CHAPTER 10

Rehabilitation Robotics

Muammer CORUM

Necmettin Erbakan University, Türkiye

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Introduction

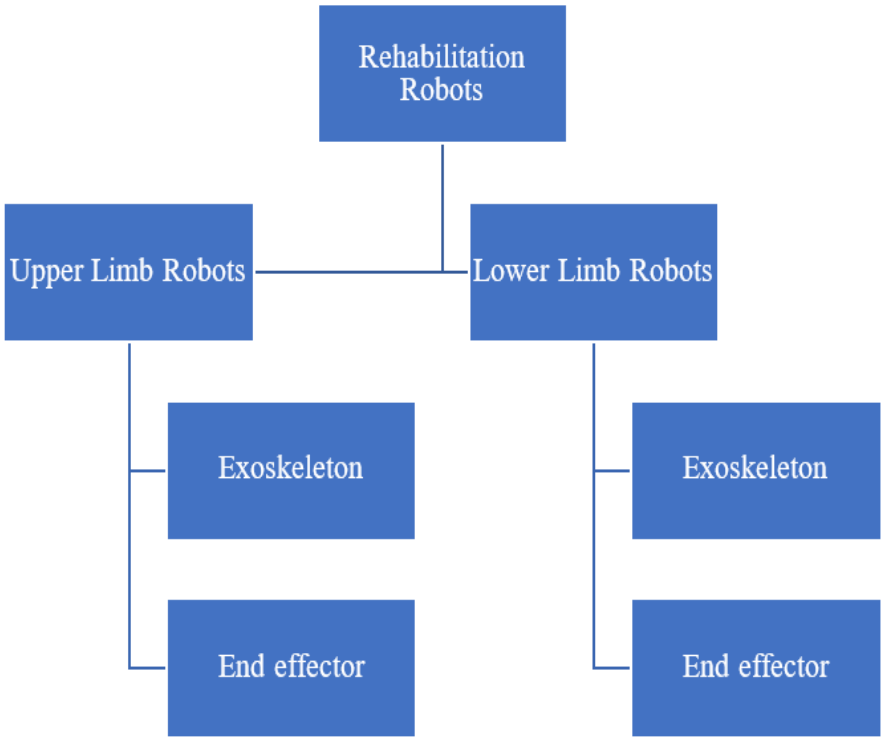
Mechatronics engineering is an engineering field that combines electrical-electronic, computer and mechanical engineering and is increasingly used in health applications. Thanks to the fields of mechatronics and biomechatronics engineering, the development of robotic devices, especially in the field of health and rehabilitation, is increasing the interest in this field (Demirbas, 2019). The ability of robotic devices to work intensively, repetitively and task-specifically has made them increasingly popular in neurorehabilitation, especially in the last two decades (Iosa et al., 2016). The main goal of neurorehabilitation is to develop a smooth movement pattern by providing muscle strength, coordination and sensory input, while facilitating neuroplasticity by reorganizing the representational areas of the cortex. Neuroplasticity, on the other hand, provides motor control and learning, making the movement permanent (Kilinc et al., 2019). Based on these principles, neurorehabilitation practices are used in the treatment of many neurological diseases such as stroke, spinal cord injury, brain trauma, Parkinson's, multiple sclerosis, and cerebral palsy (Calabrò et al., 2016).

The inadequacy in mobility that occurs in various forms and severities in neurological diseases is tried to be eliminated by applying motor learning principles in current rehabilitation methods. The most important factor in providing motor learning in rehabilitation is the repetitive performance of activities. In the development of the ability to fulfill the task, these repetitive activities should be applied variably with frequent repetition. In other words, motor learning can be realized if the activities and movements are repeated with different combinations and patterns (R. A. Schmidt & Lee, 2011). A rehabilitation program involving rehabilitation robots can provide a much higher number of activity repetitions compared to traditional neurorehabilitation applications.

Another benefit of robots in rehabilitation applications is that they provide continuous feedback to the patient and therapist. Robotic rehabilitation systems, especially integrated with virtual reality technology, provide visual and auditory feedback during the activity, providing information about the smoothness and coordination of the movement. In this way, the patient and therapist can monitor their performance instantly and continuously (Scheidt et al., 2005). In short, rehabilitation robots are technological devices that affect motor functions, can be adjusted at different speeds, provide continuous feedback by providing control in situations where the patient is inadequate, and provide personalized recovery (Conditt et al., 1997).

Today, the robots used in the field of rehabilitation are divided into two upper-extremity and lower-extremity robots specific to the body part, which is divided into two exoskeleton and end effector according to the way they work (Figure 1).

