53. Rehabilitation and Health Care Robotics

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The field of rehabilitation robotics develops robotic systems that assist persons who have a disability with necessary activities, or that provide therapy for persons seeking to improve physical or cognitive function. This chapter will discuss both of these domains and provide descriptions of the major achievements of the field over its short history. Specifically, after providing background information on world demographics (Sect. 53.1.2) and the history (Sect. 53.1.3) of the field, Sect. 53.2 describes physical therapy and training robots, and Sect. 53.3 describes robotic aids for people with disabilities. Section 53.4 then briefly discusses recent advances in smart prostheses and orthoses that are related to rehabilitation robotics. Finally, Sect. 53.5 provides an overview of recent work in diagnosis and monitoring for rehabilitation as well as other health-care issues. At the conclusion of this chapter, the reader will be familiar with the history of rehabilitation robotics and its primary accomplishments, and will understand the challenges the field faces in the future as it seeks to improve health care and the well-being of persons with disabilities. In this chapter, we will describe an application of robotics that may in the future touch many of us in an acutely personal way.

53.1 Overview

When we become unable to interact physically with our immediate environment as we desire in order to achieve our personal goals through injury or disease, or when one of our family members, friends or neighbors is in this situation, we seek technology-based solutions to assist us in relearning how to complete our activities of daily living (ADLs), or to assist us in actually doing them if we are unable to relearn. While human therapists and attendants can indeed provide the types of assistance required, the projected short-term demographics of China, Japan, and the Scandinavian countries show a growing shortage of working-age adults. Age-related disabilities will soon dominate 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 ten 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 improvements in surgical and medication interventions. Rehabilitation robotics, although only a 40-year-old discipline [53.1–3], is projected to grow quickly in the coming decades.

53.1.1 Taxonomy of Rehabilitation Robotics

The field of rehabilitation robotics is generally divided into the categories of *therapy* and *assistance robots*. In addition, rehabilitation robotics includes aspects of artificial limb (prosthetics) development, functional neural stimulation, (FNS) and technology for the diagnosis and monitoring of people during ADLs.

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. Types of therapy that have benefited from robotic assistance are upper- and lower-extremity movement therapy, enabling communication for children with autism, and enabling exploration (education) for children with cerebral palsy (CP) or other developmental disabilities. 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, 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 perhaps not yet measurable by clinical scales, any recovery of function that may have occurred, which may be highly motivating for a person to continue with the therapy; and (3) the robot may be able to engage the patient in types of therapy exercises that a therapist cannot do, such as magnifying movement errors to provoke adaptation [53.4, 5].

Assistive robots are generally grouped according to whether they focus on manipulation, mobility, or cognition. Manipulation aids are further classified into fixed-platform, 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 carry out 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 impairments to lean on them to prevent falls and provide stability. The third main type, cognitive aids, assist people who have dementia, autism or other disorders that affect communication and physical well-being.

The fields of prosthetics and FNS 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. FNS systems seek to reanimate the limb movements of weak or paralyzed people by electrically stimulating nerve and muscle. FNS 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 ADLs.

The chapter is organized according to this taxonomy. After providing background information on world demographics (Sect. 53.1.2) and the history (Sect. 53.1.3) of the field, Sect. 53.2 describes physical therapy and training robots, and Sect. 53.3 describes robotic aids for people with disabilities. Section 53.4 then reviews recent advances in smart prostheses and orthoses that are related to rehabilitation robotics. Finally, Sect. 53.5 provides an overview of recent work in diagnosis and monitoring for rehabilitation as well as other health care issues.

53.1.2 World Demographics

The various areas of rehabilitation robotics focus on different user populations, but a common characteristic of these populations is that they have a disability. Disability is defined in the *Americans with Disabilities Act* as "a physical or mental impairment that substantially limits one or more of the major life activities."

Table 53.1 Prevalence and incidence of disability and aging in selected countries [53.6]

Country	Number of 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
The 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

In the industrialized countries (e.g., Japan, US, Canada, and Europe), the incidence of disability varies between 8% and 20%, with differences likely due primarily to varying definitions of disability and reporting conventions (Table 53.1). Age is a risk factor for disability, and lower birth rates and life-extending health care are the dominant factors contributing to the aging of the population and a concomitant rise in disability. In China, the population control policies of the 1970s have created a lack of working-age adults to support the economy. The disproportionate incidence of disability in the elderly population makes it clear that developers of rehabilitation robotics will also be faced with users who, as a demographic group, generally have 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 these demographic changes.

53.1.3 Short History of the Field of Rehabilitation Robotics

The history of rehabilitation robotics is almost as old as that of robotics itself, although emanating from very different sources. Several books, chapters, and papers have been written on the history of rehabilitation robotics in more detail than this section [53.1, 7, 8], and numerous papers in the proceedings of the Institute of Electrical and Electronics Engineers (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). The Case Western University arm (1960s) and the Rancho Los Amigos *Golden Arm* (early 1970s) (reviewed in [53.7]) were both adaptations of replacement mechanical arms meant as powered orthoses [53.1]. 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 do activities of daily living (ADL) tasks such as feeding a person and turning pages [53.9]. 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 Jean Vertut, for use by people with high-level spinal cord injury as well as children with cerebral palsy [53.10]. This system did not emerge from the P&O field but was developed by the French Atomic Energy Commission (CEA), which used large telemanipulators 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, Hok Kwee, began the MANUS project, a dedicated effort to develop the first wheelchair-mounted manipulator designed expressly as a rehabilitation robot, not adapted from a design from another field.

