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Robotics

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CHAPTER OUTLINE

Background

The word robot originates from the Czech word for 'forced labour', and was coined by the Czech playwright Karel Capek in the1920s to describe machines that resemble humans. It underwent a variety of definition permutations through the decades. As defined by the Robotics Institute of America, a robot is a reprogrammable, multifunctional, manipulator designed to move material, parts, tools or specialised devices through various programmed motions for the performance of a variety of tasks (Hillman, 2004; Kurfess, 2005). Michael Brady defined robotics as the field concerned with the connection of perception to action (Brady, 1985). Robotics is a multidisciplinary field, combining areas such as mechanics, electronics, computer science, cybernetics, artificial intelligence, physics and mathematics (Veruggio, 2006).

Rehabilitation robotics is the field that applies robotics to medical rehabilitation, to enable disabled people to function with maximum autonomy and support recovery

Handbook of Electronic Assistive Technology. https://doi.org/10.1016/B978-0-12-812487-1.00011-9

(Rocon and Pons, 2011). An assistive robot is an actuated mechanism programmable in two or more axes with a degree of autonomy, which performs useful tasks for disabled and/or elderly people to overcome social, infrastructural and other barriers to independence, full participation in society and carrying out activities safely and easily (Hersh and Johnson, 2008).

The need for robotic technology is on the rise due to the global trend of a growing ageing population, which directly results in the following (Zollo et al., 2013):

- A considerably larger number of elderly people in need of care, including social, home and healthcare services.
- A smaller number of available informal caregivers (e.g., family caregivers).
- A shrinking healthcare workforce to provide care to increasing patient numbers.
- An increasing need in both developing and developed countries for assistive technology and services.

In response to these needs, specialised technologies such as assistive robots are being developed that have the potential to empower people with disabilities to be more independent and become more involved in activities in their homes, schools and communities (Zollo et al., 2013).

A Brief History of Robotics

The main era of robotic research and development was the mid-20th century, primarily within an industrial environment where repetitive movements and lifting of heavy objects made the use of machines over humans attractive. Robots were mainly employed for tasks that were too dirty, distant or dangerous for humans (Krebs and Volpe, 2013).

Joseph F. Engelberger and George Devol developed the first industrially used robot, the Unimate, in 1961. This was a hydraulically driven, programmable, 2 tonne robotic arm, adopted for automated die-casting. Engelberger had an interest in service robotics particularly in medical applications, and in 1984 he formed HelpMate Robotics. The HelpMate was used to transport medical supplies around a hospital.

In the late 1960s, Scheinman from Stanford University innovated the first successfully computer-controlled electrically powered robot arm – the Stanford arm. The articulated arm had 6 degrees of freedom (DOFs) (Moran, 2007). Within the same decade, Stanford Research Institute developed the robot 'Shakey', equipped with a vision system and bump sensors. This was the first robot which used an artificial intelligence planner to gather images of its surrounding environment and apply this to map a route to a user-specified position. The robot was able to steer by differential control of its two drive motors and could navigate its way around halls, applying information it obtained from its route (Nilsson, 1984). Shakey could move at a speed of 2 metres per hour. The robot was known as Shakey because its mounted camera shook as the robot moved.

Concurrently, Stanford also began development of the Stanford Cart, which was a remotely controlled, TV-equipped mobile robot. By 1979, the robot was able to successfully cross a room filled with chairs without any interference (Moravec, 1983). Also in the 1970s, ASEA IRB 6 was launched, which was the first robot to be electronically driven and controlled by the Intel 8008, one of their earliest microprocessors (Thiessen, 1981).

Provision of feedback from robotic devices was the next major development. The Massachusetts Institute of Technology (MIT) 'Silver Arm' was developed in 1974 to assemble small parts with the use of feedback from touch and pressure sensors (Moran, 2007).

The first robot with embedded motors, the direct drive robotic arm, was developed by Takeo Kanade in 1981. The electric motors housed within the joints removed the need for chains or tendons used in earlier robots. This circumvented the need for long transmissions and instead employed direct drive arms that minimised backlash and friction, making them faster and more accurate (Asada et al., 1983).

Emergence of Assistive Robots

Active assistive robots for upper limb rehabilitation have been developed since the 1960s. The first computerised arm, the Case Research Arm (developed at the Case Institute of Technology), was a floor-mounted, 4 DOFs, externally powered robotic arm (Leblanc and Leifer, 1982). It carried a paralysed user's arm through a range of manipulation sequences when the user directed a head-mounted light beam at photoreceptors mounted on selected objects. This work was progressed at the Rancho Los Amigos Hospital in California, where in 1969 the Rancho Golden Arm was developed. This was a battery-powered orthotic device with the same design concept as the Case system but without computer control (Moe and Schwartz, 1972). It was used to help people with disabilities by supporting and moving their arm to augment function. The arm had six joints to give it the flexibility of a human arm, and was operated by using seven tongue switches in a sequential mode (Harwin et al., 1995).

In 1978, the US Department of Veterans Affairs (VA) Palo Alto Health Care System and the School of Engineering at Stanford University (SU) collaborated on a 15-year rehabilitation robotics programme. The programme started with the 'Robotic Aid Project', which aimed to apply industrial robotics technology combined with commercial and prototype user interface devices, to develop a system that could be used by people with quadriplegia (Rocon and Pons, 2011). The system implemented voice recognition technology to control the robot. This was followed by the Clinical Robotics Laboratory project (1985–89), which was established to develop and evaluate a new generation of desktop robots, to assist people in performing activities of daily living (ADL). The Mobile Vocational Assistant Robot (MoVAR) project began in 1983. The MoVAR used a mobile base and had the ability to manipulate objects using a robotic arm (a commercial PUMA-250 arm), go through interior doorways and display its surroundings via a mounted camera system. The system interfaced with patients using voice control, keyboard or head movements. The final noteworthy collaboration (1989–94) of VA/SU was the Desktop Vocational Assistant Robot, a desktop version of the MoVAR, which was mainly developed for use in a vocational environment (Van der Loos, 1995).

Application of Robotics in Rehabilitation

The field of rehabilitation robotics is diverse and over the last few decades, robots have been developed for assistive and rehabilitative functions. They can be broadly classified into the following three categories:

1. Robots for physical therapy and movement assistance.
2. Socially assistive robots.
3. Robots for supporting Activities of Daily Living (ADL).

Robots for Physical Therapy and Movement Assistance

A number of systems have been developed to provide limb movement therapy for people with neuromuscular disorders, particularly stroke. Physiotherapy works on the principle that repetitive exercise programmes in assistive external environments, enable the rewiring or strengthening of neuromuscular pathways to the brain. A major goal of rehabilitation following stroke is to promote recovery of lost motor control. Evidence suggests that providing early, intensive, task-specific therapy with multisensory stimulation leads to effective rehabilitation outcomes (Poli et al., 2013; Masiero et al., 2014). Several studies highlight the capacity for motor learning resulting from intensive, repetitive and task-oriented motor activities. However, conventional therapy is labour intensive and physically demanding. Therefore cost and labour limitations have meant that traditional therapies are not delivered more intensively or frequently (Norouzi-Gheidari et al., 2012). A role thus exists for integrating robotic devices into clinical practice, that can provide effective therapy for neurorehabilitation, while decreasing the burden on clinical staff and the costs of health care (Lum et al., 2005).

The use of robotic technology in physical therapy offers the following benefits (Huang and Krakauer, 2009):

- Robots have the potential to provide intensive, highly repetitive rehabilitation training protocols consistently and for longer durations, thereby reducing the risk of excessive fatigue for physiotherapists and enabling standardisation of rehabilitation protocols.
- They enable us to measure movement kinematics and dynamics, and thereby objectively evaluate progress or changes in impairment in response to treatment.
- They offer the possibility to provide complex, controlled multisensory stimuli to the user enabling the performance of various task-orientated activities.

It should be noted that the application of robotic technology in clinical practice is not intended to replace physiotherapists but to support and complement conventional physiotherapy (Babaiasl et al., 2015).

Robotic rehabilitation systems developed to date can be classified based on (Gopura and Kiguchi, 2009):

- The applied segment (upper limb, lower limb).
- The number of DOFs offered.

