# Robotics for Healthcare

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**Abstract** Since the first industrial robot was introduced in the 1960s, robotic technologies have contributed to enhance the physical limits of human workers in terms of repeatability, safety, durability, and accuracy in many industrial factories including those of the automobile, consumer electronics and shipbuilding industries. In the 21st century, robots are expected to be further applied in healthcare, which requires procedures that are objective, repetitive, robust and safe for users. Fueled by the rapid improvements of medical imaging and mechatronics technologies, healthcare robots have been rapidly adopted in almost every stage of the medical procedure by surgeons and physical therapists. In this chapter, we describe applications and the state of the art of healthcare robotics developed in the last decade. We focus on research and clinical activities that have followed successful demonstrations of early pioneering robots such as daVinci telesurgical robots and LOKOMAT training robots. First, we categorize major areas of healthcare robotics. Second, we discuss robotics for surgical operating rooms. Third, we review rehabilitation and assistive technologies. Finally, we summarize challenges and limitations of biomedical robotics as assistive tools for medical personnel.

## 1 Introduction

Ever since the definition of robot as a "reprogrammable machine", people have predicted that the robot will replace the human worker in the near future. This idea has been realized at least in industry, where it is common for robots to assemble automobiles and relocate heavy loads, which might also be dirty or dangerous to human workers. (It is debatable whether robots can replace workers in performing "difficult" jobs.) The definition of the robot has continued to evolve to "professional and personal service robots" and the next area for the application of robots

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is the medical and healthcare fields, which require safety and reliability for all stock holders from patients to insurance companies [1]. According to the Merriam–Webster dictionary, the definition of healthcare is “the maintaining and restoration of health by the treatment and prevention of disease especially by trained and licensed professionals”. Healthcare robots are therefore supposed to provide trained and licensed professionals with advantages (accuracy and sturdiness) and additional information (visual and haptic) and thus improve health conditions without compromising the safety of patients.

Since the first attempts in the 1980s, robots have been used in orthopedic surgery, neurosurgery, laparoscopy, physical therapy treatments, and other several areas in the field of medicine. Several companies including Intuitive Surgical, Hocoma, Hansen Medical and Honda, have launched healthcare robots with notable success. There have been important developments in the application of robotic technologies to new healthcare procedures not limited to laparoscopic and physical training procedures.

## 1.1 Taxonomy of Healthcare Robotics

Several review papers and edited books have been treated medical robots [2], [3]. The classification of different branches of biomedical robotics is certainly not an easy task. From an engineer’s perspective, robots are often classified by their level and type of autonomy into autonomous systems, teleoperated systems and assistive systems. For example, currently used laparoscopic surgical robots are classified as teleoperated robots. In contrast, domain-specific taxonomy can be employed to categorize medical robotics into two main categories: surgical robots and physical therapy/assistant robots. The major difference between the two categories is the invasiveness of the target procedures. Surgical robots are designed to perform or assist in interventional procedures performed in operating rooms. Physical therapy/assistant robots are intended to help recovery by providing therapy and monitoring the progress or assist weakened forces in an activity of daily living. Fig. 1. shows the major categories of and important keywords relating to healthcare robots.

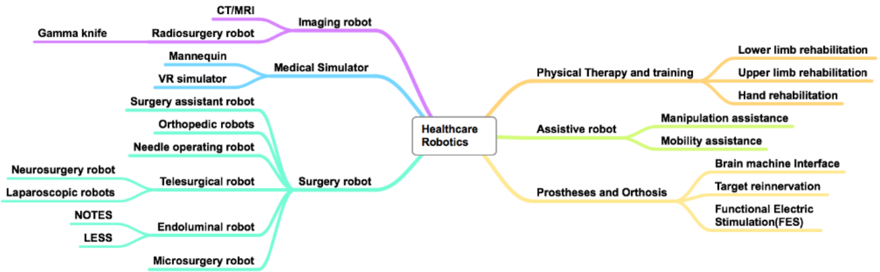

**Fig. 1** Major categories of and important keywords relating to healthcare robots

In this chapter, we review the achievements of healthcare robotics in recent decades. We first discuss robotic systems for surgical operations that improve patient safety. We then review physical therapy training/assistive robots for disabled and aging people. Here, we exclude prostheses, orthoses, and robotic transportation assistance devices owing to space limitations but these areas are also considered important in terms of robotics applications. Finally, we conclude the chapter by discussing challenges facing biomedical robotics.

## 2 Robotics for Patient Safety

Surgical robotics is a relatively young research area, with robot-assisted surgery first being reported in 1985. A Puma 560 industrial robot (Advance Research & Robotics, Oxford, CT, USA) was modified to be used for defining the trajectory of a brain biopsy, taking advantage of the features of industrial robots such as their high repetitive accuracy and absolute positioning accuracy [4].