However, 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, Larry Leifer started the vocational assistant robot program, culminating in several clinically tested versions of the desktop vocational assistant robot (DeVAR) [53.3, 11, 12], a mobile version, the mobile vocational assistant robot (MoVAR) [53.13], and finally the professional vocational assistant robot (ProVAR), which had the advanced ability for the user to program tasks in an easy-to-use browser-type environment [53.14]. This step was made since, although DeVAR made it briefly onto the market in the early 1990s, multisite user testing revealed it was still too costly for the functionality it had: ProVAR development ensued, then continued by Machiel Van der Loos. All these versions were based on the Puma-260 industrial manipulator to achieve robust, safe operation. Research shifted in 2006 to the Veterans Affairs (VA) in Syracuse, NY, to integrate sensing and autonomous features and explore new, more cost-effective manipulator options.

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 specially designed from the ground up for human service tasks. Over ten 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 the robot for assisting the integration of the disabled (RAID), then as MASTER [53.15], 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 [53.16] took over efforts to commercialize the MASTER system, which it continues to do today (2007).

The UK was also the site of the first commercially available feeding robot, Handy-I, an inexpensive and well-received device first designed by Mike Topping and then commercialized by Rehabilitation Robotics, Ltd. in the 1990s [53.17]. Primarily aimed to enabled people with cerebral palsy to achieve a measure of independence in feeding themselves, task environments later also included face washing and the application of 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 Alfred I. duPont Hospital in Delaware from 1993–1997. 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, *Rich Mahoney*, moved to ARC and was instrumental in extending the company's repertoire to the RAPTOR wheelchair-mounted arm [53.18].

In Europe, the most significant mobile manipulator project was the MANUS project [53.19] mentioned earlier. With much of the work done under the direction of Hok Kwee at the Rehabilitation Research and Development Center (iRV) in the Netherlands, the project culminated in a robot specifically designed for wheelchair mounting, with control through a joystick and feedback by a small display on the arm itself. This project has led to numerous follow-on research projects, and, most significantly, to the commercialization of the system by Exact Dynamics BV, in the Netherlands. It is currently offered free on physician prescription by the Dutch government to qualified people with a disability such as cerebral palsy or tetraplegia from a spinal cord injury.

Autonomous navigation systems on electric wheelchairs also began in the 1980s, benefiting initially from the development by Polaroid Corporation 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 ($\approx 10-500$ 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, *Zenn Bien* at the Korea Advanced Institute for Science and Technology (KAIST) Human Welfare Robotics Center began developing the KAIST rehabilitation engineering system (KARES) line of wheelchair-based navigation systems in the late 1990s [53.20] 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 [53.21, 22].

Therapy robots had a later start than assistive robots, with early exercise devices such as the BioDex [53.23] a first step in programmable, force-controlled, albeit single-axis devices, in the mid 1980s. The first multi-axis concept was published by *Khalili* and *Zomlefer* [53.24], and the first tested system by Robert Erlandson at Wayne State University emerged in the mid 1980s as well [53.25]. 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 Neville Hogan and Igo Krebs, followed a few years later by the Palo Alto VA mirror image movement enabler (MIME) project and its derivative, Driver's simulation environment for arm therapy (SEAT), with Charles Burgar, Machiel Van der Loos, and Peter Lum, as well as the Rehabilitation Institute of Chicago ARM project with Zev Rymer and David Reinkensmeyer. Each had a different philosophy on upper-extremity stroke therapy and each was able to demonstrate clinical effectiveness in a different way. All three programs, now a decade later, have made significant technical advances and are still active.

Cognitive robotics had a start in the early 1980s to aid children with communication disorders and physical disorders to achieve a measure of control of their physical space. Using mostly educational manipulators, several demonstration systems were developed. In the early 2000s, Corinna Latham of Anthrotronix, Inc. commercialized small robot systems to enable children with physical disabilities to play games with simple interfaces. Later, small mobile robots were used in clinics by *Kerstin Dautenhahn*'s group [53.26] with children who have autism; since robots have such simple interfaces, communication with them does not appear not be as challenging as with other humans. The early 2000s also saw the advent of pet robots, such as the Paro seal robot developed by *Shibata* et al. [53.27], as companions for both children and the elderly who are confined to clinics and have limited real companionship.

The applications for robotics continue 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.

53.2 Physical Therapy and Training Robots

53.2.1 Grand Challenges and Roadblocks

The human neuromuscular system exhibits use-dependent plasticity, which is to say that use alters the properties of neurons and muscles, including the pattern of their connectivity, and thus their function [53.28–30]. The process of neuro-rehabilitation seeks to exploit this use-dependent plasticity in order to help people relearn how to move following neuromuscular injuries or diseases. Neuro-rehabilitation 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 therapist have substantial strength and agility.