- The type of applied actuators.
- The power transmission methods (gear drive, cable drive, linkage mechanism, etc.).
- The function/application (assistive, rehabilitation, performance augmentation).
- Their mechanical characteristics (end-effector or exoskeleton).

Upper Limb Robotic Rehabilitation Systems

In terms of their mechanical structures, upper limb robotic systems can be broadly classified into two types: end-effector-based systems and exoskeleton-based systems (Lo and Xie, 2012).

Earlier systems that were developed were end-effector-based devices, which contact the user's limb at its most distal end. The joints of end-effector-based systems do not match that of the human limb. These systems have simple mechanical structures and can easily be adjusted to fit users with different limb lengths.

More recently, exoskeleton systems or devices mimicking the skeletal structure of the limb have been developed, where the joints and links of the robot directly correspond with human joints and limbs, and the robot axes align with the anatomical axis of the upper limb (Gopura et al., 2016). Exoskeleton systems provide more independent and precise control of the impaired limb.

Four main strategies have been employed when using robotic devices to support upper limb rehabilitation (Huang and Krakauer, 2009). These are:

1. Passive: The movement is initiated and imposed by the robot.
2. Active assisted: The user initiates the movement but the robot assists the movement along a predefined path.
3. Active resisted: The user initiates and moves against a resistance generated by the robot.
4. Bimanual exercise: Active movement of the unaffected arm is mirrored by simultaneous active/passive/assistive movement of the affected arm using the robotic device.

Many of the robotic systems developed incorporate multiple operating strategies in a single device.

Several reviews have been published exploring the effectiveness of robot-assisted therapy for upper limb rehabilitation following stroke (Veerbeek et al., 2017; Norouzi-Gheidari et al., 2012; Mehrholz et al., 2012). However, these studies have presented a mixed picture. Norouzi-Gheidari et al. concluded that robotic therapy does not provide any benefit over conventional therapy in terms of motor recovery, ADL, strength and motor control, but additional sessions of robotic therapy in addition to conventional therapy promoted better recovery of the hemiparetic elbow and shoulder (Norouzi-Gheidari et al., 2012). More recently, a review conducted by Veerbeek et al. through meta analysis of 38 trials found that robot assisted therapy in stroke rehabilitation for the upper limb led to small improvements in motor control and muscle strength of the paretic arm and a negative effect on muscle tone (Veerbeek et al., 2017). They did not find any effect of robot-assisted therapy for basic ADL. The literature comprises of findings from trials employing a range of robotic systems, training protocols and patient characteristics. This presents a challenge when assessing the outcomes robotic therapy. However, what is clear is the potential that such systems offer and the need for more high quality trials.

Some of the most prominent systems developed for upper limb rehabilitation are briefly described next.

MIT-MANUS

MIT began developing the MIT-MANUS in 1989 for the rehabilitation of the shoulder and elbow of stroke patients (Hogan et al., 1992). This was the first robot employed in clinical trials for delivering rehabilitation therapy. This end-effector-based system incorporated a 2 DOFs robot that used a direct-drive, five-bar linkage, selective compliant assembly robot arm configuration.

The commercial version of MIT-MANUS is called InMotion (Fig. 11-1), and is available through Bionik Laboratories.[1] The system employs video games to engage patients to carry out defined exercise routines. For patients who are able to initiate arm movement, the robot provides adjustable levels of assistance to facilitate the movement.

Additional modules for the system have been developed allowing 3 DOFs wrist motion (allowing abduction/adduction, flexion/extension and pronation/supination), vertical movements (via an antigravity module) and hand grasp (Lo et al., 2010). The device provides assistive or resistive forces as well as a passive mode (Krebs et al., 1999).

MIRROR IMAGE MOTION ENABLER

The Mirror Image Motion Enabler (MIME) is an end-effector-based system developed at Palo Alto Rehabilitation R&D Center. The system has 6 DOFs and performs both unilateral

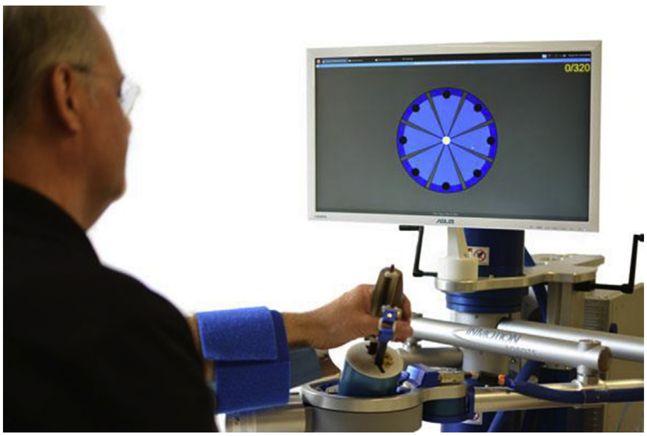

FIGURE 11-1 InMotion arm, Bionik Laboratories: http://bionikusa.com/healthcarereform/upper-extremity-rehabilitiation/inmotion2-arm/.

[1] https://www.bioniklabs.com/.

and bilateral upper limb (elbow and shoulder) training. It can be used in passive, active and bimanual modes (Ho et al., 2011). The system uses a Puma 560 robot arm to apply forces to the paretic limb and assist movement. It interfaces with the hand via a splint and a connector that breaks away if interaction forces become excessive (Lum et al., 2005).

GENTLE/S SYSTEM

The GENTLE/s project was funded by the European Commission to evaluate the effect of robot-aided therapy in stroke rehabilitation. The GENTLE/s system (Fig. 11-2)[2] is based on haptics and virtual reality visualisation techniques. It incorporates a commercial robot, the Haptic Master (FCS Robotics, Netherlands), which provides reaching movements in 3 active DOFs. The patient moves against a resisted haptic arm in a computer-generated virtual 3D room. The GENTLE/s includes three therapy modes: passive, active-assisted and active-resisted mode (Coote, 2008).

REHAROB THERAPEUTIC SYSTEM

REHAROB (Fig. 11-3)[3] was an EU-funded project under the 5th Framework Programme, looking at the development of a robotic rehabilitation system (REHAROB) to support upper limb (shoulder and elbow) physiotherapy of patients with spastic hemiparesis. The project used existing industrial robots equipped with extra safety systems to automate physiotherapy motions and mobilise patients' arms along arbitrary trajectories (Fazekas, 2009). REHAROB was an end-effector-based system, which used two industrial robots each to move the upper and lower arm. REHAROB differs from the MIT-MANUS

FIGURE 11-2 GENTLE/s.

[2] http://www.gentle.reading.ac.uk/.
[3] https://www.researchgate.net/figure/The-REHAROB-Therapeutic-System_fig1_6114872.

FIGURE 11-3 REHAROB therapeutic system (Fazekas et al., 2007).

and MIME systems, which focus on providing task-directed movements. This system focuses on executing exercises slowly with constant velocity, in high repetition numbers to decrease spasticity and increase range of motion of shoulder and elbow joints.

BI-MANU-TRACK (REHA-STIM, BERLIN, GERMANY)

The Bi-Manu-Track (Fig. 11-4)[4] is a commercially available 1 DOF end-effector-based system, which uses two motors to enable bimanual flexion and extension of the wrist joints. The system also allows patients to perform exercises to train forearm pronation and supination. The Bi-Manu-Track has three operational modes: passive, bilateral active-assisted and bilateral active-resisted mode. It has been applied for arm training for patients with stroke and Parkinson's disease (Picelli et al., 2014).

ARMin

The ARMin robot was designed for arm rehabilitation (Nef et al., 2006). It has 6 DOFs allowing shoulder actuation in 3D, flexion/extension of the elbow, lower arm pronation/supination and wrist flexion/extension. The upper arm of the user is connected to the robot by an end-effector-based structure and the lower arm is connected through an exoskeleton

[4] http://www.reha-stim.de/cms/index.php?id=60.

FIGURE 11-4 Bi-Manu-Track.

structure. It thus has a semi-exoskeletal structure. The ARMin incorporates three modes of operation: (1) passive mobilisation, (2) active game-supported arm therapy and (3) active training of ADL. An audio-visual display illustrates the movement task to the patient (Nef et al., 2006).