Minimally invasive surgery, which includes laparoscopic surgery, has been the most important advance in every specialty of surgical medicine in recent decades. Because a minimally invasive procedure uses smaller incisions or openings than conventional surgery, it has several advantages over traditional open surgery including quick recovery, less scarring and shorter hospital stays. Although there are many advantages on the patient side, the surgeon is hampered by, for example, limited vision, a lack of force feedback, a very restricted range of motion and a fulcrum effect that makes it difficult to manipulate tissue. These difficulties are interpreted by engineers as “laboriousness” and a robotic system for minimally invasive surgery was considered to overcome these difficulties. Following the success story of the da Vinci surgical system (Intuitive Surgical, Mountain View, CA, USA), which was founded in 1995, the advantages of using a robot have been well documented and accepted by many clinicians over the last two decades. A camera on an arm allows for improved or three-dimensional visualization via a stereoscopic display. Manipulators having two or three degrees of freedom (DOFs) carry the instruments. Such manipulators include the articulated EndoWrist, which provides greater dexterity, especially in suturing.

Many researchers have pursued other goals. One notable development has been the RAVEN Surgical Robot platform created by a group of researchers led by B. Hannaford, who demonstrated remote surgeries using various network conditions in 2007 [5]. Recently, the group developed the smaller RAVEN 2, which has hands that are more dexterous and can hold surgical tools during operations. They developed their software using open-source codes so that RAVEN can be connected to other devices. The da Vinci Surgical System is expensive and uses proprietary software, whereas the RAVEN robotic system is more accessible to researchers around the world [6].

Although laparoscopic suturing has been made easier by the use of EndoWrist (Intuitive Surgical, Sunnyvale, CA) tools and a single-port stereo vision system, progress in orienting and manipulating curved needles within deformable tissue has been slow. Drake *et al.* investigated an automated suturing method that adopts a single manipulator to implement a suturing task with a standard laparoscopic needle holder and curved suture needle. Three-dimensional images are obtained by a clinical endoscope employing an elliptical/circular pose measurement algorithm, which dynamically tracks the suture needle and surface markers [7].

The invasiveness of laparoscopic surgery has been decreased as the techniques and equipment have been advanced. The concept of minimal invasiveness has resulted in the evolution of new types of surgical robots that require only one opening (single-port surgery) or, in the case of NOTES (Natural Orifice Translumenal Endoscopic Surgery), no artificial opening of the skin. Such procedures mainly use endoscopic instruments, which are slender and more flexible. Single-port surgery is a surgical method performed by inserting several surgical instruments and a laparoscope through an umbilical incision [8]. The research group of D. Kwon proposed a surgical robot system for single-port surgery that uses a special joint mechanism to avoid collisions between surgical tools or arms and approaches the surgical target more easily than a conventional straight surgical tool [8]. Kim *et al.* also developed a surgical robot for single-incision laparoscopic surgery. Their robot system includes a cone-type remote center-of-motion mechanism and two articulated instruments having a flexible linkage-driven elbow. They demonstrated that the robot can carry a payload of more than 10 N and described preliminary experiments on peg transfer and suture motion using the proposed surgical robot [9]. Dario *et al.* developed the Araknes surgical system for single-port laparoscopy through international collaboration. They demonstrated their design frame for surgical robots including software architectures and hardware controllers. They summarized important considerations and steps in the development of surgical robots to be used in operating rooms [10]. The group also developed a robotic platform for laser-assisted transurethral surgery of the prostate for benign prostatic hyperplasia. The system consists of a catheter-like robot equipped with a fiber optic-based sensing system and a cable-driven actuation mechanism [11].

While procedures that are less invasive provide better surgical outcomes than laparoscopic procedures, the difficulties of manipulation and limited workspace become more serious [12]. Whereas single-port surgical robots are considered a special type of laparoscopic robot, the NOTES robot requires new technologies and faces new challenges [13]. Mathelin *et al.* developed STRAS for endoluminal and transluminal surgery. The STRAS robot was designed as a modular robotic system, compatible with the medical environment, allowing an easy setup in the operating room using flexible shafts and continuum bending sections. It provides up to 10 DOFs, allowing the three-dimensional positioning of an endoscopic camera, the positioning of two instruments and grasper opening–closing functionalities [14]. Researchers at the University of Wisconsin–Madison led by M. Zinn proposed a new approach for continuum robotic manipulation that combines flexible, actively actuated continuum segments with small, limited-stroke rigid-link actuators. The small rigid-link joints are interwoven between successive continuum segments and provide a redundant motion and error correction capability. Although they demonstrated their approach only for cases with a limited number of

DOFs, their approach had some potential to compensate for flexible segment motion errors, which the majority of NOTES robots suffer from [15]. Unlike laparoscopic robots, which are nothing but mechatronic versions of traditional instruments, NOTES cannot be easily operated or diversified using traditional endoscopic instruments. The success of NOTES will thus be determined by sufficient improvements of the NOTES robot, which requires sufficient manipulation forces during operation and sufficient flexibility during inletting of the instruments on the same platform, which is difficult to achieve owing to the contradictive nature of the requirements.