Because neuro-rehabilitation is time- and labor-intensive, in recent years health care payers have put limits on the amount of therapy that they will pay for, in an effort to contain spiraling health care costs. Ironically, at the same time, there has been increasing scientific evidence that more therapy can in some cases increase movement recovery via use-dependent plasticity. As robotics and rehabilitation researchers began to recognize beginning in the late 1980s, neuro-rehabilitation 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.

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. Meeting this challenge involves solving two key problems: determining appropriate movement tasks (what movements should patients practise and what feedback should they receive about their performance), and determining an appropriate pattern of mechanical input to the patient during these movement tasks (what forces should the robot apply to the patient's limb to provoke plasticity). The prescription of movement tasks and mechanical input fundamentally constrains the mechanical and control design of the robotic therapy device.

There are two 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 neuro-rehabilitation 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 [53.5, 31].

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. Furthermore, making the devices light 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. 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. Meeting the grand challenge of robotic therapy therefore will require substantial, interrelated advances in both clinical neuroscience and robot engineering.

53.2.2 Movement Therapy after Neurologic Injury

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 spinal cord injury (SCI). 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. Some systems have also been targeted at assisting in cognitive rehabilitation of persons with neurologic injury, as reviewed below.

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 USA alone, and about 80% of these people experience acute movement deficits [53.32]. There are over 3 000 000 survivors of stroke in the USA, with over half of these individuals experiencing persistent, disabling, movement impairments. The number of people who have experienced and survived a stroke is expected to increase substantially in the USA and other industrialized countries in the next two decades, 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.

Common motor impairments that result from stroke are hemiparesis, which refers to weakness on one side of the body; abnormal tone, which refers to an increase in the felt resistance to passive movement a limb; impaired coordination, which can manifest itself as an apparent loss in control degrees of freedom and decreased smoothness of movement; and impaired somatosensation, which refers to a decreased ability to sense the movement of body parts. Secondary impairments include muscle atrophy and disuse-related shortening and stiffening of soft tissue, resulting in decreased passive range of motion of joints. Often the ability to open the hand, and to a slightly lesser extent close the hand, is dramatically decreased.

The number of people who experience a SCI in the USA each year is relatively smaller – about 15 000, with about 200 000 people alive who have survived a SCI – but the consequences can be even more costly than stroke [53.32]. 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. The resulting pattern of movement impairment depends strongly on the vertebrae at which the spinal cord is injured, since nerves branch out to the head, arms, legs, and bladder and bowel at different vertebrae. About 50% of spinal cord injuries are incomplete, meaning that some sensation or motor function is preserved below the level of the injury. Spinal cord injuries are commonly bilateral and thus are often more functionally devastating in comparison to strokes, which at least leave a person with one side of their body that is relatively normal (which we will refer to as the *less impaired* side). Individuals experience especially severe disability if the lesion is high enough to involve the arms as well as the legs.

53.2.3 Robotic Therapy for the Upper Extremity

The following sections describe the best-known clinically tested upper-limb therapy robot systems that have been developed since the 1980s (Fig. 53.1).

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. [53.33]. MIT-MANUS is a planar two-joint arm that makes use of the selective compliant assembly robot arm (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-effecter, 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 tabletop as the patient plays simple video

Fig. 53.1a–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)

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 [53.34], wrist motion [53.35], and hand grasp [53.36]. Software has been developed for providing graded resistance as well as assistance to movement [53.37], and for varying the firmness and timing of assistance based on real-time measurements of the patient's performance on the video games [53.38].

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 conventional therapy and a brief, sham exposure to the robot [53.39]. 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 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 practised additional movements with MIT-MANUS with the motors 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 confirmed that robotic therapy can also benefit chronic stroke patients [53.40]. The device has been used to compare two different types of therapy – assisting movement versus resisting movement – in chronic stroke subjects, but with inconclusive results: both types of therapy produced benefits [53.37]. The device has also been used to compare assistive robot therapy with another technological approach to rehabilitation – electrical stimulation of finger and wrist muscles [53.41]. Again, significant benefits were found for both therapies, and those benefits were specific to the movements practised, 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.

MIME

Several other systems have undergone clinical testing. The mirror image movement enhancer (MIME) system uses a Puma-560 robot arm to assist in movement of the patient's arm [53.42]. 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 (DOFs), 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 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 tabletop exercises with an occupational therapist [53.42]. The robot group even surpassed the gains from human-delivered therapy for the outcome measures of reaching range of motion and strength at key joints of the arm. A follow-on study is being undertaken to elucidate which of the control modes or what combination of MIME exercises caused the gains [53.43].

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. The ARM guide is a trombone-like device that can be oriented then locked in different directions and assist in reaching in a straight line. Chronic stroke patients who received assistance during reaching with the robot improved their movement ability [53.44]. However, they improved about as much as a control group that simply practised 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 its ability to resolve the size of the difference between guided and unguided therapy.