Lower Limb Robotic Rehabilitation Systems

Gait impairments following neurological disorders such as spinal cord injuries (SCIs) and stroke are often disabling and have a negative impact on quality of life. Therefore recovery of walking is a top priority and considered one of the primary objectives of the rehabilitation process.

Allowing wheelchair users to stand and ambulate can influence community mobility, social participation and profoundly combat secondary medical issues associated with lack of weight bearing such as osteoporosis, urinary tract infections and pressure sores (Karimi, 2011).

Gait training enables the user to practise walking movements repetitively and in a physically correct manner to induce improvements of motor cortex representations, recover and strengthen the muscle groups and improve coordination (Calabrò et al., 2016). Conventional gait training generally involves exercises on a treadmill with partial body weight support (BWS) and manual assistance of physiotherapists. The main limitation of this treatment is that it is labour intensive, and requires a lot of effort by physiotherapists in assisting the gait of patients, setting the paretic limb and controlling trunk movements (Werner et al., 2002). To overcome these issues, there has been an effort towards applying robotic devices for gait training.

Robot-assisted gait training has been explored for patients with traumatic brain injury, SCIs, stroke, cerebral palsy, multiple sclerosis and Parkinson's disease (Calabrò et al., 2016).

Robotic exoskeletons are wearable electromechanical devices that have been developed as augmentative devices to enhance the physical performance of the wearer or as orthotic devices for gait rehabilitation or locomotion assistance. These enable users with appropriate physical abilities to stand, walk, climb stairs and perform ADL (Miller et al., 2016). According to the Food and Drug Administration (FDA) a powered exoskeleton is 'a prescription device that is composed of an external, powered, motorized orthosis used for medical purposes that is placed over a person's paralyzed or weakened limbs for the purpose of providing ambulation' (Food and Drug Administration-HHS, 2015). Potential benefits of robotic exoskeletons include:

- Increasing user independence.
- Secondary benefits such as improved bowel/bladder function, decreased chronic pain, reduced spasticity and increased bone marrow density (Contreras-Vidal et al., 2016).
- The reduction of energy required by the user to move joints, i.e., knee, hip and ankle, as this load is taken by the exoskeleton itself.
- Providing repetitive, long and intense physiotherapy sessions, yet reducing both therapist burden and healthcare costs (Bruni et al., 2018).
- Providing measurements of several kinematic and dynamic parameters of patient limb movement and therefore performance-related indicators (e.g., range of motion, velocity, smoothness) to objectively quantify patient progress (Masiero et al., 2014).

The robotic rehabilitation systems for the lower limbs can be classified into:

- Fixed site/stationary and
- Mobile/overground walking systems.

At present the range of disabilities that this type of appliance benefits is limited and while used for rehabilitation, they are not yet at a stage where prosthetic limb exoskeletons are used throughout the day for typical daily ambulation.

FIXED/STATIONARY SYSTEMS

Fixed or stationary exoskeletons systems incorporate a fixed structure combined with a moving ground platform (such as a treadmill or footplates) and aim to automate traditional therapies (Calabrò et al., 2016). They may be treadmill-based or programmable foot end-effector devices. Treadmill-based systems use a robotic orthotic/exoskeleton connected to the patient's lower limbs together with a body weight system to offload a part of the weight of the patient during the stance phase of the gait, reducing the load needed to be overcome by the patient, and ensuring safety and stability during walking (Bruni et al., 2018). Foot end-effector systems use driven footplates for guiding the feet and simulating the phases of the gait.

Examples of fixed/ stationary systems include:

LOKOMAT (HOCOMA, VOLKETSWIL, SWITZERLAND) The Lokomat (Fig. 11-5)[5] is one of the more well-researched stationary robotic systems developed to support and automate treadmill training (Riener et al., 2010). It is a modular device consisting of a powered orthosis/exoskeleton, a suspension system to provide BWS and a treadmill (Mayr et al., 2007). The hip and knee joints are actuated by linear drives integrated into an exoskeletal structure. The system offers 2 DOFs in each leg, enabling hip and knee flexion and extension movements in the sagittal plane (Lunenburger et al., 2004). The patient is fixed to the orthosis with straps around the waist, thighs and shanks and the system can be adjusted to the individual's anthropometry. During training, the Lokomat moves the patient's legs through a preprogrammed gait pattern. An augmented feedback module provides feedback to the patient while walking, by projecting the results of the exercises on a display panel to enhance their motivation.

LOWER EXTREMITY POWERED EXOSKELETON The Lower Extremity Powered ExoSkeleton (LOPES) was developed at the University of Twente to assist stroke patients in walking rehabilitation and to evaluate motor skills (Veneman et al., 2007). The LOPES is a combination of an exoskeleton robot for the legs and an end-effector robot for the pelvis. It has a 2D pelvic control system and an exoskeleton leg with 4 actuated DOFs assisting in hip flexion/extension, adduction/abduction, knee flexion/extension and ankle flexion/extension (Low, 2011). It allows forward stepping motions while also maintaining the fundamental instability of standing/walking to allow 'patient-in-charge' or 'robot-in-charge' modes (Veneman et al., 2007).

THE GAITTRAINER (REHA STIM, BERLIN, GERMANY) The GaitTrainer (Fig. 11-6)[6] is a footplate-based end-effector-based device designed to improve a patient's ability to walk by repeated practice. In contrast to a treadmill, it consists of two footplates that are positioned on two bars, rockers and cranks to provide propulsion (Masiero et al., 2014). The patient is attached to a harness for BWS and the footplates move the feet along a fixed trajectory.

OVERGROUND WALKING SYSTEMS/MOBILE EXOSKELETONS

Lower extremity exoskeletons developed for human locomotion assistance are used to help patients who have completely lost mobility in the lower limbs due to conditions such as SCI, multiple sclerosis, etc. These systems offer external torque at the location of human joints to replace the patients' impaired motor function, enabling them to perform daily movements such as standing up, sitting down and walking (Chen et al., 2016).

They can function as assistive and rehabilitative devices. Most of these exoskeletons require the patients to balance themselves and therefore a healthy upper body is required. Compared to stationary systems such as the Lokomat and LOPES, powered robotic exoskeletons are compact, lightweight and portable and can therefore be potentially used at home.

[5] http://exoskeletonreport.com/product/lokomat/.
[6] http://www.reha-stim.de/cms/index.php?id=76.

FIGURE 11-5 Lokomat (Hocoma, Switzerland).

Some of the most widely used mobile exoskeleton technologies developed for users who have lower-limb mobility impairments are briefly described next. A summary of the main features of these mobile exoskeletons is given in Table 11-1. A more systematic review of powered exoskeletons for bipedal locomotion can be found in Contreras-Vidal et al. (2016).

REWALK (ARGO MEDICAL TECHNOLOGIES LTD, ISRAEL: HTTP://REWALK.COM/) ReWalk was the first FDA-approved exoskeleton in 2014 to be used as a personal device at home and in the community. It is approved for home use, when accompanied by a specially trained caregiver, for people with paraplegia due to SCIs at levels T7–L5, and for use in rehabilitation centres for patients with SCIs at the T4–T6 level.

It contains pairs of electric direct current (DC) motors at the knee and hip joints to enable the user to walk, stand, turn and navigate stairs, and safely manoeuvre sit-to-stand positions. The ankle joint is unactuated and allows passive spring-assisted dorsiflexion. The motors are powered by rechargeable batteries, and an on-board computer system is incorporated in a backpack worn by the user. Sensors located on the user's chest determine the angle of the torso and measure the shift in gravity and upper body movements to estimate the user's walking intention. The system is then driven by generating a prescribed hip and knee displacement (Low, 2011; Lajeunesse et al., 2016).

FIGURE 11-6 GaitTrainer.