## *2.1 Medical Simulation*

The nature of minimally invasive procedures resulted in the development of another new interesting technology, namely virtual reality technologies, in the area of medical training. Because the sense of touch has been reduced by the introduction of minimally invasive techniques when compared to the open surgery, surgeons have to rely more on the sensation of tool–tissue interactions through a long slender instrument and require more training for successful operation on patients. In fact, refinement of the surgeon's sensorimotor system takes an important role in the art of minimally invasive surgery. [16]

Medical simulations based on virtual reality provide an environment identical to that of real medical surgery for the training of surgeons, and therefore the surgeons can obtain numerous medical skills without causing real-world problems. In particular, the emergence of haptic devices with high-fidelity graphics provides a sufficient level of realism in the simulation of laparoscopic surgery, which requires only a limited scope of images and force feedback through long, slender tools. For example, Simbionix (Cleveland, OH, USA) provides an expanding set of modules including those for the training of knot tying, suturing, and gastric bypass along with decision making and teamwork tasks [17]. It also covers various procedures such as endovascular procedures and laparoscopic surgeries. Although there have been extensive discussions on the effectiveness of simulation-based training, a recent systematic study showed that simulation-based training for laparoscopic surgery has great benefits when compared with no intervention and is moderately more effective than instruction without simulation, which used to be the apprenticeship-based model of training [17], [18]. Currently, researchers and medical simulation industries are strongly pushing the development of a more versatile force feedback device, cost-effective tactile feedback and software curriculum design and training metrics.

## *2.2 Mechatronic Devices for Operating Rooms*

Despite the success of da Vinci robots, there are many procedures awaiting advanced technologies. Still, behind the scenes, many robotic devices and technologies have been applied to traditional surgical procedures and minimally invasive surgeries.

First, many mechatronic components were added to traditional surgical instruments to enhance tool–tissue interaction forces or to measure forces critical to the design specifications of surgical device/robots. Recently, Jo *et al.* created two-DOF compliant forceps for the measurement of pulling and grasping forces at the tip of a surgical instrument for improvement of the haptic feedback of a surgical robot [19]. Zhang *et al.* designed and fabricated a multiple-DOF force-sensing instrument to compute operating forces using a cable-driven mechanism [20].

Sutherland *et al.* designed micro force-sensing units that measure the forces exerted by surgeons during neurosurgical procedures. In a human cadaver study, they found that the forces needed to manipulate brain tissue were very low and varied depending on the anatomical structure being manipulated [21]. Yang *et al.* designed a hand-held device capable of amplifying delicate micromanipulation forces during minimal invasive surgical tasks. The device relays measured forces imparted to the user from the surgical instrument. They showed a five-times reduction in the minimum force threshold perceived by the subjects during microsurgery [22].

The group led by I. Iordachita and R. Tayer reported the development of a fiber Bragg grating sensor that has the ability not just to sense forces at the tip of a surgical instrument located inside the eye but also to provide information about the interaction force between the shaft of the instrument and the sclera during vitreoretinal surgery. The sclera section provides vital feedback for cooperative robot control to minimize potentially dangerous forces acting on the eye. The use of the force scaling robot allowed significant reduction of forces on the sclera [23].

Second, instrumented surgical devices with advanced material structures have been actively investigated. Webster *et al.* developed a telerobotic system for transnasal surgery that employs a concentric tube continuum mechanism. The catheter-sized continuum robots are appropriate for minimally invasive surgery within confined body cavities [24]. They showed the potential for surgical procedures such as endonasal skull base surgery, which requires more dexterity in using instruments. A similar mechanism was investigated for a neurosurgical example that involves choroid plexus cauterization for hydrocephalus treatment and closure of a patent foramen ovale inside the beating heart [25]. Recently, Webster's group developed a new hand-held robotic system for new holmium laser enucleation of the prostate (HoLEP), which is known to have better clinical outcomes than TURP (Transurethral Resection of the Prostate) yet is underused because of how challenging it is for the surgeon to perform using conventional endoscopic instruments. The system provides the surgeon with two concentric tube manipulators that can aim the laser and manipulate tissue simultaneously. The manipulators are deployed through a 5-mm working channel in a #26-French (8.66-mm) endoscope clinically used for transurethral procedures [26].