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 [53.45], the Bi-Manu-Track uses two motors, one for each hand, to allow bimanual wrist-flexion extension [53.46]. 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) practised 800 movements with the device for 20 min per day, five days per week for six weeks [53.46]. For half of 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 0–5 points [53.47].

Other Devices to Undergo Clinical Testing

Other 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 [53.48, 49]. The Rutgers hand 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 [53.50]. Simple force-feedback controlled devices, including a one-DOF wrist manipulator and a two-DOF elbow–shoulder manipulator, were also recently shown to improve movement ability of chronic stroke subjects who exercised with the devices [53.51]. 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 [53.52]. By incorporating a simple hand-grasp sensor, this device allows substantially weakened patients to practise simple virtual reality exercises that simulate functional tasks such as shopping and cooking. Chronic stroke patients who practised exercising with this non-robotic device recovered significant amounts of movement ability, comparable with the Fugl-Meyer gains seen with MIT-MANUS and MIME. NeReBot is a three-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 [53.53]. RehaRob uses an industrial robot arm to mobilize patients' arms along arbitrary trajectories following stroke [53.54].

Other Systems Currently under Development

Several other robotic therapy devices are currently under development. For example, at the high end of cost and complexity are the ARM-In [53.55] and Pneu-WREX systems [53.56], 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 [53.57]. A wearable exoskeleton driven by pneumatic muscles is described in [53.58]. 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 [53.59–62]. Examples of recent, novel robotic devices for the hand are given in [53.63–65]: these devices typically follow an active assist therapy paradigm in that they are designed to help open and close the hand. One robotic therapy system for the hand incorporates the idea of using visual feedback distortion to enhance motivation of patients during movement therapy [53.66]. Using robotic force fields to amplify the kinematic errors of stroke patients during reaching may provoke novel forms of adaptation of those patterns [53.4, 67].

53.2.4 Robotic Therapy for Walking

Background

Scientific evidence that gait training improves 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 partial support of the body weight and assistance of leg movements [53.68, 69]. 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 up to three therapists [53.70–73]. Depending on the patient's impairment level, from one to three therapists are needed for body-weight supported treadmill training (BWSTT), 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 functional reorganization and recovery of the injured neural circuitry [53.74]. In the 1990s, several independent studies indicated that BWSTT improves stepping in people with SCI or hemiplegia after stroke [53.70–72].

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 overground gait training because BWSTT is done on a stationary setup in a well-defined manner and thus can be more easily automated than overground gait training. Randomized, controlled clinical trials have shown that BWSTT is comparable in effectiveness to conventional physical therapy for various gait-impairing diseases [53.75–80]. These trials support the efforts towards 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 [53.76] 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

Three gait-training robot systems are already in use for therapy in several clinics worldwide: the gait trainer GT-I [53.81], the Lokomat® [53.82], and the AutoAmbulator™ [53.83] (Fig. 53.2).

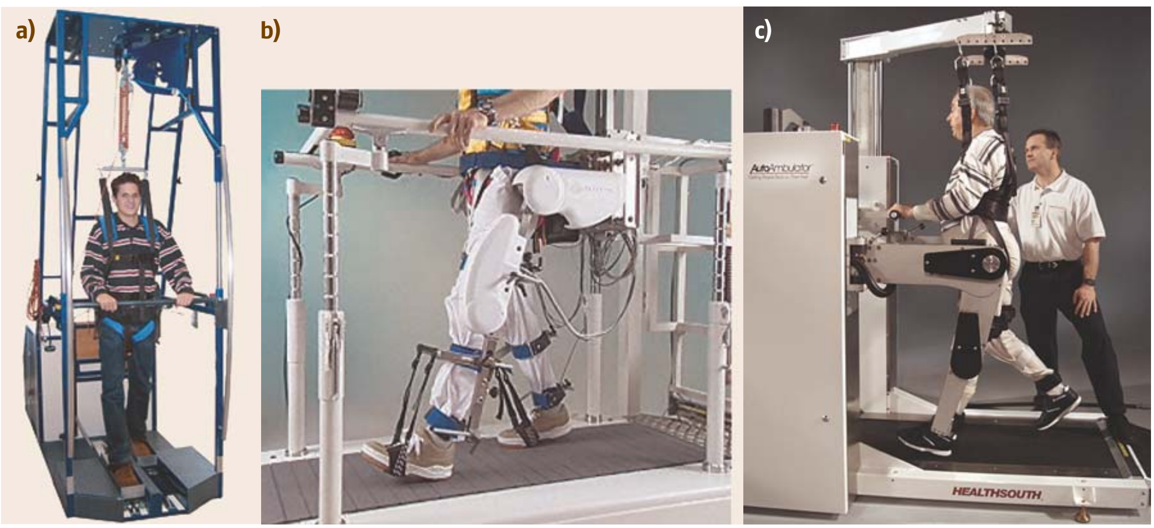

Fig. 53.2a–c Gait-training robotic systems currently in use in clinics; **(a)** the gait trainer GT-I, developed by Hesse's group and commercialized by Reha-Stim (Germany); **(b)** the Lokomat®, developed by Colombo and colleagues and commercialized by Hocoma AG (Switzerland), and **(c)** AutoAmbulator™, developed by the HealthSouth Corporation (USA)

Of these three robot systems, the GT-I 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 [53.81]. 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 [53.84]. The robot group improved their overground walking ability more than the control group, although differences were not significant at six-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 GT-I with a time-matched amount of conventional training alone with subacute stroke patients found that the group that received some robotic training recovered walking ability to a great extent [53.85].