Table 11-1 Summary of Main Features of Some Commercially Available Mobile Lower Body Assistive Exoskeletons

Device	Maximum Speed (m/s)	Weight (kg)	Battery Life (Continuous Walking)	User Height (m)	Maximum User Weight (kg)	References
ReWalk	~0.6	23.3	4 h	1.6–1.9	100	http://rewalk.com/faqs/
Rex	0.06	38	2 h	1.42–1.93	100	Gardner et al. (2017)
Indego	~0.6	12.3	4 h	1.55–1.91	113	FDA (2017) and Lajeunesse et al. (2016)
Ekso	0.89	20.41	4 h	1.58–1.88	100	Lajeunesse et al. (2016)
HAL		23	2 h 40 m	1.5–1.9	95	Nitschke et al. (2014)
Atlas	≤1	9	–	0.95–1.4	40	Sanz-Merodio et al. (2014) and Garcia et al. (2014)

ReWalk requires the wearer to use crutches to maintain balance. Some contraindications to using the ReWalk include:

- History of severe neurological injuries other than SCI (multiple sclerosis, cerebral palsy, motor neuron disease, traumatic brain injury, etc.).
- Severe concurrent medical diseases: infections, circulatory, heart or lung, pressure sores.
- Severe spasticity.
- Significant contractures.
- Psychiatric or cognitive situations that may interfere with proper operation of the device.

REX (REX BIONICS, NEW ZEALAND)[7] REX (Fig. 11-7)[8] is an exoskeleton with actuators at the knee, hip and ankle joints. It enables the user to walk and climb stairs. The device is suitable for manual wheelchair users who can self-transfer and operate hand controls. It is suitable for use with patients who have SCIs at levels up to C4/C5 and is also being explored in clinical trials for users with stroke and multiple sclerosis. REX is self-balancing and does not require any additional supportive aids or crutches for balance. The legs of the device cover the user's leg significantly more than other devices, thereby increasing the bulk of the device. The system is operated using joystick control with a user-friendly interface. There are two versions of REX – REX P (i.e., for personal use and customised to the individual's size) and an alternative REX, which is designed for use in rehabilitation clinics and is adjustable to fit different users. REX is CE marked in Europe as a Class 1 medical device under the European Medical Device Directive.

HYBRID ASSISTIVE LIMB[9] The Hybrid Assistive Limb (HAL) is a bilateral lower limb exoskeleton that has been developed for both performance augmentation and rehabilitation purposes. HAL has 3 DOFs for actuating the hip, knee and ankle joints. It is a hybrid system, which allows a voluntary and autonomous mode of operation to support gait training, depending on the treatment purpose and user's capabilities. Its 'cybernic voluntary strategy' is based on estimating the voluntary muscle activity from surface electromyography signals and adjusting joint torques depending on the measured muscle activity (Tsukahara et al., 2010). The second strategy, 'cybernic autonomous control', is based on the user's weight shifting and input from in-shoe force pressure sensors or ground contact forces with the exoskeleton (Bortole et al., 2015). This mode is used in the case of complete loss of voluntary activation of gait muscles.

The device is used with a cane for stability during walking. HAL for medical use is CE marked as a medical device.

[7] https://www.rexbionics.com/.
[8] https://www.rexbionics.com/rex-for-home-use/.
[9] Cyberdyne Inc., Tsukuba, Japan: http://cyberdyne.jp/english/.

FIGURE 11-7 REX robotic exoskeleton.

EKSO EXOSKELETON[10] Ekso is a wearable lower extremity robotic exoskeleton designed for the assistance and rehabilitation of patients with various levels of lower extremity weakness. The system has 3 DOFs in each leg with active hip and knee joints and passive ankle joints. Both legs are connected to a torso structure containing the computer and batteries.

The torso is aligned to the user's lower back, and the exoskeleton legs are fastened to the user's legs by hook-and-loop fastener straps that align the user's lower back and joints with those of the device. Two additional straps are tightened over the user's shoulders to help support the torso structure.

The device has powered (bilateral) hip and knee joints and passive (spring) ankle joint movements in the sagittal plane. Currently, Ekso has four walk modes enabling either user or therapist to actuate movements using a push button or gait intention detection by detecting forward and lateral movement of the user's hips (for weight shifting) or the user's weight shift and intention of forward leg movement.

[10] Ekso Bionics, Richmond, CA, USA: http://eksobionics.com/.

Ekso requires the use of crutches to ensure stability and safety of the user. The undersides of the crutches are fitted with force sensors to ensure firm placement on the ground and at least partial weight bearing. A step will therefore not be triggered unless both crutches are firmly on the ground (Contreras-Vidal et al., 2016). This exoskeleton also has a backpack that contains a battery and the control centre.

EksoGT is the first robotic exoskeleton to be granted FDA clearance for use with stroke patients. It is approved for:

- Individuals with hemiplegia due to stroke.
- Individuals with SCIs at levels T4–L5.
- Individuals with SCIs at levels T3–C7 (ASIA impairment scale D).
- It is CE marked.

INDEGO[11] Indego (also known as the Vanderbilt exoskeleton) is a powered lower limb exoskeleton designed to enable people with SCIs to walk and for use as a therapy tool. Indego consists of a hip segment, a right and left thigh segment and a right and left shank segment. The device is strapped to the user around the waist and actuated at the hip and knee joints bilaterally.

Each thigh segment is designed with two brushless DC motors, which are used to actuate the hip and knee joints. The system is designed to be used with a standard ankle foot orthosis to support the ankle and prevent foot drop in the swing phase of gait (Lajeunesse et al., 2016). It does not have any exposed cables, can be operated wirelessly using a mobile phone app and does not require a backpack.

The Indego incorporates a modular design enabling patients themselves to quickly assemble and disassemble the device. Its total weight is 12 kg, which is relatively light compared to other exoskeletons. The lean nature of the device means the user can wear it while also using a wheelchair. The Indego allows walking, sitting and standing movements but is not intended for sports or stair climbing.

For use as a rehabilitative tool, Indego comes with a software application, which displays gait parameters (such as stride length and pace) to aid gait training.

Indego has received FDA clearance to perform ambulatory functions for:

- Individuals with SCIs at levels T3–L5 with supervision of a specially trained companion.
- Individuals with SCIs at levels C7–L5 to perform ambulatory functions in rehabilitation institutions.
- People with hemiplegia as a result of stroke to perform ambulatory functions in rehabilitation institutions.
- The Indego is CE marked.

[11] Parker-Hannifin, Ohio, USA: http://indego.com/indego/en/home.

ATLAS EXOSKELETON[12] The ATLAS (Fig. 11-8) is a wearable exoskeleton designed to provide walking capabilities for children affected by paraplegia, tetraplegia, muscular atrophy and myopathies.[13,14] It offers a 6 DOFs mechanism, with 3 DOFs per leg, allowing hip, knee and ankle flexion and extension in the sagittal plane. The structure is attached to the user's body through comfortable belts. The system requires the use of a supporting frame for postural balance that is attached to the device. Thus there is no need for the user to apply their upper limbs and trunk to control balance during walking. The ATLAS exoskeleton is adjustable for children between the heights of 95 and 140 cm and is able to support a child weighing up to 40 kg (Garcia et al., 2014).

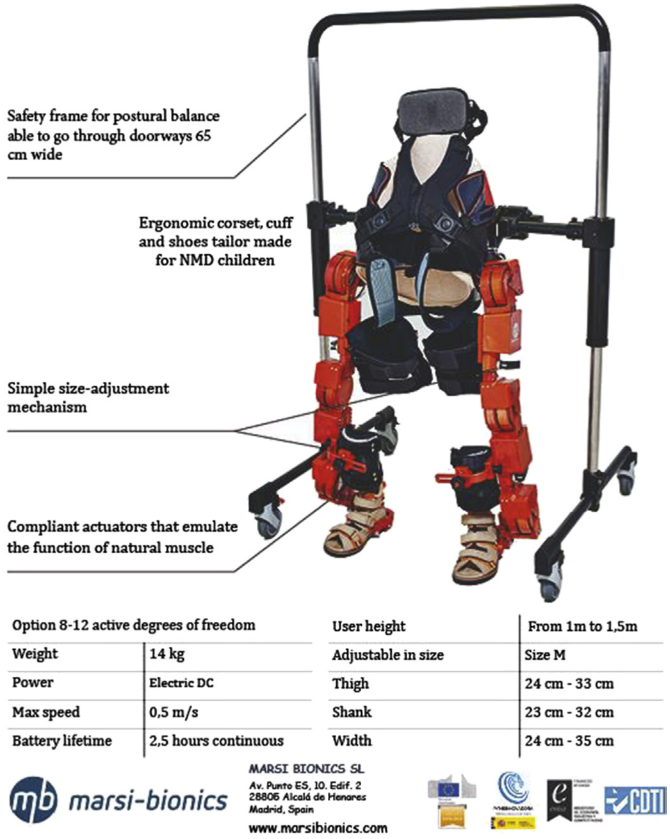

FIGURE 11-8 ATLAS 2030 pediatric wearable gait exoskeleton. *NMD*, neuromuscular disease. *Courtesy of Marsi Bionics.*

[12] Marsi Bionics, Spain: http://www.marsibionics.com/.
[13] http://www.marsibionics.com.
[14] http://www.marsibionics.com/portfolio/atlas-2020/.