Third, special surgical procedures have specific engineering challenges. Robotics researchers collaborated with clinicians to overcome these challenges.

Howe *et al.* developed a special control algorithm for beating-heart surgery. By controlling a teleoperated robot to continuously follow the heart's vibrating motion, the heart can be made to appear stationary. Using Smith predictor theory, they successfully tracked heart motion during a surgical procedure [27]. A research group at Johns Hopkins University developed an integrated assistive system for membrane peeling in vitreoretinal procedures, combining an active tremor-canceling handheld micromanipulator with force-sensing motorized micro-forceps. Their micro-forceps are a 20-Ga instrument that is mechanically decoupled from its handle and senses the transverse forces at its tips with accuracy of 0.3 mN [28].

Finally, robotic devices were developed to help adopt new imaging modalities or new procedures. Simaan *et al.* designed a robotic manipulator with 11 DOFs for retinal micro-vascular surgery. It uses stents to maintain the structural integrity in artery/vein crossings for ophthalmic microsurgery. The robot also allows for the quick exchange of surgical graspers and the integration of a custom-made B-mode optical coherence tomography probe for image guidance [29]. The SSSA group led by A. Menciassi developed a multi-viewpoint, magnetic actuated laparoscope to implement nine-view autostereoscopic displays in minimally invasive surgery. The system is anchored by a magnetic link to the abdomen and freely moved by magnetic actuation to adjust the points of view and the horizons of the cameras [30].

Gitlin developed the Miniature Anchored Robotic Videoscope for Expedited Laparoscopy (MARVEL) and a wireless laparoscopic camera module that allow wireless robotic laparoscopic imaging. Two MARVEL camera modules were successfully tested *in vivo* in a porcine subject [31].

## 3 Rehabilitation and Assistive Robots

### *3.1 Conventional Therapy and Robot-Aided Therapy*

Robot-aided therapies and their applications have been proposed to meet the increasing demands of an aging society. The number of therapists is insufficient compared with the number of patients. Physical therapy involves the laborious and repetitive intervention of therapists. In gait rehabilitation, a patient is forced to move his/her legs passively by three therapists. Moreover, physical therapists and occupational therapists work together in conjunction to treat patients. Robotic rehabilitation is expected to support a therapist, allowing more intensive and repetitive training, and to assess patients' motor recovery quantitatively, measuring changes in movement kinematics and forces. Many kinds of robotic rehabilitation systems have been developed but not clinically evaluated thoroughly. In this section, we describe recent studies on clinical evaluation and commercially available robotic systems, from the perspective of conventional rehabilitation. The scope excludes hand rehabilitation systems.

#### 3.1.1 Perspective of Conventional Rehabilitation

Physical therapy focuses on evaluating and diagnosing movement dysfunctions as well as treating a patient injury. As compared with physical therapy, occupational therapy tends to focus more on improving functional abilities. A patient is treated with a combination of the two therapies by the therapist or medical doctor.

An effective therapy protocol is required in consideration of cost and time. Taub *et al.* proposed a concept of constraint-induced movement therapy (CIMT), which involves repetitive exercises of the affected limb under the instruction of therapists [34]. Standard prescription for the hemiplegic upper limb has not involved CIMT due to the cost of resources needed. Participants generally receive up to 6 hours of one-on-one therapy in a day. Electrical stimulation is one of the tools to be used following the therapist's conventional approaches that can be implemented easily. Electrical stimulation is able to improve function of weak muscles of arm and leg [36]. Mirror therapy is also prescribed to the affected side in the case of hemiplegia, especially for improvements of the arms and hands functions. In mirror therapy, a patient uses movements of the unaffected side to trick his/her brain into thinking that the affected arm is moving virtually, utilizing visual feedback [37]. The Bobath concept, also known as neurodevelopmental treatment, is a therapy based on the movement of components that emphasizes the integration of selective movements in the production of coordinated sequences of a movement [38]. Task practice is part of entire motion to assess an individual movement and to identify specific deficits of neurological functions. Finally, proprioceptive neuromuscular facilitation (PNF) stretching is an exercise based on the principles of functional human anatomy and neuromuscular functions to enhance the active and passive range of motion [39]. PNF uses proprioceptive, cutaneous and auditory input to produce functional improvement in motor output, especially for sports related injuries.

