently been developed that address interaction safety as a priority criterion in their design. Take for instance JACO [64.223], iARM [64.224] and RAPUDA [64.225] as examples of robot arms achieving safety by limiting the performance of the robotic arm in terms of arm-movement speed and acceleration in space, end-effector force and maximum possible payload. Examples of robots addressing safety through backdrivable joints (as in the WAM Arm [64.226]) or through active impedance control (as in KARES II, WAM Arm, Elumotion RT2 [64.227], DLR LWR-III [64.228]] can also be mentioned.

While a robot conventionally connotes a standalone system with some automation features, a smart bed and a smart home can legitimately be termed robots since they sense and act with motors under the shared control of its human users and its real-time software programming. Smart beds, such as SleepSmart measures body position and temperature, as well as trends and anomalies over the course of a night. Restlessness can be measured, and bed geometry (tilt of bed segments) and ambient conditions (light, temperature, sounds) can be adjusted according to presets and preferences [64.229].

Smart homes, such as the AwareHome domotic environment at Georgia Tech, NL-iRV, and the University of Tokyo [64.230], provide integrated climate, security, lighting, entertainment and transport assistance, which is enabling especially to persons with severe functional disabilities. Coupled with health care-related functionality (following section), these robotic homes can allow a person with a cognitive or physical disability to control many ADL functions and live safely through monitoring.

Manipulation Aids: Wheelchair Manipulator Arm Systems

A need for electric wheelchair users is the manipulation of objects while navigating a home or a public place such as a restaurant or grocery store. The assistive robot service manipulator (ARM) (Exact Dynamics, Netherlands) – previously known as MANUS – is a commercial robot arm that can be attached to an existing wheelchair to the side of the lap tray and controlled by the wheelchair's own joystick or a number pad [64.23, 231] (Fig. 64.13). The robot has undergone numerous user studies with persons who have muscular dystrophy, a high-level SCI or CP. Worldwide, this is currently the only commercial rehabilitation robot arm that can be prescribed by a physician and that is reimbursed by a government health care system.

Weston [64.232] and Bridgit [64.233] are two wheelchair manipulator arm systems addressing the issue of interaction safety in their design, as for some of the manipulation aids with a fixed base presented earlier. Weston uses low-power motors in order to statically and intrinsically limiting the arm's acceleration, force and payload. Bridgit is a manipulator arm placed

Fig. 64.13 Wheelchair manipulator robot MANUS developed at the Rehabilitation R&D Center, Hoensbroek, and marketed by Exact Dynamics (The Netherlands)

on a wheelchair on a rail system. The robot moves over the rail system resulting in optimal positioning for each task. The rail system also allows for easy docking of the robot either on the back or front side of the wheelchair when not in use.

Manipulation Aids: Mobile Autonomous Systems

The most commonly thought-of form of a robot is that of an autonomous, mobile system with arms, having sensory-motor functionality similar to that of a human being, while serving people in performing menial physical tasks. This Handbook's chapter on Humanoid Robots explores the domain as well (Chap. 67). Since locomotion is a key requirement for Humanoid robotics, other robots with wheeled bases have been developed before the first walking robots were invented to explore more applied domains with more short-term usefulness. In film, robots such as Star Wars' R2D2 have made this form factor commonly known around the world. More recently, real robots such as the HelpMate [64.234] have been employed in US hospitals as fetch-and-carry robot orderlies, using floor maps and short-range ultrasonic sensors for navigation and obstacle avoidance. The Italian MovAid research robot platform [64.235] (in Fig. 64.14) adds manipulation and vision to these capabilities to navigate in home-like environments to provide object manipulation and device operation to individual users. The European project Robot-Era [64.236] is following up these developments with a specific target on the needs of aging population. The German Care-O-bot [64.237] has explored advanced navigation and sensing in a wheeled robot that can also be used as a physical support to people requiring mobility and stability assistance. It has also doubled as a mobile kiosk, moving around a trade show floor and delivering information to attendees. In [64.238] a case study of a personal robot based on the PR2 Humanoid robot (Willow Garage, Menlo Park) is presented. The approach pursued consists of developing a diverse suite of open-source software tools that blend the capabilities of the user and the robot in order to enable the assistive mobile manipulators to move in real homes and work with people with disabilities.