HEI EXOSKELETON[15] Researchers at the HEI-YNCREA School of Advanced Engineering Studies have produced a noncommercial rehabilitation exoskeleton specifically focused on children with multiple disabilities. The HEI exoskeleton was started as part of the 'Motion' project in 2013 (Wang et al., 2018). The exoskeleton is motorised, presents with 6 DOFs and uses steel wires to animate its junctions (Figs. 11-9 and 11-10).

In its first phase, the project aimed to achieve a slow-walking model for children with intermittently straight knees, similar to humans, to avoid sudden, jerky movements, and to minimise stress on the joints. Psychomotor therapy management in children with multiple disabilities is more difficult than for adults. Coupled with an inability to communicate or express the feeling of pain or discomfort, children prove unsuitable subjects in the development of robotic orthotic devices. Because of these safety concerns, Wang et al. made use of the NAO humanoid robot (Fig. 11-11) as an intermediate platform to simulate the straight-knee walking mode in a simulated environment for building and testing the control system of the exoskeleton (Wang et al., 2016).

A neural network-based proportional–integral–derivative control system was also explored by Zhang et al. for the HEI exoskeleton, with improved results in a simulated environment over a traditional proportional–derivative controller (Zhang et al., 2015, 2018).

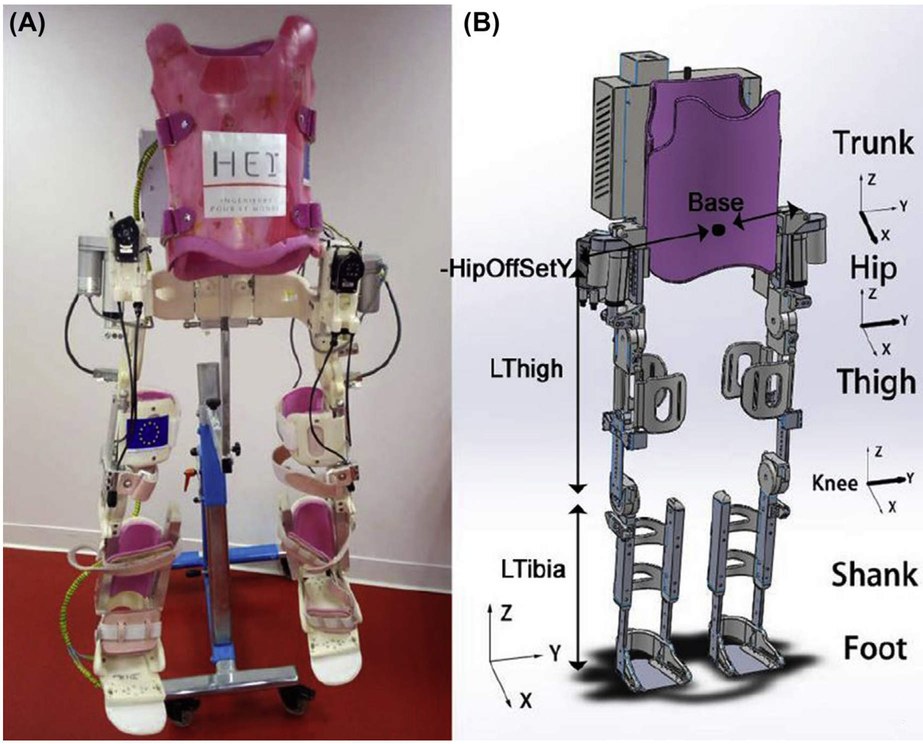

FIGURE 11-9 (A) HEI (Wang et al., 2018) exoskeleton. (B) Joints and structure of exoskeleton.

[15] HEI Lille – School of Advanced Engineering Studies, France: http://www.hei.fr/.

Their research hopes to control the stability of the exoskeleton in the real world while walking with a human operator.

Socially Assistive Robots

Socially assistive robots (SARs), also known as contactless assistive robots, help users through social interaction rather than physical interaction (Zollo et al., 2013). SARs have been developed to provide companionship, improve mental health, reduce stress and may be used to monitor the safety of the vulnerable population (Mordoch et al., 2013). Thus they establish therapeutic efficacy through physiological, psychological and behavioural measures of the user (Chang et al., 2014).

There are several categories of SARs, though most technologies overlap between these (Zollo et al., 2013):

- Companion robots – such as robotic pets, which are used with the intention of reducing solitude and stress.
- Contactless motivating robotic therapists – robots that encourage and assist the user through social interaction, but with no physical intervention.
- Assistive robots used for patients with cognitive disabilities – robots that teach the user social skills and assist to transfer these skills to human interactions.

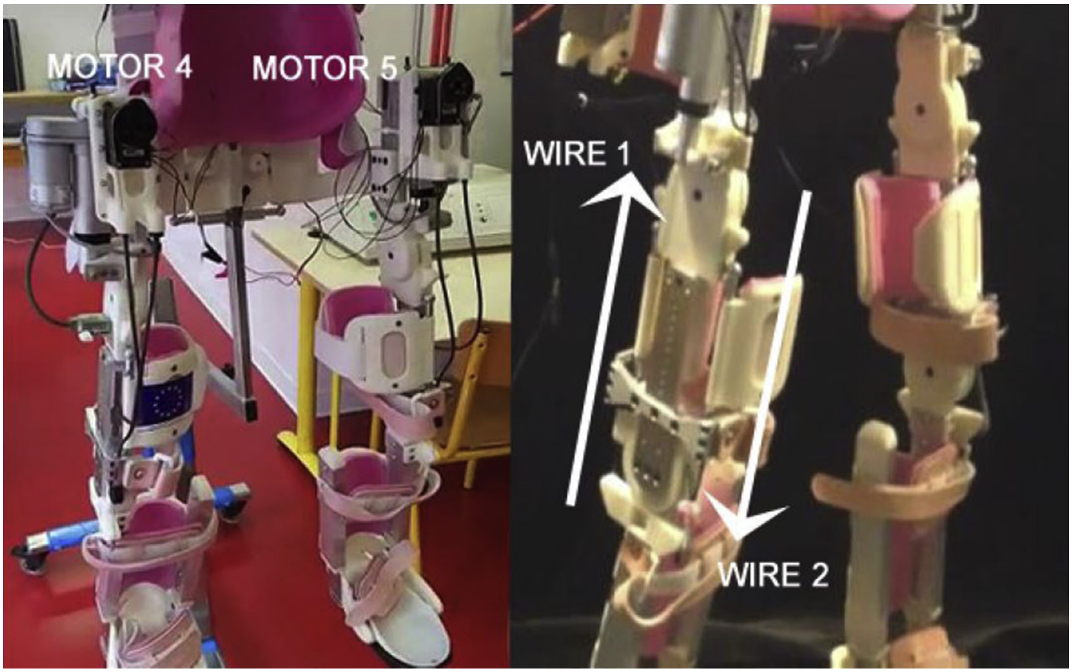

FIGURE 11-10 HEI (Wang et al., 2018) exoskeleton motors (*left*). Knee movement mechanism (*right*).