### 3.1.2 Robotic Rehabilitation Approaches

Developing a robotic rehabilitation system is multidisciplinary work involving a robotic engineering group and physical medicine and rehabilitation specialists. A robotic engineering group first suggests a robot-aided therapy as an alternative to a laborious physical therapy. Many robotic devices have been developed for the arm and gait therapy of individuals who have suffered a stroke [40], [41], but only a few have been widely known at clinical field; e.g., MIT-Manus [42]-[44], Mirror Image Movement Enabler (MIME) [45], [46], Bi-Manu-Track [47]-[49], Armin [50], [51], and Lokomat [52]-[55]. Most commercially available robotic systems were first developed at universities and other academic institutes. As mentioned in the previous section, the safety of the robotic system is the most important consideration for the user. The certification of the electrical and mechanical safety is issued by professional organizations.

For rehabilitation of the upper limb, the MIT Manus system provided sufficient workspace for horizontal motion [42] and vertical motion in most workspace in ADL. One of trends in the development of rehabilitation robotics has been the development of an exoskeleton system with a full range of motion employing multiple actuators. ArmeoPower was the first commercially available exoskeleton-type

**Table 1** Summary of clinically evaluated studies and commercialized works in respect to perspectives of conventional therapy

| Conventional rehabilitation perspectives | Robotics system | Clinical evaluation | Commercialization |
|---|---|---|---|
| Constraint-induced movement therapy [35] (1918) | MIT Manus [42] (Kreps *et al.* 1998) | Kreps *et al.*, Freeman *et al.* [43-44] (2004) | InMotion Arm (Interactive Motion Tech., Inc., US, 2009) |
| | ARMIN I [50] (Nef *et al.* 2003) | Nef *et al.* [51] (2009) | ArmeoPower (Hocoma AG, Switzerland, 2013) |
| | T-WREX [56] (Sanchez *et al.* 2004) | Sanchez *et al.* [57] (2006) | ArmeoSpring [58] (Hocoma AG, Switzerland, 2011) |
| Electrical stimulation [36] (1968) | - | Freeman *et al.* [64] (2009) | NeuroMove (Zynex Medical, Inc., US). |
| Mirror therapy [37] (1998) | Robotic assisted arm trainer [47] (Hesse *et al.* 2003) | Hesse *et al.* [48,49] (2005,2008) | Bi-Manu-Track (Reha-Stim Co., Germany) |
| | Mirror image motion enhancer(MIME) [45] (Lum *et al.* 2002) | Lum *et al.* [46] (2006) | - |
| Bobath (NDT: Neurodevelopmental treatment) [38] (1990) | Continuous passive motion (CPM) [63] (Volpe *et al.* 2000) | - | CPM manchines |
| Proprioceptive neuromascular facilitation [39] (1968) | Ankle rehabilitation system [65] (Zhou *et al.* 2014) | - | - |
| Gait therapy* | Lokomat [53] (Jezernik *et al.* 2003) | Mayr *et al.* [54-56] ( 2003) | Lokomat (Hocoma AG, Switzerland, 2009) |
| | LokoHelp (Freivogel *et al.* 2008) | Freivogel *et al.* (2009) | LokoHelp (LokoHelp Group) |

* All the systems are grouped according to the related perspective of conventional therapy. Gait therapy was difficult to classify them into a particular group.

rehabilitation robot for motor abilities and provides ADL-based arm training in a large workspace. The ARMin was designed by Prof R. Riener team at ETH Zurich University for patients suffered traumatic brain injuries, strokes, and neurological disorders to improve hand and arm functions [50], [51]. ArmeoSpring is passive assistive device for upper-limb rehabilitation utilizing spring-based gravity compensation mechanism. The assistive force is adjusted in consideration of muscle strength and arm weight of the user. The efficacy of the ArmeoSpring was reported by Prof. D. Reinkensmeyer at the University of California at the Rehabilitation Institute of Chicago [56], [57]. NeuroMove detects the EMG signals using three electrodes, and the electrical stimulation is provided for the user. The muscle signals are also displayed for the user in real-time for relearning the movement. Bi-Manu-Track provides bimanual arm training on the basis of mirror therapy. Movements of affected side are assisted by the help of the unaffected limb [47]. In this manner, a cortical representation of the hand larger than the representation of the shoulder was observed. ReoGo is a three-dimensional upper-limb rehabilitation system for repetitive arm movements training [59]. The system has advantage of a wide variety of patients, adjusting assistance level. The variety of the assistance level and motion-based games enhance the motivation of the user.

In terms of rehabilitation of the lower limb, Lokomat, combined with a robotic gait orthosis, an advanced body-weight support, and treadmill, was the first commercially available active gait rehabilitation system. Presently, Lokomat is the most well-known lower-limb rehabilitation system, showing clinical evaluation results [53]-[55]. LokoHelp consists of a harness that supports the body weight and a programmable pedal. Although clinical evaluations of the LokoHelp have also performed, the results showed that the efficacy of the system was similar to a manual training. However, the effort and discomfort of therapist is reduced, when using LokoHelp. ReoAmbulator is one of treadmill-based lower-limb rehabilitation systems, including body-weight supporting harness and robotic arms strapped to the thigh and ankle of user [62].