The Lokomat is a robotic exoskeleton worn by the patients during treadmill walking [53.82]. Four motorized joints (two per leg) move the hip and knee. The actuators consist of ball screws connected to direct-current (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 passive parallelogram mechanism allows vertical translation of the patient's torso, restricting lateral translation. The patient's body weight is unloaded as needed through an overhead harness. The Lokomat is currently being used in dozens of research labs and clinics worldwide. In 2005, *Wirz* and coworkers [53.86] 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. *Hornby* and colleagues [53.76] studied the effects of robot-assisted BWSTT with the Lokomat on individuals with subacute SCI. Thirty patients were randomly assigned to one of three training groups: robot-assisted BWSTT, therapist-assisted BWSTT, and therapist-assisted overground ambulation. Improvements in motor and functional abilities were similar in the three training groups, with the robot-assisted BWSTT requiring significantly less labor than the other two therapy methods.

The AutoAmbulator (http://www.autoambulator.com) 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 AutoAmbulator is currently being used in 57 HealthSouth rehabilitation centers, all of them in the United States. A single-blind, randomized clinical trial to assess its effectiveness in stroke patients is currently underway.

Further Research and Development on Robotic Therapy for Walking

Several groups worldwide are working toward improving gait-training robotic technologies. A great deal of effort has been going into incorporating and investigating the ability to assist as needed [53.31, 87–91], 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 [53.92]. Some effort has also been directed towards adding more active DOF, particularly for torso manipulation [53.90, 93]. 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 HapticWalker [53.87], which maintains the permanent foot/machine contact but allows the footplates to move along three-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 and machine [53.88]. It has been tested on unimpaired and SCI patients, who were able to influence the gait trajectories towards a more desired motion by means of their own motor activity [53.88, 94].

The pelvic assist manipulator (PAM) is a five-DOF robot for torso manipulation, and the pneumatically operated gait orthosis (POGO) is a leg robot with two DOFs per leg. PAM's and POGO's actuators are pneumatic, which cost less than electric motors and have higher power-to-weight ratios [53.93]. The robots' ability to control forces and yield to patients and/or therapists has been tested with unimpaired and SCI patients [53.95]. 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 patient varies the timing or size of steps.

Based on the string-puppet principle, the String-Man achieves weight bearing and compliant six-DOF torso manipulation by means of seven wires and a force sensor on each wire [53.90]. 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 the help of foot force sensors.

Veneman and colleagues [53.91] are developing actuation systems for robotic exoskeletons that combine 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 force feedback control loop with a position sensor that measures the spring elongation, a concept inspired from the series-elastic actuation concept described by *Pratt* and coworkers [53.96]. In addition, series elasticity is useful to reduce the negative effects that static friction and unmodeled dynamics have on the stability of force control, thus improving the achievable force control bandwidth [53.97, 98], which is especially important for a Bowden-cable-based system. Series elasticity worsens positional accuracy, but this is not a critical issue for gait-training robots. Veneman's first experimental results show that adequate force control bandwidth was achieved by a prototype of their Bowden-cable-based actuation design [53.91], so that a robot incorporating this actuation concept can plausibly execute both a stiff, position-dominated robot-in-charge mode as well as a compliant, low-impedance patient-in-charge mode.

A different approach to gait training was taken with the KineAssist device [53.99]. KineAssist is a motorized mobile platform that follows patient and therapist as they move over ground 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.

Other efforts include *Ferris* and coworkers [53.100], 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 six-DOF pneumatic system based on a Stewart platform that allows exercise of the ankle [53.101]. Also in the USA, *Agrawal*'s group proposes the use of gravity-balancing leg orthoses for people with gait impairments to practise walking [53.102]. 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 to include actuators with reduced torque requirements [53.103]. A robot has been used to provide graded body weight support as a patient who cannot bear his full weight because of a medical problem walks in a circle [53.104].

Other Robotic Movement Therapy Approaches

As reviewed above, most of the work to date in robotic therapy devices has focused on robots that attach to patients to assist them in practising 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 [53.24], and using a multi-axis robot arm to place targets for patients doing reaching exercises [53.105]. 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 [53.59, 106, 107].

53.3 Aids for People with Disabilities

53.3.1 Grand Challenges and Enabling Technologies

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. 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, but also specifically dependent on the algorithmic developments that issue from the community of robotics researchers.

Research on robotic aids has so far primarily targeted persons with mobility and manipulation limitations, rather than children and adults with cognitive impairments. However, increases in the prevalence of cognitive impairments related to aging will make the latter focus increasingly important. 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 today therefore 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.