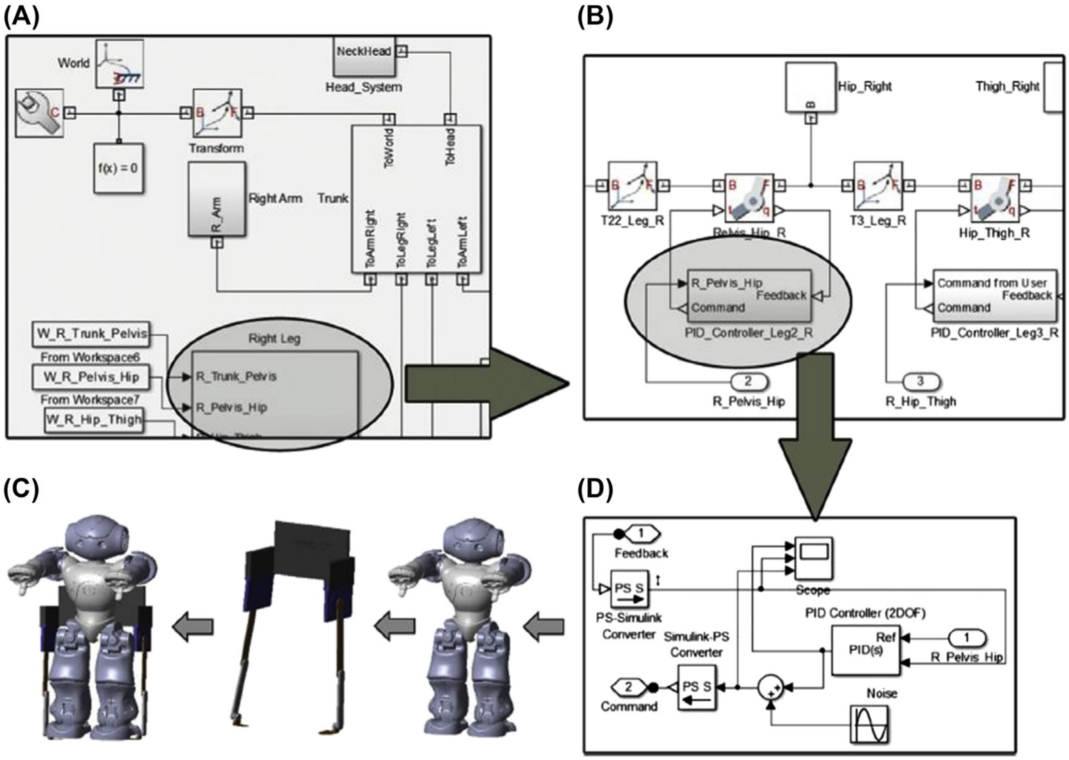

FIGURE 11-11 Controllers application of SimMechanics-Simulink on NAO (Wang et al., 2016). (A) full geometric model of NAO in Simmechanics; (B) sub-system model of right leg; (C) simulation of NAO and its exoskeleton in Simulink-Simmechanics; (D) PID controller of hip-pelvis joint of the right leg.

SARs have been used in mental healthcare applications, primarily children with autism spectrum disorder and older adults with dementia. They have been used as therapy aids for children dealing with grief and loss, as social mediators for children with autism and as companions in nursing homes and elementary schools (Feil-Seifer and Matari, 2005).

SARs can be designed to have animal-like, machine-like and human-like forms. Many animal and related animal-inspired designs have been used in SAR applications, including dogs, cats, seals and dinosaurs (Rabbitt et al., 2015). In the United States animal-assisted therapy and animal-assisted activities have become widely recognised. Both of these are considered to have three main positive effects: psychological, physiological and social (Bemelmans et al., 2012). However, this type of therapy has its drawbacks, e.g., possible physical risks such as allergy, infection and injury, as well as cost and accessibility. These potential restrictions may be addressed by robots with the physical appearance of animals and the ability to respond to human interaction. Such robots, have been shown to effectively reduce depression and stress (Kachouie et al., 2014).

Although SARs enhance the human–human interaction, and have been seen to have an increased interaction with caregivers, it is important to note that currently technologies

Table 11-2 Socially Assistive Robots

Robot	Company/Project	References
AIBO	Sony	Kaplan (2000)
Care-O-Bot	Fraunhofer IPA	Schaeffer and May (1999)
CompanionAble	The European FP7 Project CompanionAble (2008–12)	Gross et al. (2011)
Huggable	Massachusetts Institute of Technology	Santos (2012)
iCAT	EU FP7 ICT-215554 project LIREC German Research Foundation (DFG) within the SFB 673 – Alignment in Communication – Project C2	van Breemen et al. (2005)
MeBot	The Digital Life and Things That Think Consortia	Adalgeirsson and Breazeal (2010)
NAO	Aldebaran-Robotics	Gouaillier et al. (2009)
Nexi	National Science Foundation Research Grants BCS 08-27084	Fink (2012)
NurseBot	Information Technology Research ITR Program (Grant No. 0085796)	Pollack (2002)
Paro	Intelligent System Co., Ltd	Kidd et al. (2006)
QRIO	Socially Intelligent Machines Lab (designed by Carla Diana and Meka Robotics)	Geppert (2004)
RIBA	Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science	Mukai et al. (2010)
USC Robot	National Science Foundation under Grants IIS-0713697, CNS-0709296 and IIS-1117279	Fasola and Mataric (2010)

available are not able to replace human care. It is paramount that both SARs and human interaction work hand in hand. If the component of human caregiver interaction is no longer in place, there is a concern over the user's increased isolation, despite therapeutic benefits (Feil-Seifer and Mataric, 2011).

Some of the more popular SARs in research papers are listed in Table 11-2.

The Huggable Robot (Santos, 2012) is the creation of the Personal Robots Group, MIT. This robot was designed to look like a teddy bear, as a symbol of comfort for paediatric users. The Huggable has two modes of function: (1) being a fully autonomous robot the Huggable is able to interpret and respond to human interactions with it, and (2) the Huggable is able to work as a semi-autonomous robot avatar, which can be controlled on some level.

PARO was created by Takanori Shibata from the Intelligent System Research Institute in Japan (Kidd et al., 2006). It is modelled after a baby harp seal and is programmed to respond to touch using simple sound and movement. PARO is mostly used as a companion robot. Several studies have been conducted particularly on its use with people with dementia. In one study, where PARO was left in the public space of a nursing home, residents saw an increase in social activity through interaction with PARO.

To date studies using these SAR devices are generally small scale, i.e., a limited number of participants. However, this is a growing field of research interest.

Robots for Supporting Activities of Daily Living (ADL)

Robots have been developed for providing support with performing daily tasks such as feeding, grooming and lifting by, for instance, power assistance or tremor suppression. An example of this is the Handy 1 robot (Rehab Robotics, UK), which was initially developed in 1987 to assist a child with cerebral palsy to eat. The system can be operated with a single switch. Extensions for the system were later designed to allow it to be used in other applications such as face hygiene and cosmetics (Topping, 2002). Other commercially available feeding support systems include MySpoon (Secom, Tokyo, Japan), NeaterEater (Buxton, UK) shown in Fig. 11-12 and Obi.[16–18]

The iARM (Exact Dynamics, Netherlands) is a portable robot arm for object manipulation that can be mounted on a wheelchair (Fig. 11-13)[19]. It weighs 9 kg and can be powered by the user's wheelchair battery. The system can be controlled by different access methods such as a keypad, joystick or single switch.

These types of devices appear to have made limited inroads into the homes of people with disabilities perhaps because of cost, technical or aesthetic reasons (Maciejasz et al., 2014).

Design Considerations for Robotic Exoskeletons

The following are important features to consider when designing robotic exoskeletons:

Safety: Safety is an important design consideration for exoskeletons. These systems encapsulate the user who may have pathologies resulting in impaired motor control and/or muscle weakness. Safety aspects should be considered in all stages of design, and

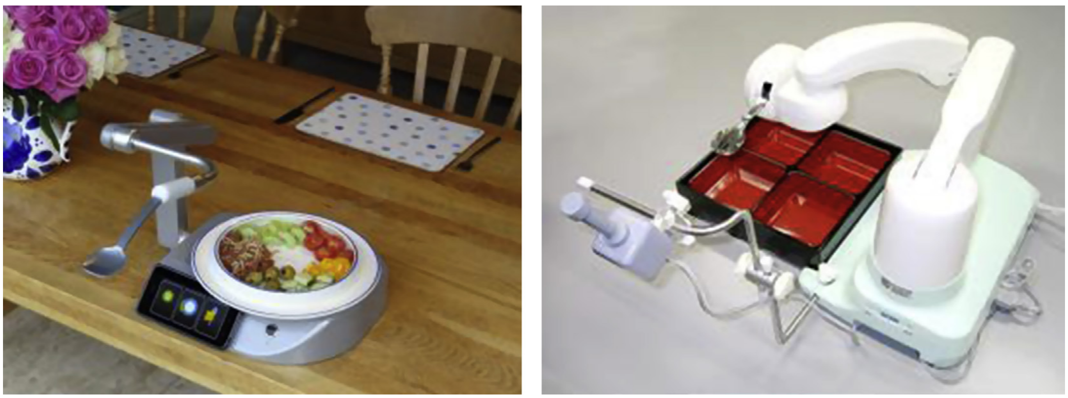

FIGURE 11-12 (*Left*) NeaterEater robotic feeding device. (*Right*) MySpoon robotic feeding device.