## *3.2 Assistive Robots*

An assistive robot is, by conventional definition, a robot that physically assists disabled people perform activities of daily living, while the broader definition of an assistive robot encompasses social assistance as well as physical assistance [66]. This subsection focuses on physically assistive robots, which can be classified by assistance type, form, and method of intention recognition. The type of assistance that assistive robots provide can be categorized as either manipulation or mobility assistance. Manipulation assistance robots support the functionalities of the arm and hand in diverse tasks such as self-feeding. Manipulation assistance robots can be classified by form as end-effectors, arm supports, and wearable exoskeletons. Mobility assistance robots have the form of a wheeled platform or wearable exoskeleton. The method of intention recognition is an essential technology required for controlling the assistive robot. The user's motion intention can be extracted from signals acquired by either noninvasive or invasive sensing methods. The invasive methods, however, necessitate the implantation of sensors in the user's body, and noninvasive methods are therefore preferred to allow easy application to a wide variety of users [67]. Manual or intuitive control methods are used for noninvasive intention recognition. Manual control is performed using a joystick, trackball, buttons or similar devices that can be handled by the user, while the intuitive control method captures the intention from the user's natural motion or biosignals.

There have been numerous achievements in the area of assistive robots including robotic arm supports and exoskeletons, meal assistance devices, robotic wheelchairs and mobile platforms, and wearable walking assistance robots. Among the achievements, this subsection introduces recently published research and commercially available products. The assistive robots are classified by the prescribed three criteria—assistance type, form, and intention recognition method—as listed in Table 2.

**Table 2** Classification of assistive robots based on assistance type, form, and intention recognition method

| Assistance type | Form | Intention recognition method | References |
|---|---|---|---|
| Manipulation | End-effector | Manual control (Joystick / button) | Bestic [68]<br>My Spoon [70] |
| | Arm support | Manual control (Button) | Neater Arm Support [71] |
| | Wearable exoskeleton (arm) | Manual control (Joystick / trackball)<br>sEMG | Hasegawa *et al.* [72] |
| | | sEMG | Kiguchi and Hayashi [73] |
| | Wearable exoskeleton (hand) | Contact force (Force sensor) | SEM Glove [75]<br>Heo and Kim [77] |
| Mobility | Wheeled platform | Manual control (Joystick) | TEK [78]<br>Nakajima [79] |
| | Wearable exoskeleton | Tilt sensor at torso | ReWalk [80] |
| | | Manual control (Button)<br>Hip/leg motion | Ekso [83] |
| | | Manual control (Joystick) | Rex [85] |
| | | Estimated center of pressure | Indego [87] |

### 3.2.1 Manipulation Assistance

Bestic (Bestic AB, Stockholm, Sweden) [68], [69] and My Spoon (SECOM Co., Ltd., Tokyo, Japan) [70] are commercially available meal assistance robots that aid people with disabilities to feed themselves. They have the form of an end-effector that is fixed to a table, and their key functions are picking or scooping food and bringing the food to the user's mouth. My Spoon has three operation modes: manual, semi-automatic, and automatic. The three modes differ in terms of the amount of user intervention during the feeding motion. In the manual mode, the user controls every single movement of the device with a joystick, whereas a button initiates automatic completion of a preconfigured feeding motion in the automatic mode. Bestic can be controlled by buttons or a joystick to set the location for picking food and to initiate a preconfigured motion.

Neater Arm Support (Neater Solutions Ltd., Buxton, UK) is a commercially available motorized arm support device that enables people with muscle weakness to use their arms [71]. It allows free motion within a horizontal plane via a serial link mechanism having three free rotational joints. One additional inclined rotational joint connecting the forearm brace and link mechanism allows automatic lowering of the elbow upon raising the hand to the level of the mouth. Only the vertical motion is motorized and the user manually controls this motion using buttons to raise or lower the arm.

An assistive exoskeleton that can be worn on the user's body is promising because it resembles a person's natural motion while seamlessly combining with the human body. Hasegawa *et al.* developed an exoskeleton having four DOFs for the support of shoulder (flexion/extension, abduction/adduction, and medial/lateral rotation) and elbow (flexion/extension) motion [72]. A direct-current (DC) motor actuates each DOF through a wire-driven mechanism. The exoskeleton can be controlled manually by a joystick or trackball, and can also be controlled by a surface electromyography (sEMG) signal from the muscles of the arm in conjunction with supportive manual control.