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 cerebral palsy (CP), and more generally for anyone who lacks the ability to manipulate household objects. A market research study conducted ten years ago specifically for rehabilitation robotics clients conservatively projected a US market of 100 000 people [53.108]. 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. A rehabilitation 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 [53.109].

Interfaces of assistive robots tap into the 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–backwards and left–right. With proper placement of push buttons, a joystick, or non-contact 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 control of a computer, such as head-position cursor control, eye-trackers, speech recognition systems, track balls, and special keyboards, can be used to provide access to computer-based robot functionality.

Even more so 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 track ball, 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 effective use of the robot.

53.3.2 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. 53.3). Other examples are mentioned in the history in Sect. 53.1.3.

Manipulation Aids: Fixed Base

Common robots of this type are ADL and vocational manipulation aids and kitchen robots. In the US, 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 tabletop, bringing objects (like a drink of water or throat lozenge) to the robot's operator. The interface is via a Java or virtual-reality modeling language (VRML) plug-in to a common Internet browser, delivering high-level control to disabled office workers in a conventional pull-down menu and control screen interface [53.14, 110]. This system and its predecessor DeVAR have been field tested by over 50 subjects at five rehabilitation clinics to assess feasibility and acceptability [53.111, 112]. At a cost of over US$ 100 000 currently, it is poised to be re-engineered with a simpler, cheaper arm for eventual product introduction.

In the European Union (EU), following a development path parallel to ProVAR's, 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 is in limited production [53.16].

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 [53.113]. 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 three degrees of freedom designed for one-switch operation by persons with cerebral palsy [53.17]. 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 [53.8] is on sale worldwide at about US$ 5000, and is designed for eating only.

While a robot conventionally connotes a stand-alone 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 [53.114].

Smart homes, such as the domotic environment at Georgia Tech, NL-iRV, and the University of Tokyo [53.115], 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 (see the next section), these robotic homes can allow a person with a cognitive or physical disability to control many ADL functions and live safely through monitoring.

Fig. 53.3a–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)

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 [53.19, 116] (Fig. 53.4). The robot has undergone numerous user studies with persons who have muscular dystrophy, a high-level SCI, or cerebral palsy. 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.

Manipulation Aids: Mobile Autonomous Systems

The most commonly conceived form of a robot is that of an autonomous, mobile system with arms, having sensorimotor functionality similar to that of a human being, while serving people in performing menial physical tasks. Chapter 56 of this Handbook explores the domain as well. 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

Fig. 53.4 Wheelchair manipulator robot MANUS developed at the Rehabilitation R&D Center, Hoensbroek, and marketed by Exact Dynamics (The Netherlands)

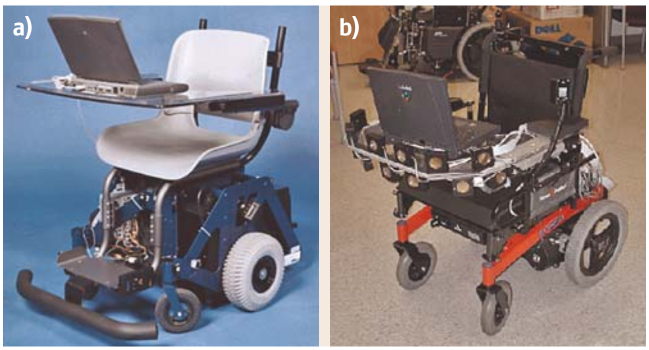

Fig. 53.5a,b Wheelchair navigation aids: **(a)** Wheelesley and **(b)** Hepahaestus

around the world. More recently, real robots such as the HelpMate [53.117] 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 [53.118] adds manipulation and vision to these capabilities to navigate in home-like environments to provide object manipulation and device operation to individual users. The German Care-O-bot [53.119] 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.

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 semi-autonomous navigation assistance (Fig. 53.5). Add-ons to commercial wheelchairs have been developed by numerous research groups for this service. The NavChair [53.120] 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 [53.22] 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 [53.121] and KARES [53.20] robots have explored similar functionality using a vision system for scene analysis and way-finding.

Mobility Aids: Walking Assistance Systems

A third type of mobile robot for stability assistance has the particularity that it is underactuated and has similarity with a *co-bot* in that the wheels are not driven, but are actively steered and braked (Fig. 53.6). The Pam-Aid [53.122] 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 before), designed originally as a mobile autonomous robot of approximately human size, has a similar set of handlebars to Pam-Aid so it can be used as a smart walker. The larger mass of the Care-O-bot, however, requires it to be motorized.

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 example, the

Fig. 53.6a–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

PARO robot looks like a baby harp seal, and can respond to sound, contact, light, and tilt by moving its head and eyelids [53.123]. The device has been used to facilitate interaction with children with autism and elderly adults. The CosmoBot, a small humanoid robot with multiple degrees of freedom and a control panel, has been used to motivate speech and motor behavior by children with cerebral palsy, Down's syndrome, and autism [53.124]. The Japanese Wakamaru robot [53.125] was announced by Mitsubishi Heavy Industries in 2003 as a home health monitoring robot to assist persons living alone but at risk of falls and in need of information services and reminders related to their own health care. An interesting feature of this robot is that its arms and programmable facial features are used for gesturing only, not manipulation and sensing, to assist in effectively communicating to its users. A small, talking mobile robot was recently developed to motivate and measure rehabilitation exercises by stroke patients [53.126]. There is also extensive related work in the development of virtual-reality interfaces for motivating rehabilitation therapy [53.127].