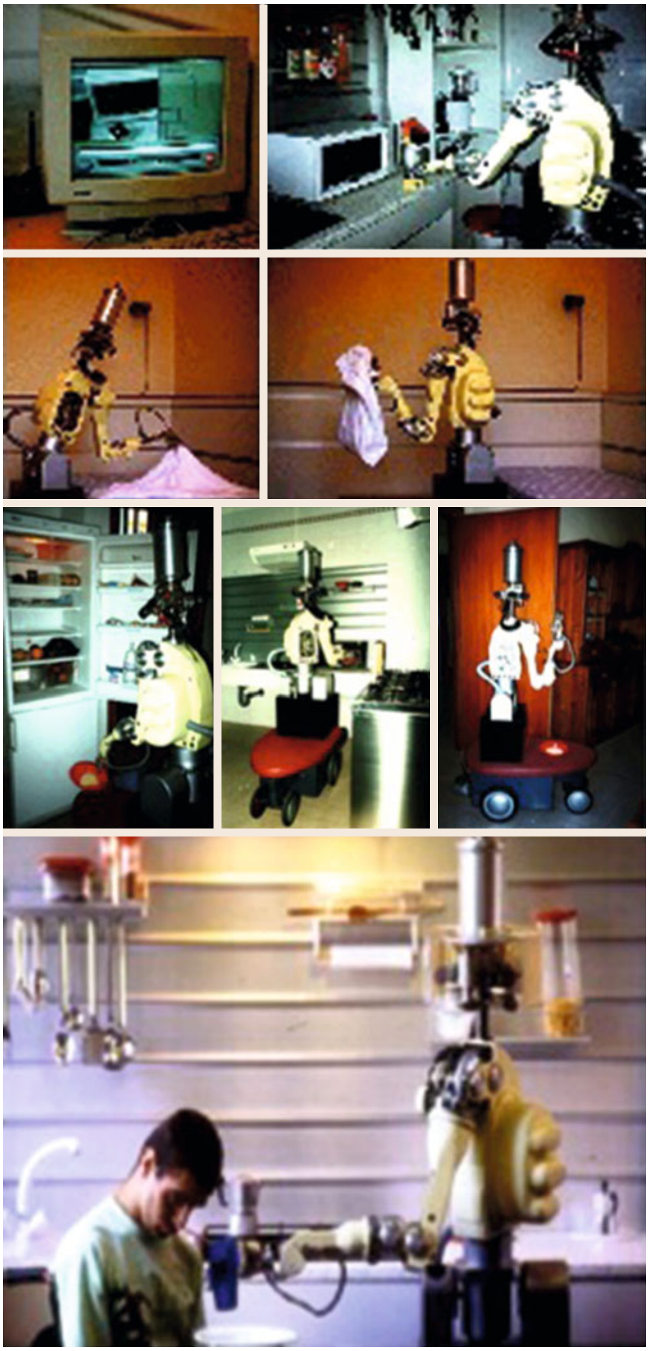

Fig. 64.14 MovAid (after [64.239])

Mobility Aids: Wheelchair Navigation Systems

A critical function for people who use electric wheelchairs for their mobility impairment and who in addition have communication or cognitive disability is semiautonomous navigation assistance (Fig. 64.15).

Add-ons to commercial wheelchairs have been developed by numerous research groups for this service. Such wheelchairs are typically referred to as smart or intelligent wheelchairs. As proposed by *Simpson* [64.240], smart wheelchairs can be classified by form factor: early smart wheelchairs were mobile robots with added seats. The vast majority of smart wheelchairs developed until 2005 were based on heavily modified, commercially available, powered wheelchairs. Only a smaller fraction of them were

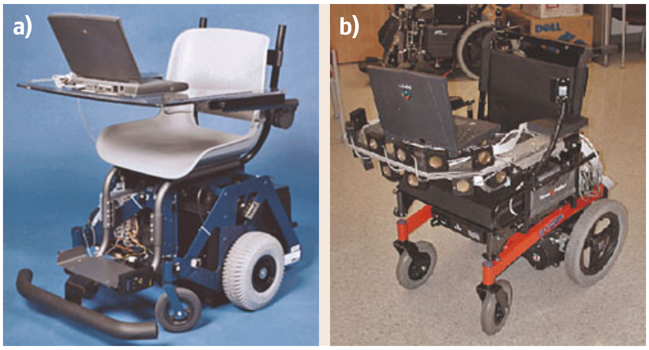

Fig.64.15a,b Wheelchair navigation aids: **(a)** Wheelesley and **(b)** Hepahaestus

equipped with *add-on* units that could be attached to and removed from the underlying powered wheelchair.

The NavChair [64.241] was one of the first to demonstrate robust wall-following, door passage even with narrow doorways, and speed adaptation to people walking in front of the wheelchair, all using only short-range ultrasonic and other sensors, but not vision. The Hephaestus [64.35] is a next-generation system made specifically as a commercial accessory for a variety of wheelchair brands, tapping into the joystick controller and power system. The *Wheelseley* [64.242] and KARES [64.33] robots have explored similar functionality using a vision system for scene analysis and way-finding.

More recently, the CanWheel project team developed an intelligent wheelchair system called NOAH [64.243, 244]. The system has three main capabilities: collision avoidance, infer the user's goal location/activity and provide automated reminders, provide navigation assistance using prompts. The rationale for proposing such solutions is to enhance mobility and to help improving the quality of life of older adults with cognitive impairments, while simultaneously reducing the burden on caregivers.

In 2013, *How* et al. [64.245] proposed a new intelligent wheelchair system (IWS) with anticollision and navigation features. User trials showed the IWS's potential to improve powered wheelchair safety and subjective usability.

The IntellWheels [64.246] project proposes a modular platform based on a multiagent system paradigm for the development of intelligent wheelchairs based on commercial products. Within this project, promising results have been achieved on the development of adapted control methods for CP users of an intelligent wheelchair. Experiments demonstrated that users felt that they had better control over the wheelchair movement when using shared control rather than manual or automatic control modalities [64.247].

The iBOT [64.248–250] is a powered wheelchair for persons with mobility impairment developed by Kamen, in a partnership between DEKA and Johnson & Johnson's Independence Technology division. Research on iBOT was discontinued in 2009. The iBOT features self-balancing technology, which allows users to go up and down staircases, to navigate on uneven terrain and to *stand* at an eye level with people walking nearby.