Kiguchi and Hayashi developed an exoskeleton that is controlled by an sEMG signal to aid arm motion [73]. It has seven DOFs—three for the shoulder (flexion/extension, abduction/adduction, and internal/external rotation), one for elbow flexion/extension, one for forearm supination/pronation, and two for the wrist (flexion/extension and radial/ulnar deviation)—that are controlled according to the user's joint torques estimated from 16 channels of sEMG signals. All the actuated joints are powered by DC motors mounted to a wheelchair frame or the exoskeleton's arm. A neuro-fuzzy modifier adopting a neural network structure needs to be trained before using the exoskeleton to build a proper model for the estimation of joint torques from the sEMG signals.

Because of the large contribution of the hand function in performing activities of daily living [74], there have been several works on the development of assistive robots for the hand. Among assistive robots for the hand, there is a commercially available assistive glove named the Soft Extra Muscle (SEM) Glove (Bioservo Technologies AB, Kista, Sweden) [75], [76]. The SEM Glove has three actuated fingers—middle and ring fingers and a thumb. The index finger is left unassisted to provide fine motor capability as well as undisturbed tactile sensation for the index finger. As a force sensor for measuring the user's gripping force, a force-sensing resistor is mounted at the fingerpad of each of the actuated fingers. Flexion forces for the actuated fingers are generated by DC motors. A wire-driven mechanism is employed to transmit a force to the fingers.

A hand exoskeleton developed by Heo and Kim has a palmar opening at the fingerpad that allows for direct contact between the user's fingerpad and objects to make use of the user's own tactile sensation [77]. The user's pinch gripping force is estimated by load cells mounted to lateral side walls at the end of the finger module. The assistance force is generated by a pneumatic cylinder and then transmitted to the finger through a link mechanism.

### 3.2.2 Mobility Assistance

The Tek Robotic Mobilization Device (Matia Robotics, Istanbul, Turkey) is a commercially available, four-wheeled mobile platform that supports disabled people in standing up and sitting down as well as moving around in a standing posture [78]. The standing-up motion is performed by the user him or herself, assisted by the force of a compressed gas spring so that he or she can accomplish the transition with little effort. The user can drive this device using a joystick in an upright position.

Nakajima developed a robotic wheelchair that is capable of negotiating rough terrain using its wheel mechanisms as legs, while traversing smooth terrain with its wheels [79]. The wheelchair is equipped with two axles whose steering and rolling motions can be independently controlled to mimic legged locomotion. At the end of each axle, there is a wheel driven by a DC motor. To negotiate a step or other rough terrain, the axle is controlled to lift one wheel off the ground and then move forward while using the grounded wheel as a pivot point.

There are several walking assistance robots commercially available today. Because they enable walking based on a preprogrammed gait pattern or they aid voluntary movements of leg joints, they can also be used for rehabilitation. ReWalk (ReWalk Robotics, Ltd., Yokneam Ilit, Israel) enables wheelchair users having lower-limb disabilities to sit, stand, walk, and climb/descend stairs [80]. The movements of hip and knee joints in the sagittal plane are assisted by DC motors, while the ankle joint is not powered. The ankle joint is a simple double-action orthotic joint having limited range of motion and spring-assisted dorsiflexion [81]. A tilt sensor located at the torso detects the motion of the upper body to recognize the user's intention and to initiate the preprogrammed gait movement [82]. Owing to the need for crutches to maintain balance and stability, ReWalk is suitable for users with unimpaired upper-limb functionalities.

Ekso (Ekso Bionics, Richmond, CA, USA) can operate in four ways. In the easiest mode, called First Step, a physical therapist usually manipulates buttons of a remote controller to control the steps. The motion of the user's legs is achieved through the actuation of the device's hip and knee joints powered by DC motors. While walking, the user maintains balance using instrumented crutches and by shifting their body weight [83]. At the next level, Active Step, the user controls the steps via buttons installed on crutches or a walker. The next level, Pro Step, uses the forward movement of the user's hip to initiate step motion. The next mode, New Pro Step Plus, recognizes the user's walking intention from the user's weight shift and the initiation of forward leg movement. Ekso has hip and knee joints that can be actuated in the sagittal plane while the other DOFs at these joints are locked out or passively supported by a spring [84]. Like ReWalk, Ekso requires the use of crutches to maintain stability.

REX (Rex Bionics Plc, Auckland, New Zealand) is a robotic mobility device that does not require crutches or a walking frame for stability, and the physical burden on the shoulder, arm, and hand is thus much lower than that for other devices necessitating crutches [85]. The user controls the device with a joystick, and the device thus does not use sensors to estimate the user's motion intention [82].