As an example using robots to motivate therapy, Dautenhahn and colleagues have studied the use of robotic toys as tools to stimulate communicative and social skills and facilitate human contact in children with autism. Children and adults with autism often avoid social interactions and have difficulty interpreting facial expressions and other social cues in interactions with people. As reviewed by *Dautenhahn* [53.26], research suggests that children with autism generally feel more comfortable in predictable environments. Human social behavior is subtle, elaborate, and unpredictable. Many children with autism are however interested to play with mechanical toys or computers. In addition, Dautenhahn's studies show that children with autism have greater interest in interactions with autonomous robotic toys than with inanimate toys. In a study spanning several months [53.128], four children with autism were comfortable interacting with a humanoid robotic doll called Robota, participating in imitation, turn-taking, and role-switching. The children even started, by their own initiative, to include the investigator in their shared experience with the robot. Robins et al. suggest that robots could be used to encourage social interactions by children with autism, to allow care-givers to observe and monitor the children's play behavior and progress and to address specific therapeutic goals by targeted programming.

Other cognitive aids are focused on caretaker tasks such as monitoring vital signs and performing reminding functions. *Joseph Engelberger* popularized the concept with the HelpMate robot prototype in the 1990s [53.129], and Mitsubishi Heavy Industries commercialized the Wakamaru robot [53.130] for home use, with clinical trials pending. Even though it is not capable of manipulating objects, it uses its arms to gesture and provide communication cues to people in the home, in addition to using speech output and speech recognition.

53.4 Smart Prostheses and Orthoses

53.4.1 Grand Challenges and Roadblocks

In 2005, the Defense Sciences Office (DSO) of the US governmental research agency, the Defense Advanced Research Projects Agency (DARPA) launched a program to revolutionize prosthetics in a four year timeframe. According to the agency website (http://www.darpa.mil/dso/thrust/biosci/revprost.htm), 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 four 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.*

This program announcement lays down the grand challenge for prosthetics research in an ambitious timeframe: develop an artificial limb that has functionality 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. 62 on neurorobotics. For an overview of the design of conventional prosthetic hands and arms, the reader is referred to [53.131].

53.4.2 Targeted Reinnervation

Standard prosthetic arms and hands are commonly controlled with a cable drive or by 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. [53.132] recently developed a novel approach to improving control of a multijointed prosthetic arm. In this targeted reinnervation technique, they rerouted 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 reinnervated 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 rerouted nerves reinnervated sensors, so that now when the person's chest is touched, the person perceives it as a touch to his missing limb. This sensory reinnervation 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 [53.133]. It has also recently been shown that direct electrical stimulation of a residual peripheral nerve can provide usable information regarding force to a person with an amputation [53.134].

53.4.3 Brain–Machine Interfaces

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, Vol. 442 [53.135]). The ability to decode an intended movement directly from brain activity could make it possible to control a prosthetic limb or orthotic device directly by thought.

Brain–computer interfaces can be divided into non-invasive and invasive approaches. In noninvasive approaches, electrical activity is recorded from the surface of the skull using surface electrodes to form an electroencephalogram (EEG) (for a review see [53.136]). Individuals can 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.

Invasive approaches involve implanting electrodes on the surface of the brain (electrocorticogram) or into the brain itself. Electrodes implanted inside the brain can detect action potentials from single neurons. The first demonstration of this technique in humans [53.137] was in a person with end-stage amyotrophic lateral sclerosis (ALS), a disease that paralyzes muscles but leaves cognition intact. A cone electrode was implanted in the motor cortex, along with growth factors that encouraged growth of neurites, or branches of neurons, into the cone. Stable action potentials were recorded for several months, and the patient was able to increase or decrease the firing rate of the action potentials recorded by the electrode.

Subsequent work in monkeys demonstrated that recordings from multiple neurons (ranging from as few as tens to hundreds) can be used in real time to decode the three-dimensional trajectory of the arm using straightforward signal processing (see review [53.138]). The first human volunteer, a person with tetraplegia due to spinal cord injury, has now been implanted with the BrainGate electrode array, and has been able to control the movement of a cursor on a computer screen [53.135]. Other work in brain–machine interfaces has focused on detecting higher-level control signals, such as the intent to move, preferences for different rewards, and motivation to perform a task [53.139].

Given this progress, 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 reinnervation and brain–machine interfaces has allowed three to four degrees of freedom of control in a naturalistic manner, which is an advance over conventional prosthetic control techniques.