Mobility Aids: Walking Assistance Systems

A third type of mobile robot for stability assistance has the peculiarity that it is underactuated and has similarity with the *co-bot* concept, in that the wheels are not driven, but are actively steered and braked (Fig. 64.16). The concept of collaborative *co-bots* was originally introduced by *Colgate* et al. for robots operating in di-

Fig.64.16a–c Human assistance robots: **(a)** Care-O-bot, developed by the Fraunhofer Research Institute (Germany). **(b)** Helpmate by Transitions Research Inc., USA. **(c)** Pam-Aid (aka Guido), developed in the UK

rect physical interaction with a human factory worker, handling a shared payload. They are a marked departure from autonomous industrial robots, which must be isolated from people for safety reasons [64.251, 252]. Co-bots interact with people by producing software-defined *virtual surfaces* which constrain and guide the motion of the shared payload, but add little or no power [64.253]. Today, cobots are being prototyped in the rehabilitative and assistive context, e.g., for bed to chair/wheelchair transfer or table-top upper limb, stroke rehabilitation at home. For example, the Pam-Aid [64.254] looks like a closed-front walker on wheels and has bicycle-type handlebars. The person walking behind the device turns the handlebars, causing the wheels to turn in the correct direction. If the ultrasonic sensors detect an obstacle in front of it, the brakes prevent the user and device from colliding with it. The Care-O-bot (see earlier) designed originally as a mobile autonomous robot approximately human size, has a similar set of handlebars, similar to the Pam-Aid it, so it can be used as a smart walker. The larger mass of the Care-O-bot, however, requires it to be motorized.

Mobility Aids: Exoskeletons

Exoskeletons for walking assistance are similar to robots used in treadmill-based environments for rehabilitation. These systems are portable and autonomous and intended to be used in daily life scenarios. Several review papers have been recently published [64.255–257] on this topic.

In the framework of NISTs Advanced Technology Program, Ekso Bionics (Berkeley, USA) developed the Ekso device [64.258] (Fig. 64.17). This robot has been developed for people with lower extremity weakness or paralysis due to neurological disease or injury (e.g., spinal cord injuries, multiple sclerosis, Guillain–Barré syndrome) and it has an almost anthropomorphic structure with hip and knee joints actuated in the sagittal plane. The ankle joints are not actuated but are compliant in the sagittal plane and locked out in the other DOFs. Testing of the device has included paraplegic persons with complete or incomplete paralysis [64.259] and chronic stroke patients [64.260].

The ReWalk was developed by Argo Medical Technologies [64.261]. It is actuated by DC (direct current) motors at the hip and knee joints in the sagittal plane, while the ankle joint is not actuated. The system is designed with a remote controller that can be used to change the motion mode (e.g., ground walking, climbing stairs). A posture sensor on the torso detects the upper body movement of the user and estimates motion intention. The wearer also has to use crutches for stability and safety reasons. The system is undergoing clinical trials among other research centers at MossRehab (Philadelphia, USA) and at the Centro Protesi INAIL di Vigorso di Budrio (Bologna, Italy) on paraplegic subjects. The device is now available on the market in two versions: the ReWalk-Rehabilitation for institutional use and the ReWalk-Personal developed for daily use (Fig. 64.18).


Fig. 64.17 Ekso Bionics exoskeleton for paraplegics (after [64.258])

Sankai's group at the University of Tsukuba (Japan) developed an exoskeleton both for performance augmentation and for rehabilitation and assistance [64.263, 264]. The current version, HAL-5, powers the flexion/extension of hip and knee via DC motors while ankle dorsi/plantar flexion DOF is passive. The HAL-5 system (Fig. 64.19) integrates a number of sensors: skin-surface EMG electrodes placed below the hip and above the knee on both the anterior (front) and posterior (back) sides of the wearer's body, potentiometers for joints angles measurement, ground reaction force sensors, a gyroscope and accelerometer mounted on the backpack for torso posture estimation. HAL-5 is currently commercialized by the spinoff company Cyberdyne (Tsukuba, Japan). To date, it appears that no peer-reviewed, quantitative results have been published

Fig. 64.18 ReWalk computerized exoskeleton (ReWalk Robotics, Inc., USA; after [64.262])

on the effectiveness of the exoskeleton for the improvement of walking functions.

The Vanderbilt powered orthosis [64.265] is a powered lower limb exoskeleton intended to provide gait assistance to individuals suffering from spinal cord injury by providing assistive torques in the sagittal plane for both the hip and knee joints. It includes neither a portion that is worn over the shoulders, nor a portion that is worn under the shoes. Each joint is powered by a brushless DC motor. The orthotic is intended to be worn together with a standard ankle–foot orthosis, which provides support at the ankle and prevents foot drop during swing. In order to demonstrate its ability to assist walking, the orthosis was experimentally tested on paraplegic subjects. Experimental results indicate that the orthosis is capable of providing a repeatable gait with knee and hip joint amplitudes that are similar to those observed during non-SCI walking.

Fig. 64.19 Robot suit HAL-5 designed by Japanese robotics firm Cyberdene

REX, produced by REX Bionics (Auckland, New Zealand), is an anthropomorphic lower body robot designed for sit-to-stand, stair climbing and overground walking, without the use of crutches. The system does not use sensors to detect the intention of the user but rather it uses a joystick as its interface. The system has been tested with healthy subjects, and for sit-to-stand of wheelchair users [64.266].

Cognitive Aids

There has recently been increased interest in using robots as motivational and educational agents during rehabilitation therapy. This approach typically involves small, pet-like, toy-like, approachable devices that do not physically interact with the patient, but exist primarily to engage the patient in an affective way that promotes personal health, growth, and interaction. For more information, please see Chap. 73.