Indego (Parker Hannifin, Cleveland, OH, USA) is a commercialized version of the Vanderbilt powered lower limb orthosis that assists the motion of hip and knee joints in the sagittal plane [86], [87]. This device does not have a part that is worn under the shoes, and is intentionally designed to be used with a standard ankle–foot orthosis. Each joint is actuated by a DC motor, and the joint angle trajectories are preprogrammed for standing, sitting, and walking movements. The operation mode can be automatically selected according to the location of the estimated center of pressure, defined as the center of mass projection onto the horizontal ground plane [86].

## 4 Conclusions and Further Research Directions

In this chapter, we presented recent achievements and important works relating to healthcare robotics, the success of which relies on the collaboration between clinicians and engineers in front of real patients in operating/training rooms. In other words, the development of medical robotics is typical translational research relying on collaboration and intercommunication.

From a research perspective, the major types of medical robotics discussed can be categorized as physical human–robot interactions. Ishiguro *et al.* summarized challenges in physical human–robot interaction research, which apply also to biomedical robotics [32]. These challenges are the guarantee of safety at all times including during pre- and post-procedure, designing robot reactions that are appropriate for the intentions of the human interaction partner, and improving human–machine interfaces including those in cognitive and learning stages. One important improvement of current medical robots is the development of systems that provide a realistic level of force feedback (tactile feedback) in terms of the DOFs, magnitude, and safety. Robots that are currently commercially available provide a certain level of force feedback but their performance is far from that expected by the medical community. One challenge facing surgical robots is the manipulation of thin tissues and the suturing of small openings because the lack of force feedback makes these operations more difficult than their open-surgery counterparts.

From a clinical perspective, there remain points to consider before using robots in healthcare applications. Yang *et al.* summarized these barriers, which include the risk of malfunctioning/failure, setup procedures that are yet to be established, such as procedures of patient safety control, and insurance policy [33]. Finally, the further development of new technologies and effective robotic instruments will increase the acceptance of robotic assistance in healthcare to an even higher level. We are certain that healthcare professionals of the future will employ assistive robotics without anxiety or technical barriers. However, the degree of automation between medical practitioners and robotic systems in control of a healthcare procedure should be addressed thoughtfully.

In robot-aided therapy, the actual role of the robotic system remains to be clarified. Clinical studies show that early robotic training of the upper limb can improve ADL significantly more than chronic-phase training. The successful motor rehabilitation of stroke survivors requires early intensive and task-specific training, whereas the efficacy of the rehabilitation protocol for the chronic phase remains controversial. The most accepted result on robotic rehabilitation is that patient attention and effort are critical to the efficacy of the protocol. Neuroimaging techniques will be utilized to rehabilitation engineering field to suggest a guideline for efficient rehabilitation protocol and design method of such rehabilitation devices. Nowadays, a brain activation pattern for a specific therapy can be observed using brain imaging techniques. Among these techniques, functional magnetic resonance imaging is a powerful tool with which to monitor brain activations and to assess the therapy protocol. The monitoring of progress in real time requires actuating and sensing devices that are compatible with magnetic resonance imaging. A rehabilitation robotic system compatible with magnetic resonance imaging is expected to analyze the efficacies of robot-aided therapies.

Assistive robots have to perform appropriate actions according to the user's motion intention, and the intention recognition method is therefore a primary concern in the development of an assistive robot. Conventional manual control methods such as the use of a joystick and buttons are simple to apply and they do not require complicated algorithms for extracting the user's motion intention. However, when close physical coordination with the human body is required, especially in the case of wearable exoskeletons, manual control methods lack intuitiveness because the user's motion for manipulating the controller device does not directly match the resulting action of the assistive robot. Intention recognition methods based on human motion sensing or interaction force measurement at the human–robot interface are widely adopted methods for the control of exoskeleton-type devices. Such methods are intuitive and can thus capture the user's motion intention without the need for intensive learning about how to manipulate the controller devices. Nevertheless, external disturbances acting on the user's body or the robot may result in unwanted behaviors of the robot because the disturbances cannot be easily discriminated from motion intention. Although healthier users may cope with the disturbances through their own sensory feedback, such disturbances are more difficult for people with disabilities to overcome. A biosignal-based approach including the use of sEMG can be applied to estimate the muscle force without measuring the contact force or motion. However, the sEMG signal is very weak and extremely sensitive to skin conditions and electrode locations [88], and it is also susceptible to motion artifacts [89]. Furthermore, estimating forces for multiple DOFs simultaneously from an sEMG signal requires a large number of electrodes and a complex algorithm [90], making it difficult to use sEMG for practical applications.

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