[16] https://meetobi.com/.
[17] http://www.neater.co.uk/neater-eater-2-2/.
[18] https://www.secom.co.jp/english/myspoon/.
[19] http://www.exactdynamics.nl/site/?page=pictures&id=3.

FIGURE 11-13 iARM used for making a phone call.

measures should be incorporated at the software (control), hardware and operator levels (Beyl et al., 2009; Roderick and Carignan, 2005).

Roderick and Carignan (2005) suggest the following potential hazards in the use of exoskeletons (Roderick and Carignan, 2005):

- Moving the patient beyond the safe limit of their range of motion.
- Moving the patient at an excessive velocity – sudden movement from the device may provide muscle strain leading to further injuries.
- Applying an excessive torque to the patient or having the patient apply an excessive torque against the robot.

Parameters, such as operational velocities and interactive pressure, should be measured in real time, and safety constraints and control strategies should be in place to ensure the user's stability and safety in an emergency (Huo et al., 2016).

A common approach to ensure safety is to incorporate multiple safety features (Van der Loos and Reinkensmeyer, 2008). Exoskeletons are designed with passive safety features, such as having no sharp edges, mechanical end stops to prevent joints from exceeding the anatomical range of motion of the human limb, and emergency switches to turn off the robot (Saba et al., 2013; Nef et al., 2006). The mechanical stops should be able to withstand the maximum torque that the actuators can apply. Additional sensors can be included to detect the malfunctioning of other sensors and implement a safe protocol. Overall, the system should be fail safe, meaning it should be able to achieve a safe state in the presence of a detected fault. When a fault is detected, the exoskeleton should either stop motion and hold the current position, or remove power to the motors (Roderick and Carignan, 2005; Baniqued et al., 2015).

Safety features that can also be incorporated in the software include current and speed monitoring, collision detection, routines to interrupt the power supply to the motors, software checks to limit forces, motions and speeds and user adjustments to control parameters, as well as checks for sensor health and other dangerous situations (Nef et al., 2006; Van der Loos and Reinkensmeyer, 2008).

It should also be possible for the robot to be moved manually by a therapist to release the patient from a potentially uncomfortable or dangerous position (Nef et al., 2006). This can be achieved by using backdrivable hardware (Babaiasl et al., 2015). Achieving both high-force production capability and backdrivability is an engineering challenge in rehabilitation robots.

Biomechanical function: Exoskeletons are wearable devices that operate mechanically on the human body, with possible interference and friction with limb natural movement (Bruni et al., 2018). Therefore an understanding of the biomechanics of the joints and the biomechanics of human walking is essential in the design of exoskeletons for the lower limbs (Dollar and Herr, 2008; Low, 2011). Although robotic joints are generally designed to mimic human joint kinematics in terms of structure, range of motion and DOFs, the complex nature of human joints means that robotic joints tend to be simplified. This can lead to low kinematic compatibility between the human and robotic joint causing unwanted interaction forces between the human and exoskeleton. However, increasing the complexity of the joint may lead to increased costs and reduce the reliability of the system.

Similarly, a high number of DOFs allow a wider variety of movements, with many anatomical joint axes involved (Nef et al., 2006). However, trade-offs exist between the numbers of DOFs to provide the range of requirement movements and the size, weight and cost of the device. The human leg can be approximated into a structure with a total of seven DOFs: three rotational DOFs at the hip, three at the ankle and one at the knee (Calabrò et al., 2016). The upper limb effectively has a total of nine DOFs, excluding the finger joints. Ideally, the exoskeleton should be kinematically compatible with the human joint while still providing satisfactory functionality (Low, 2011).

The hip, knee and ankle are weight-bearing joints, which rely on sufficient muscle force for stability. Mobile medical exoskeletons should therefore provide sufficient external joint moment to compensate the lack of forces in these joints and also provide BWS to minimise the weight loaded on these joints (Low, 2011).

The user should not feel the weight of the robot. The robot must be capable of generating sufficient force to move a patient's limb, and they should be able to move the device easily.

Autonomy/shared control: A shared control system must have the ability to determine the user's intention, verify that the desired action to be performed is safe, and when appropriate be able to adjust the control signal to manoeuvre the device safely and efficiently (Carlson and Demiris, 2012). In essence, this is a division of labour between the user and the robot. However, the user has power to determine the level of robotic aid they would require. The system should be able to goal orientate itself in accordance with the user's intention, and be able to modify these goals in parallel with those of the user.

The degree of autonomy of the robot is an important consideration in the design process so as not to reduce the user's independence or dignity, but rather assist and support, thus giving the user the higest possible level of control over the robot. A study exploring the effects of different levels of autonomy on the user found that the higher the autonomy of the robot, the less satisfied the user was with the system (Kim et al., 2012).

Adaptability: It is important that the robotic exoskeleton can be adapted to fit people with differences in gender, size, limb segment lengths, joint range of motion, etc. Therefore consideration of human anthropomorphic data is key. Exoskeletons usually incorporate adjustable frames to account for the different anatomical profiles of users (Baniqued et al., 2015).

Motivation: Evidence suggests that therapy with an emphasis on ADL increases patient motivation and results in improved therapeutic outcomes compared with single joint movements (Nef et al., 2006; Langhammer and Stanghelle, 2000; Chan et al., 2006). Motivational factors also contribute to a patient's active participation during therapy. An effective way of increasing motivation is to use games as part of the exercises during therapy. Virtual games are an engaging way to provide feedback to the patient in the form of visual, haptic, acoustic media.

Flexibility and usability: Though users may have particular disabilities, their requirements may vary based on their abilities and preferences. Usability is a highly important variable within the design of robotic devices. The device should be customisable and user friendly. This includes the ease with which the system is set up and the time it takes. The interface with which the user interacts must be as simple as possible while also being intuitive (Babaiasl et al., 2015).

Costs: Currently, the costs of robotic devices are quite high and cater to only a small population of users who are able to afford such devices, unless government funded or subsidised. High device costs are especially apparent when users have more complex or specialised requirements which are not met by more generic devices (Garcia et al., 2013). Some possible cost-cutting strategies while designing assistive robots are:

- Hardware design using readily available components on the market.
- Trade precision for robustness.
- Reduce complexity of the mechanical design of the system, i.e., add on more functionality to sensors and software design (Meng and Lee, 2006).

Aesthetics and portability: Portability of the device is a major factor that limits the application of robotic exoskeletons outside of clinical therapy (Dollar and Herr, 2008). Increasing the aesthetic value of a rehabilitation device makes patients more relaxed and willing to use the device (Baniqued et al., 2015).

The physical interface to the user: The design of the physical interface to the user is important as this affects the transfer of mechanical power from the robotic exoskeleton to the user. Exoskeletons are generally attached to a user using padding and straps. The interface should be comfortable and provide good support to the user to prevent injuries. It should be customisable to an individual's own contours and anatomical needs (Chen et al., 2016). The contact method, contact intensity and contact areas on the body should be considered in the design. The interface should also ideally tap into the user's residual capabilities.

Control strategies: The strategies that have been employed for controlling robotic exoskeletons are conventional control, intuitive control and biosignal integration control. Typically, exoskeletons are controlled using conventional systems such as joysticks, buttons, steering wheels and touchscreens. To develop the exoskeleton to function with more accuracy to user intent, intuitive control becomes important – this is where the user is able to control the device with use of motion, gesture, eye movement and force.