64.4 Smart Prostheses and Orthoses

In 2005, the Defense Sciences Office (DSO) of the US governmental research agency DARPA launched a program to revolutionize prosthetics in a four-year timeframe. According to the agency website, this program will:

> *deliver a prosthetic arm for clinical trials that is far more advanced than any currently available. This device will enable many degrees of freedom for grasping and other hand functions, and will be rugged and resilient to environmental factors. In 4 years, DSO will deliver a prosthetic for clinical trials that has function almost identical to a natural limb in terms of motor control and dexterity, sensory feedback (including proprioception), weight and environmental resilience. The four-year device will be directly controlled by neural signals. The results of this program will allow upper limb amputees to have as normal a life as possible despite their severe injuries.*

64.4.1 Grand Challenges and Roadblocks

This program announcement lays down the grand challenge for prosthetics research in an ambitious timeframe: develop an artificial limb that has function and durability at least as good as a natural limb. There are several roadblocks to meeting this challenge. First, providing an intuitive way for individuals to control and coordinate multiple joints of a robotic limb is challenging. Second, robots do not yet match the human arm in terms of the combination of range of force, weight, and duration of use with a portable power source. Third, human limbs are rich with tactile and movement sensors. Installing artificial sensors on a robotic limb, and then returning information from those sensors in a way that is usable by the user is challenging. Thus, solving the grand challenge will require better sensory–motor interfaces for prosthetic limbs, as well as lighter, stronger actuators, and better power sources.

Substantial progress has recently been made in improving sensory-motor interfaces for prosthetic limbs, and this progress is the focus of this section. For the current state of robotic actuators that could be used in prosthetic devices, the reader is referred to Chap. 77 on Neurorobotics. For an overview of the design of conventional prosthetic hands and arms, the reader is referred to [64.267].

64.4.2 Targeted Re-Innervation

Standard prosthetic arms and hands are commonly controlled with a cable drive or by electromyogram (EMG) signals from residual muscles. For example, to open and close an artificial hand, one common technique is to place a Bowden cable around the shoulders in a harness, and connect the cable directly to the artificial hand. The user can then shrug the shoulders to move the cable and open and close the hand. Alternately, electrodes can be placed on a muscle in the residual limb or on the user's back, for example, and then used to control a motor on the artificial hand. The cable technique has the advantages of simplicity, and of having the property of extended physiological proprioception (EPP), which refers to the fact that the grip force is mechanically transmitted back to the user's shoulder muscle force sensors so that the user can gauge the strength of the grasp. Because of their simplicity and EPP, cable drives (or body powered prostheses) have been more popular than myoelectric (or externally powered) prostheses. However, the body-powered technique is amenable to controlling only one degree of freedom at a time, although chin switches, for example, can be used to switch between degrees of freedom in a somewhat cumbersome way. The myoelectric approach can be used to control multiple degrees of freedom, but such control is nonintuitive and cumbersome. Also, multiple control sites for reading out EMG are not available for people who have lost their entire arm. Thus, prosthetic control systems are typically limited to one or two degrees of freedom, while functional arm and hand movement benefits from at least four degrees of freedom (three to position the hand, and one to open and close it).

Kuiken et al. [64.268] recently developed a novel approach to improving control of a multijointed prosthetic arm. In this targeted re-innervation technique, they re-routed the nerves that previously innervated the lost limb to a spared muscle, and then read out the user's intent to move the limb using electromyography at the spared muscle. They demonstrated this technique in a bilateral shoulder disarticulation amputee who had lost both of his arms in an electrical power accident. They took the residual brachial plexus nerve for the left arm, which normally innervates the left elbow, wrist, and hand, and moved it to the pectoralis muscle. The subject could still contract his pectoralis muscle, but this muscle was no longer useful to him since it used to attach to his now-missing humerus. A surgeon dissected portions of the nerve associated with different muscles in the elbow, wrist, and hand, and innervated three bundles of the pectoralis muscle. After three months, the nerve re-innervated the bundles so that the patient could cause the bundles to twitch by trying to bend his missing elbow, for example. Surface EMG electrodes were placed over the bundles. Then, when the user willed to open his hand, for example, a pectoralis muscle bundle contracted, and this contraction was detectable with the EMG electrodes. The EMG signal was in turn used to control the hand motor of the prosthetic arm. The net result was that the user could will his different (missing) anatomical joints to move, and the corresponding joints on the robotic arm would move. He could simultaneously operate two joints, such as the elbow and the hand. The user became able to do tasks that he was not able to do before with his conventional myoelectric controlled arm, such as feeding himself, shaving and throwing a ball. A secondary remarkable finding was that the sensory neurons in the re-routed nerves re-innervated sensors, so that now when the person's chest is touched, the person perceives it as a touch to his missing limb. This sensory re-innervation could possibly be made into an interface to provide tactile sensation from the artificial limb. These findings were recently confirmed in another person who received targeted reinnervation [64.269].