53.4.4 Advances in Neural Stimulation

Unlike people who suffer an amputation, individuals who suffer from paralysis due to neurologic injury retain their limbs. Frustratingly, however, they often do not achieve as good of control as people with artificial limbs. The situation is ironic because the actuator in the limb muscle, is very sophisticated and can still be activated by stimulating the nerves that innervate the muscles. Thus, one viewpoint of the problem of restoring motion for paralyzed people is that excellent hardware for solving the problem already exists (i. e., the limbs themselves), but that we must find ways to replace the control system to control it.

Functional neural stimulation techniques (FNS) seek to stimulate the residual nervous system electrically to reanimate 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 ease of use of systems that use surface electrodes, duration of use before fatigue, risk from implantation and complexity of the associated control problems. The systems that have been most successful are foot-drop stimulators, which aid individuals who suffer from neurologic conditions in lifting a drooping foot while walking. These systems detect the phase of the gait cycle (using a foot switch or accelerometer, for example) and then stimulate a nerve in the leg to lift the foot at the appropriate time.

Two recent innovations may help move the FNS field forward. The first innovation is a hardware innovation. The bionic neuron (BION) is an injectable stimulator the size of a very large grain of cooked rice [53.140]. The initial version is powered through electromagnetic transduction via a coil on the outside of the body, but versions are under development that include a battery. Communication with the individually addressable, programmable stimulator on the BION is through radio frequencies. Sensors, including accelerometers, can also be packaged into the capsule, so that the multiple implanted devices could communicate with themselves to calculate limb position. Two potential advantages of the BION which may make FNS more practical are that it can be inserted without surgery (using a large-gauge needle), and that it may be more robust and resistant to infections, since it does not require implanted wires that can become roadways for infections to spread.

The second innovation that may push FNS forward is 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 (see review [53.141]). The key realization here is that there exists modular circuitry in the spinal cord, and perhaps elsewhere, that can be electrically activated in order to produce coordinated patterns of muscle activity in multiple muscles. Thus, one electrode can produce coordinated, multijoint muscle activity, reducing the number of needed control sites, and perhaps improving the smoothness and time to fatigue of the resulting contractions because of use of more natural muscle recruitment mechanisms.

53.4.5 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 (see the review in [53.142]). The first microprocessor knee introduced was the Otto Bock C-Leg, 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 9th September 2001 with only minor bruising to his residual stump [53.143]. Other microprocessor-controlled knees are the Endolite adaptive prosthesis, which uses pneumatic and hydraulic valves, the Rheo Knee (Ossur hf, Iceland), which uses magnetorheologic 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 Ossur 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.

53.5 Augmentation for Diagnosis and Monitoring

53.5.1 Introduction: Grand Challenges and Enabling Technologies

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 as well as their care-givers. 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. 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 nanorobotic drug dispensers and clot-busters will aid in rehabilitation.

53.5.2 Smart Clinics with Automated 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 hour 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 identity badges with embedded radiofrequency identification (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 [53.144, 145].

53.5.3 Home-Based Rehabilitation Monitoring Systems

Numerous smart homes have been developed for non-rehabilitation as well as assistive purposes [53.146]. These systems have as their goal the safety of people with disabilities living in the home and communication with care-givers outside of the home. Care-givers 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 as well as people- and object-specific parameters (e.g., person location, stove-top 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 bidirectional communication with the host computer. This network can be wireless (e.g., 802.11g), wired (e.g., coaxial cable), or dependent on an existing network (e.g., signals superimposed on current carried by the electrical mains 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 input/output (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 an in-home alarm when stove-top power is on and no pot is on the stove). More advanced features that involve multi-input and multi-output control and adaptive, predictive, context-aware operation [53.147] are areas of active research, and especially important to the rehabilitation community.

53.5.4 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.) [53.148] 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 [53.149] is an example of a system that use on-person position and motion sensing to detect potentially dangerous or undesirable situations.

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 microelectronics, nanotechnologies, software algorithms, and networking capabilities will drive the research and consumer acceptance of this technology sector.

53.6 Safety, Ethics, Access, and Economics

Rehabilitation robots interact closely with humans, often sharing the same workspace and sometimes physically attaching to humans, as is 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. See Chap. 56 for an in-depth discussion of safety and robotics.

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. Breakaway 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 shut down the machine safely. 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 systems 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 [53.150]. 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, back-drivable 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 that is more in line with a human's own arm characteristics, and thereby provides a safe yet high-performance solution. An added benefit of 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 [53.151, 152] based on accepted risk analysis methods. While industrial robots have benefited from International Organization for Standardization (ISO) user safety regulations since 1992 (ISO 10218), the fundamental issue of human proximity to robots for the personal, service, and rehabilitation sectors have prevented any consensus to date for a similar standard. 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 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 [53.153, 154], which to date have been the purview of only futurists and science fiction writers. Chapter 64 in this Handbook 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 device 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.

53.7 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, sensorimotor 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 ten 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 [53.155–157]; (2) review articles in journals and periodicals such as [53.158–161]; and (3) articles that deal with individual topics, such as those in the reference list below, and conferences such as the International Conference on Rehabilitation

Robotics (ICORR), Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) conferences, RO-MAN, and the Association for the Advancement of Assistive Technology in Europe (AAATE) conferences, 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.

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