Actuation mechanisms: Ideally, the robotic exoskeleton should generate natural movements of the limb with the wearer not subjected to any vibration, jerk or sudden motion change. The choice of actuator has a significant effect on the performance of robots in terms of the generated output force/torque, efficiency and portability (Huo et al., 2016). For the active joints of lower limb exoskeletons, actuators with a small volume, a high power-to-weight ratio, high efficiency and compliance are needed (Chen et al., 2016). Current actuator mechanisms used in robotic exoskeletons are:

1. Electric motors – these are the most widely used due to their relatively high power output; they are easy to power through portable rechargeable batteries and can be controlled by analog or digital input signals from a control circuitry system (Maciejasz et al., 2014).
2. Pneumatic actuators – these are powered by compressed air. They are lighter than electric actuators and have lower inherent impedance but are harder to control due to their nonlinear nature. Since they require pressurised air, the overall size of the system is increased by the size of the compressor. Pneumatic actuators are suitable in applications where the system remains stationary (Weightman et al., 2014).
3. Hydraulic actuators – these are powered by hydraulic pressure. They have a high torque output and are very sensitive and responsive (Maciejasz et al., 2014). However, their weight, predisposition to fluid leakages and larger size makes them less favourable choices for robotic rehabilitating applications (Gopura et al., 2011). Due to their high power output-to-weight ratio, hydraulic and pneumatic actuators are generally suitable for exoskeletons for human performance augmentation (Huo et al., 2016).
4. Pneumatic muscle actuators (PMAs) – these actuators are commonly used and consist of a rubber inner tube surrounded by a braided mesh shell with flexible, but nonextensible, threads. When the inner tube is pressurised it expands in a balloon-like manner but the expansion is constrained by the braided shell (Tsagarakis and Caldwell, 2003). As the volume of the inner tube increases with the increase in pressure, the pneumatic muscle shortens and/or produces tension if it is coupled to a mechanical load. Due to such physical configuration, PMAs have generally lower weight compared to other actuators, but also have slow and nonlinear dynamic

response. In addition, PMAs can only generate a tension force through contraction; therefore at least two actuators are often used for each DOF to provide antagonistic movements like natural skeletal muscles (Huo et al., 2016). The pneumatic muscles are compliant and well known for their exceptionally high power and force-to-weight/volume ratios, which make them attractive for use in rehabilitation robots (Yeh et al., 2010).

5. Series elastic actuators (SEAs) – SEAs place an elastic component between the power source and the output shaft. By measuring the deflection of the elastic component, the output force is then measured based on Hooke's law. It decreases the inertia and intrinsic impedance of the actuator, allowing a more accurate and stable force control in unconstrained environments and thereby increases patient safety (Maciejasz et al., 2014; Huo et al., 2016).

Roboethics

Robot ethics or roboethics is an area of study which aims to understand the ethical implications and consequences of robotic technology (Scheutz, 2013). The basis of roboethics are the laws of robotics, written by the author and scientist Isaac Asimov. In his publication (Asimov, 1950), he defined the 'laws of robotics' as:

- First Law: A robot may not harm a human being or, through inaction, allow a human being to come to harm.
- Second Law: A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.
- Third Law: A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.
- Fourth Law (Law Zero): No robot may harm humanity or, through inaction, allow humanity to come to harm.

Though at the time the 'laws' were conceived these technologies seemed far-fetched, the current status of robotic technology is closer to what Asimov had envisaged. Murphy and Woods (2009) suggest that Asimov's laws are based on functional morality, which assumes that robots have (or will have) sufficient agency and cognition to make moral decisions (Murphy and Woods, 2009). Morality can be defined as the ability to distinguish between what is right and what is wrong. Asimov's laws assume that robots behave as if they were people. However, it is humans who design and use the robots who must be subject to any law and the ultimate responsibility for ensuring robots behave well must always lie with human beings (Boden et al., 2017).

In the field of assistive technology, the area of roboethics is particularly important to address for the safeguarding of patients. There have been ongoing debates surrounding the topic of the ethical implications of the anthropomorphism of robots (Alsegier, 2016). The application of robotics is still in its early stages and hence understanding the consequences it has to society is also developing.

For a machine to be classified as intelligent it needs to draw from human concepts such as autonomy, consciousness, learning, free will and decision-making. Autonomy is defined as the ability required for carrying on successful activities (Amigoni and Schiaffonati, 2005). Robotics is steadfastly heading toward the replication of an intelligent and autonomous being. It is argued that the more autonomy a robot or machine is allowed, there is an increasing need for it to abide by a set of principles that are compatible with a socially aligned moral code.

New technology must meet certain requirements to be accepted. This includes legal, social and global considerations. The concern is that there is no centralised system to establish responsibility for ensuring these requirements are in place. According to Alsegier (2016), when a robot incurs a technical problem causing harm to the individual using it, various questions arise: Who becomes the responsible party in this event? Who is responsible for the ethical implications? Is it a possibility that the robot itself is held responsible? Is the engineer who developed the robot responsible? Is the company or the government who allowed the use of the robot the responsible party?

Other concerns also exist when considering robots in human environments:

- Robots replacing humans could bring an increase in human unemployment, and thereby possibly increase socioeconomic problems.
- Psychological problems may be caused due to problems with attachment to other humans, and further in the future when robots are posited to anthropomorphise, possible confusion between what is real and what is robotic.

The need for a centralised protocol is required. Alsegier suggests a set of solutions for the future (Alsegier, 2016):

1. The creation of limitations and laws which would be applied to the development and control of robots. A part of this would be making the content of robotic research available to the public, and scientists would take it as their responsibility to inform and educate the public on the uses of any new robots, and clearly state what the short-term and long-term effects of use would be.
2. Any humanoid robots (including SARs) would have to pass a series of tests and would be evaluated by 'neutral' scientists who would be able to assess any technical issues the user may face when using the robot. Due to the human-like nature of these devices, it was suggested that sociologists should be involved to understand the effects on people's behaviour and be part of the review process for new products, ensuring there are no damaging effects to society.
3. The final stage of testing comes under the jurisdiction of the government. It would be their responsibility to clearly state the legal liabilities involved in the development of new robotics.
4. A universal set of rules in the production of intelligent robots would include ethical responsibilities and safety considerations.

Future of Robotics

There have been a large number of assistive robots developed over several decades, but only a minority of these is commercially available, with the majority still in the research and development phase. It is evident that assistive robotics is an area which is rapidly progressing, but is still in need of considerable development.

To date, the financial advantage of applying robotic systems for rehabilitation purposes has not been demonstrated. In addition to this, factors such as lack of clinical evidence, limited functionality, safety concerns, equipment size and usability issues have most likely inhibited them from being adopted in clinical settings or in homes (Van der Loos and Reinkensmeyer, 2008; Babaiasl et al., 2015).

Progress needs to be specially made in making widespread availability of low-cost robotic devices.

Zollo et al. (2013) outlined four main challenges in the development and widespread use of assistive robotic technology:

1. Developing standardised research tools and objectively measured outcomes to evaluate robotic systems from the user's standpoint.
2. Conducting more user trials for the device in 'natural' environments to assess device safety, reliability, efficacy and acceptability.
3. Improving the synergy between clinicians and technology to enable the technology to be adopted in clinical settings. This would have the potential to allow users increased independence and reduce the burden on caregivers.
4. Promote communication with the industry to share robotic developments and allow their integration in commercial systems.

Ideal future robotic assistive technologies would concurrently overcome these challenges and fulfil the ethical requirements as suggested by Alsegier (2016).

In the area of robotic exoskeletons for gait, areas where further research would benefit include walking performance characterisation, reduction in the metabolic energy expenditure of the user while wearing the device, alternative access to devices and development of efficient and lightweight power supplies, actuators and transmission mechanisms (Weightman et al., 2014; Chen et al., 2016; Dollar and Herr, 2008). For mobility purposes, most robotic exoskeletons for gait assistance use batteries as a power source. Limited by current battery technology, the weight of the battery pack of an exoskeleton system is usually heavy. The energy efficiency of exoskeletons needs to be improved to prolong operation time.

The price of assistive robots is a challenging issue. Existing systems are beyond the financial reach of most people with mobility disorders. Research efforts should focus on developing systems that are affordable. With improvements in robotics and mechatronics technologies, the price of high-performance actuators and sensors could potentially decrease, making the exoskeleton systems more affordable.

Increased evidence of their efficacy in the rehabilitation of users with specific clinical conditions would ensure these devices target the appropriate client groups.

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