64.4.3 Neural Interfaces for Limb Prosthetic Devices

Neural interfaces provide an interesting and challenging solution to retrieve the natural way of interfacing the human nervous system to prosthetic artifacts. They are systems capable of recording either invasively or noninvasively the electrical activity of peripheral nerves as well as of the brain cortex. It has also recently been shown that the direct electrical stimulation of a residual peripheral nerve can provide usable information regarding force to a person with an amputation [64.270], thus paving the way for bidirectional neural interfaces capable of restoring both efferent and afferent information flow to/from the prosthesis. Recently, thin film intrafascicular electrodes implantable in peripheral nerves have been developed [64.271], and successfully validated in 2008 in Italy at Campus Bio-Medico University of Rome on a human amputee [64.272] within the LifeHand project, a cluster of European and Italian research actions focused on neural interfaces for prosthetics (Fig. 64.20). In 2013, a second round of experiments in Italy demonstrated the possibility of delivering physiologically appropriate (near-natural) sensory information to an amputee during the real-time decoding of different grasping tasks to control a dexterous hand prosthesis by stimulating the median and ulnar nerve fascicles using transversal multichannel intrafascicular electrodes, according to the information provided by the artificial sensors from a hand prosthesis [64.273]. The results also demonstrate that the subject was able to identify the stiffness and shape of three different objects by exploiting different characteristics of the elicited tactile sensations. These results are in line with earlier studies which outlined the importance of restoring tactile feedback on a prosthetic device, such as the one proposed by *Meek* et al. in 1989 [64.274].

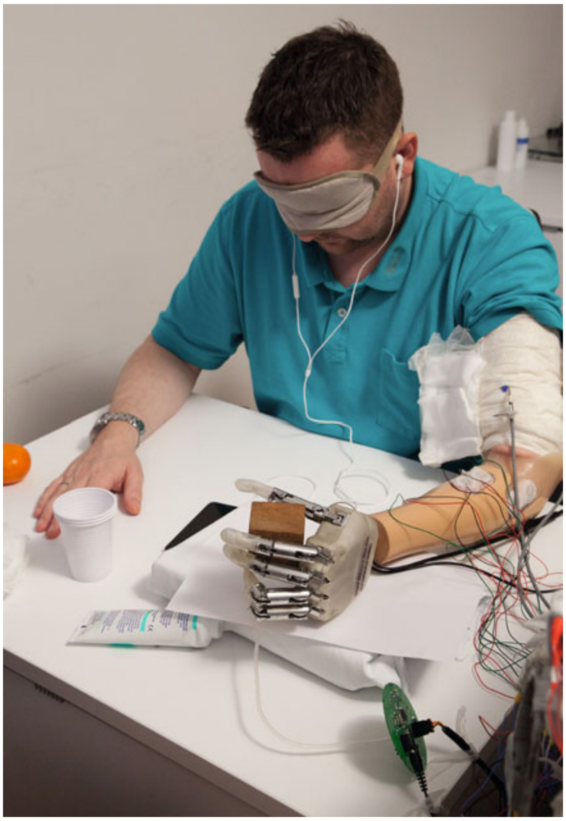
Fig. 64.20 LifeHand aims to create a completely implantable prosthesis system, richly sensorized and crontrolled through the patient's nervous system, with a dexterity comparable to a natural limb (courtesy of Campus Bio-Medico University Rome, Italy)

Today the above mentioned approach is trying to be extended on lower limb prosthetics as well. *Herr* et al. a MIT pioneered a new class of bio-hybrid smart prostheses and exoskeletons [64.275] aiming at improving the quality of life of people with physical challenges. Some of these devices are now commercialized by a spin-off company, BiOM. For instance, a computer-controlled prosthesis called the Rheo Knee [64.275] is outfitted with a microprocessor that continually senses the joint's position and the loads applied to the limb. A powered ankle–foot prosthesis emulates the action of a biological leg to create a natural gait, allowing amputees to walk with normal levels of speed and metabolism as if their legs were biological [64.275].

There has also recently been progress in decoding movement-related signals in real-time directly from the brain (see the cover story and related articles in *Nature* of 13 July 2006 [64.276]. The first of several recent human volunteers, a person with tetraplegia due to SCI, has received a BrainGate electrode array implant, and has been able to control the movement of a cursor on a computer screen [64.277]. Noninvasive systems operate by recording brain activity from *the outside* of the skull via well-known clinical noninvasive diagnostic devices [64.278] such as electro-encephalogram (EEG). Individuals have been demonstrated to be able to learn to control the amplitude of the EEG signal as a function of time, or the amplitude of specific frequency components of the EEG signal, with a moderate amount of practice (several hours to several days). The level of control is sufficient to operate a typing program on a computer, or to control the movement of a cursor to multiple targets.

In summary, given the significant progress observed in the last decade, it appears that future control systems for smart prosthetics and orthoses will have the option to rely on direct interfaces to the brain, which should allow control of multiple joints through thought alone. The initial work on both targeted re-innervation and brain–machine interfaces to the PNS or to the CNS has allowed three to 4-DOF of control in a naturalistic manner and elicitation of some sensory feedback, which is an advance over conventional prosthetic control techniques.

64.4.4 Advances in Neural Stimulation

Functional neural stimulation techniques (FNSs) seek to electrically stimulate the residual nervous system to re-animate the limbs. FNS for standing, walking, reaching, and grasping has been demonstrated, but these techniques have met with limited commercial success because of a combination of factors, including the ease of use of systems that use surface electrodes, duration of use before fatigue, risk from implantation and complexity of the associated control problems.

Two research lines are being pursued to help move the FNS field forward. The first one focuses on hardware innovation. A good example is the BION, an injectable stimulator the size of a very large grain of cooked rice [64.279], which can be inserted without surgery (using a large-gauge needle) and is robust and resistant to infections. The second research line aims at stimulating the control circuits in the nervous system rather than individual muscles. For example, it has been shown that locomotor-like movements can be eliciting in multiple muscles of the cat hind limb by stimulating regions of the spinal cord directly [64.280].

64.4.5 Embedded Intelligence

Recent robotics-related advances for prosthetic legs have included embedding microprocessors and passive braking systems into artificial knees, so that the knees can, for example, be made relatively stiff during the stance phase of gait, and free to move during the swing phase of gait [64.281]. The first microprocessor knee introduced was the Ottobock C-Leg (Germany), introduced in 1999. The C-Leg uses a servomotor to adjust valves to hydraulic pistons. The rechargeable battery lasts about 24 hours. The pattern of resistance throughout the gait cycle can be adjusted for each user. A dramatic example of the benefit of the C-Leg is the story of a man who made it down from the 70th floor of the World Trade Center on 9/11/2001 with only minor bruising to his residual stump [64.282]. Other microprocessor-controlled knees are the endolite adaptive prosthesis, which uses pneumatic and hydraulic valves, the Rheo Knee (Össür Hf, Iceland), which uses magneto-rheologic fluid to vary the knee impedance and the Intelligent Prosthesis.

The first powered knee that can generate power, rather than just dissipate energy, is currently being commercialized by Össur as the Power Knee. The system combines an electromechanical power source that will be controlled with input from sensors on the sound leg shoe. Initial reports suggest that this is the first knee that allows the user to walk up stairs with a step-over-step pattern.

64.5 Augmentation for Diagnosis and Monitoring

A critical aspect of rehabilitation is health maintenance with age-related or degenerative functional decline and after a medical intervention. In-home diagnostic equipment, devices worn on or in the body for vital signs monitoring, tele-health services, and institution-based monitoring automation are all examples of systems being developed to improve the quality of life for both persons at risk and their caregivers. Institutional systems of this nature, more properly part of the field of clinical engineering, are incorporating more robotic, networked and autonomous devices to take more accurate diagnostics, provide better information to physicians and provide faster alerts. Key enabling technologies in this field are advanced materials and nanotechnologies.

64.5.1 Grand Challenges and Enabling Technologies

For all devices that are worn on the body, the interface must be skin compatible. A grand challenge for this field in the near-term is the better incorporation of active and sensing elements with textiles. Several prototype sensor shirts show promise, but rehabilitation will have a much richer toolset for diagnosis and monitoring with advances in this area. Nanotechnology, an enabling technology for the longer term, has the promise to miniaturize virtually everything mechatronic that is currently macroscopic. Injected devices, such as nano-robotic drug dispensers and clot-busters will aid in rehabilitation.

64.5.2 Smart Homes for Health Care Monitoring and Care

A special class of fixed-station rehabilitation robots is an automation system designed to provide a safe environment to assist and monitor a person with a disability living at home or in an institutionalized setting such as an assisted living facility or nursing home.

Smart Nursing Home Automation

An assisted living, hospice, or nursing care institutional facility will include residents who have mild to severe cognitive impairment in addition to physical disabilities. The facility may have zones to separate residents who have different levels of dependency since the architectural, monitoring and personnel needs are different. To better serve residents and guests, to optimize function and to minimize cost, only the areas for persons with high dependency have a 24 h staffed vital signs monitoring and alert capability, for example. Facility care is highly staff-intensive, though automation through diagnostic vital signs monitoring, electronic surveillance, and patient tracking continue to improve safety and efficiency. Robotics and automation are beginning to find applications in the physical tasks associated with patient care, therapy and oversight. Some examples are described below.

Examples of the State of the Art

Wandering, especially at night, is a significant problem for institutional facilities with ambulatory residents who are cognitively impaired. Simple architectural modifications include painting the hallway in front of doors black to make them look like deep holes. An automated voice system triggered by a motion detector to say *Go back to bed* is effective, but not fool-proof, either. Resident detection systems based on ID badges with embedded RFID chips that can be sensed in a hallway work, but only if the resident is wearing it. A robotic sentry system, including mobile platforms to aid in solving this problem, especially at night, has not yet been developed.

A serious rehabilitation issue in institutionalized facilities is the transfer of residents from bed to wheelchair and other surfaces. A number of manual, electric, and robotic devices have been developed to assist the nursing staff to safely transfer residents and patients who may be significantly heaver than they are. This remains an unmet clinical need, though not for lack of innovative attempts [64.283, 284].

64.5.3 Home-Based Rehabilitation Monitoring and Therapy Systems

Numerous smart homes have been developed for non-rehabilitation as well as assistive purposes [64.285]. These systems have as their goal the safety of people with disabilities living in the home and communication with caregivers outside of the home. Caregivers can be live-in family or attendants who, even when they are not home, need to be kept informed on the status of the disabled person, as well as clinicians who need to be sent regular vital signs and other medical/therapy reports. In-home systems typically feature the same principal elements:

1. Sensors to monitor both ambient and as people- and object-specific parameters (e.g., person location, stovetop operation); actuators to modify ambient conditions (heat, lighting, sound system, etc.) and operate devices (doors, refrigerator, etc.).
2. A means to network all the sensors and actuators for uni- or bi-directional communication with the host computer. This network can be wireless (e.g., 802.11 g), wired (e.g., coaxial cable), or dependent on an existing network (e.g., signals superimposed on current carried by the electrical mains wiring or phone wiring).
3. A host computer that allows all sensor states to be displayed and actuators to be operated from one or more locations in the home by the inhabitant(s) using common computer I/O devices. Higher order functions are built upon this basic capability.
4. An external network to allow communication with the Internet via phone, cable, satellite or other means. This capability allows for remote monitoring and operation, sending of alarms and discussions with rehabilitation professionals at medical centers.

The host computer software may also have higher order features, for example timers for repetitive actuation of lights and monitoring for anomalous sensor readings (e.g., call security when the smoke detector activates, alert inhabitants with in-home alarm when stove top power is on and no pot is on the stove). More advanced features that involve multi-input and multioutput control and adaptive, predictive, context-aware operation [64.286] are areas of active research, and especially important to the rehabilitation community.

As previously mentioned in this chapter, devices for home-based robot-assisted therapy have been recently developed, and home-based therapy delivered by robotic devices is expected to have a significant growth in the short-medium term.

CBM Motus [64.126] and T-WREX, [64.287, 288], a passive exoskeleton for upper limb rehabilitation now sold by Hocoma AG as ArmeoSpring, are just two examples of systems for home-based therapy described above (Sect. 64.2.3). Another example is the Hand Mentor, which is a device which uses video games and robotics to cognitively involve the patient in his/her rehabilitation [64.289, 290]. The Hand Mentor can be used in the clinic, or taken at home and incorporated into patients' daily therapy sessions to lengthen shortened tissues, facilitate hand opening and closing, and reduce spasticity. It is mainly conceived for stroke patients' rehabilitation and is commercialized by Kinetic Muscles, Inc.

64.5.4 Wearable Monitoring Devices

One component of an automated rehabilitation environment is the subsystem that a person wears to be able to measure, analyze, and communicate physiological signals to an external computer wirelessly. Systems such as the LifeShirt (VivoMetrics, Inc., Ventura) [64.291] have been and are being developed for front-line soldiers and rescue operation personnel whose health may become imperiled when out of touch with and unable to communicate verbally with their base command. For rehabilitative purposes, for example, the Intel Proactive Health Initiative [64.292] is an example of a system that use on-person position and motion sensing to detect potentially dangerous or undesirable situations.

The use of a robot to deliver therapy already enables measuring information on the patient state by exploiting robot sensors and other wearable units, if needed [64.293]. Such capability can be exploited for patient monitoring. A recent work proposed a method for reconstructing the human arm kinematics by resorting to an inverse kinematics technique for redundant robot arms [64.294].

The most significant obstacles to the widespread adoption of these technologies in the short term are cost, false-positive alarms, inconvenience and encumbrance. Advances in micro-electronics, nanotechnologies, software algorithms, and networking capabilities will continue to drive the research and consumer acceptance of this technology sector.

64.6 Safety, Ethics, Access and Economics

Rehabilitation robots interact closely with humans, often sharing the same workspace and sometimes physically attaching to humans, as in the case of robotic movement training devices and prosthetic limbs. Furthermore, the devices are by necessity powerful enough to manipulate the environment or the user's own limbs, which means that they are also often powerful enough to injure the user or another person nearby by colliding with them or moving their limbs inappropriately. Safety is clearly of paramount importance.

A common strategy for ensuring safety is to incorporate multiple, redundant safety features. A device can be designed to be mechanically incapable of moving itself or the user's limbs in such a way as to cause injury. Limits can be placed on the range, strength and speed of actuators so that they can accomplish the desired task but no more. Break-away attachments can be used to attach to users' limbs. Covers can protect the user from pinch points in the device. Redundant sensors can be included, so that if one sensor malfunctions another sensor can identify the malfunction and help safely shut down the machine. Watchdog timers can monitor the health of the control computer. Software checks can limit forces, motions, speeds, and user adjustments to control parameters, as well as check for sensor health and other dangerous situations. Control strategies can be designed so that the device is mechanically compliant, reducing the risk of forcing a limb into an undesirable configuration, or of a high-impact collision. A manual override switch can be incorporated so that the user can shutdown the system. Finally, the user can be instructed on how to safely operate the device and avoid dangerous situations. Safety ultimately depends, however, on careful and rigorous failure mode analysis and remediation by the system designers.

From a system's perspective, when all else fails actively to protect the user, it must be the design itself that makes the robot inherently unable to injure its user. Part of the solution is in reducing the weight, rounding the surface characteristics, and making appropriate materials choices. The goal of inherent safety, however, is often at odds with high performance and adequate payload for real-life tasks. Recently, several approaches to designing personal robots – in other words – the class to which assistive rehabilitation robots belong – have sought to address both goals by dividing the two tasks of compensating for gravity (arm plus payload) and moving the payload around in space [64.295]. The solution is to provide two actuators per joint on the joints that support the arm segments and payload against gravity: one slow, gear-reduced motor and energy storing device such as a large spring or compressed air volume, and one small, backdrivable motor that provides the power needed to move objects around quickly and precisely. Most robot manipulators have approximately a 1 : 10 (or worse) payload-to-weight ratio. A system with a dual, parallel actuator system that requires only the small, fast actuator to be carried in the arm, leaving the slow energy-storage system on the base and not contributing to the inertia of the arm itself, can lead to a 1 : 1 payload-to-weight ratio more in line with a human's own arm characteristics, and thereby provides a safe yet high-performance solution. An added benefit from this type of arrangement is that the movements of the arm will tend to be more human-like, providing a measure of confidence to the user that the robot is performing properly and moving in a safe way.

Strategies for improving safety have been proposed and methods to assess safety have been developed and adapted for rehabilitation robotics [64.296, 297] based on accepted risk analysis methods. While industrial robots have benefited from ISO user safety regulations since 1992 (ISO 10218), the fundamental issue of human proximity to robots for the personal, service, and rehabilitation sectors has prevented that standard from being applicable to rehabilitation robots. Currently, a draft of a new *safety requirements for personal care robots* standard, ISO 13482, is under development. Currently, the existing industrial standards, augmented with provisions from medical equipment standards and buttressed by engineering best practices and adherence to professional codes of ethics by designers, have guided rehabilitation robotics designers. Clearly, as products appear on the market and the expected rapid expansion of this sector happens, better regulations and standards must be developed.

Beyond safety, there are other ethical concerns that will emerge as robotics technology becomes more intelligent with advances in cognitive software, more invasive with nanotechnologies and better integrated with human systems through bioengineering advances. Ethicists and roboticists are starting to deal with these issues [64.298, 299], which to date have been the purview of only futurists and science fiction writers. Chap. 80 deals with these issues in detail.

An economic advantage has not yet been demonstrated in a decisive way for most rehabilitation robotics. For example, the therapeutic benefits conferred by robotic therapy devices, and the assistive benefits conferred by wheelchair-mounted robots relative to the devices' cost, have not yet been large enough to cause widespread adoption. Improvements in their efficacy and reductions in their cost will increase their usage. For example, a robotic therapy device that helps people learn to walk after a stroke, in a way that is decisively better than other training techniques, would become widely used very quickly. Likewise, a wheelchair-mounted robot that gives a disabled person a substantial and efficient increase in autonomy at a reasonable cost would also quickly become widely used. An example of a robotics technology that has achieved an attractive cost-benefit ratio and thus is commercially successful is the powered wheelchair.

64.7 Conclusions and Further Readings

Rehabilitation robotics is a dynamic application area because its grand challenges are at the forefront of both robotics and biology research. The ongoing major themes of the field can be summarized as the development of robotic therapy devices, smart prostheses, orthoses, functional aids and nurses that match or exceed the capabilities of their human counterparts. Rehabilitation robotics is also a highly motivating field because the technology developed will directly help people who are limited in major life activities. The field will continue to grow because of the dramatic aging of the populations of industrialized countries that is just beginning.

The grand challenges of rehabilitation robotics are grounded in the distinguishing features of the field: functional involvement with humans, a physical user interface and behavior that is intelligent, adaptive, and safe. These characteristics require high levels of redundancy, sensory-motor capability, adaptability, and multilevel software architecture. The grand challenges therefore span the domains of electromechanical design, software design, and, due to the applied and innately human-focused nature of rehabilitation robotics, all aspects of user interface design, including physical, communication, learning, emotional, and motivational factors. The first products in this field have come on the market in only the last 15 years; worldwide demographic trends will provide the force to accelerate product development in the future.

For further investigation on rehabilitation robotics, there are three major sources of published information:

1. Books on personal, service and rehabilitation robotics, such as: [64.300–302]
2. Review articles in journals and periodicals, such as [64.303–307] and
3. Articles that deal with individual topics, such as those in the reference list below, and conferences such as ICORR, RESNA, RO-MAN, BIOROB, and AAATE, which are also represented in the reference list.

Cutting-edge research will be reported on the websites of investigators at academic, government and corporate research labs, and it is recommended to start at the sites of the researchers cited in this chapter.

Video-References

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VIDEO 496	MIT Manus robotic therapy robot and other robots from the MIT group available from http://handbookofrobotics.org/view-chapter/64/videodetails/496
VIDEO 500	MANUS assistive robot available from http://handbookofrobotics.org/view-chapter/64/videodetails/500
VIDEO 502	The ArmeoSpring therapy exoskeleton available from http://handbookofrobotics.org/view-chapter/64/videodetails/502
VIDEO 503	Lokomat available from http://handbookofrobotics.org/view-chapter/64/videodetails/503
VIDEO 504	Gait Trainer GT 1 available from http://handbookofrobotics.org/view-chapter/64/videodetails/504
VIDEO 505	Kineassist available from http://handbookofrobotics.org/view-chapter/64/videodetails/505
VIDEO 507	Ekso available from http://handbookofrobotics.org/view-chapter/64/videodetails/507
VIDEO 508	ReWalk available from http://handbookofrobotics.org/view-chapter/64/videodetails/508
VIDEO 509	HAL available from http://handbookofrobotics.org/view-chapter/64/videodetails/509
VIDEO 510	Indego available from http://handbookofrobotics.org/view-chapter/64/videodetails/510
VIDEO 511	REX available from http://handbookofrobotics.org/view-chapter/64/videodetails/511
VIDEO 513	Targetted reinnervation and the DEKA arm available from http://handbookofrobotics.org/view-chapter/64/videodetails/513
VIDEO 515	PAM available from http://handbookofrobotics.org/view-chapter/64/videodetails/515
VIDEO 494	The Arm Guide available from http://handbookofrobotics.org/view-chapter/64/videodetails/494
VIDEO 497	ARMin plus HandSOME robotic therapy system available from http://handbookofrobotics.org/view-chapter/64/videodetails/497
VIDEO 498	BONES and SUE exoskeletons for robotic therapy available from http://handbookofrobotics.org/view-chapter/64/videodetails/498
VIDEO 495	The MIME rehabilitation therapy robot available from http://handbookofrobotics.org/view-chapter/64/videodetails/495
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