Figure 1.
Classification of Rehabilitation Robots



History of Rehabilitation Robots

In the field of rehabilitation, the robot called "Case Manipulator" was first used in the 1960s. The robot with four degrees of freedom was used to move the arm. Later, in Mexico, a seven-degree-of-freedom robot called "Rancho Los Amigos" was produced, which is the ancestor of today's exoskeleton robots (Hillman, 2004). In the 1970s, Roesler from Germany and Seamone and Schmeisser from the USA developed devices for robotic rehabilitation in 1974. In addition, robotic technologies continued to develop with the Spartacus and Master projects of France and the Manus project of the Netherlands. In 1978, Leifer and Van der Loos from Stanford University developed the first occupational assistant robot in their DeVAR project. In the mid-1980s, programmable, force-controlled, but single-axis devices such as BioDex began to be used in upper extremity rehabilitation. The first multi-axis project was designed by Khalili and Zomlefer. Later, robots began to use advanced force-based control, which required considerable computer power. However, in the early 1990s, the MIT-MANUS project by Hogan and Krebs and the Palo Alto VA MIME project at the University of California Berkeley by Lum et al. (Siciliano & Khatib, 2016).

In the 1980s, research and development in the field of rehabilitation robotics were led by the United States, the United Kingdom and Canada. After 1990, with the differentiation of rehabilitation robots into different types and extensive developments, research in this field has spread to industrial regions such as the USA, UK, Canada, Europe and Scandinavia-Japan (Li et al., 2017).

Features of Rehabilitation Robots

Today, robotic devices used in the field of rehabilitation can be considered assistive and controller devices that enable the user to move. They can operate in different modes as active, active assisted, passive, resistive, trajectory determining and corrective according

to the needs of the patient during movement. It is designed in such a way that it can provide support or even resistance in cases where the patient can perform the movement or any stage of the movement, or it can help the patient in cases where the patient cannot perform the movement. Robotic rehabilitation devices have a working mechanism called degree of freedom according to the movement and joint level they support. The degree of freedom refers to the planes and axes in which the robot moves (Kilinc et al., 2019). For example, if the robot can only perform abduction-adduction movement to the hip joint, it has one degree of freedom, while if it can perform flexion-extension to the knee joint and dorsiflexion-plantar flexion to the ankle joint, it has three degrees of freedom. As the degree of freedom of the robotic device increases, its mobility and competence increases.

Robotic devices can also be integrated with virtual reality applications to provide visual and auditory feedback to the user and provide information about the smoothness of the movement. In this way, a rehabilitation program can be carried out according to motor learning principles with plenty of repetitive and purposeful activities (Kilinc et al., 2019).

Upper Extremity Rehabilitation Robots

Exoskeleton-type rehabilitation robots act directly on specific joints of the user (Figure 2). They can be adjusted for users of different sizes. They are more difficult to design because they are fixed to the limb from different areas. Exoskeletons designed for the upper limb are difficult to move because they are attached to different parts of the limb. This causes the patient to perform compensatory activities while moving (Lum et al., 1999, 2004, 2006). Exoskeletons can resist or assist the movement of limb segments. Each joint can move independently of the other joints. In this way, isolated or combined joint movements can be performed within anatomical and physiological movement limits. One of the most important benefits of exoskeleton robots is that they integrate daily life activities with virtual reality and video games to practice repetitive and intensive, purpose-oriented activities (Kilinc et al., 2019).

Upper limb end effector robots are utilized using a manipulandum, which is grasped by hand. The manipulandum is connected to a robotic arm that senses motion through motion sensors while providing force to the user when needed. Since the forces and measurements take place on a single interface, they can be easily adjusted for different users without major changes to the system (Colombo et al., 2005; Mehrholz & Pohl, 2012). Sensory and motor training using a robotic device is realized through video games controlled by the movement of the manipulandum. The user tries to perform tasks such as drawing shapes or moving along a plane by moving an icon on the screen with the manipulandum (Fasoli et al., 2003; Ferraro et al., 2003). In addition, in some robotic devices, the movements of the manipulandum are converted into kinematic data through sensors, allowing the user's motor functions to be evaluated (Krebs et al., 1998).

Upper Extremity Exoskeleton Robots

MIT Manus

The MIT Manus was designed by the Massachusetts Institute of Technology (MIT) in the early 1990s to improve arm function in stroke patients (Figure 2). The robot can assist or resist movement while enabling reaching movements in the horizontal plane. The device has two degrees of freedom allowing shoulder and elbow joint movements. It can be integrated with video games (Hidler et al., 2005).

Figure 2.
a. MIT Manus, b. MIME (Hidler et al., 2005)



Mirror-Image Motion Enabler (MIME)

MIME is a six-degree-of-freedom rehabilitation robot for the shoulder and elbow joint, produced in collaboration with the Veteran Administration Medical Center in Palo Alto and Stanford University (Figure 2). It is the first device that can operate bilateral upper extremities, as well as allowing the movements performed with the intact upper extremity to be mimicked with the affected side (Burgar et al., 2000; Lum et al., 2006).

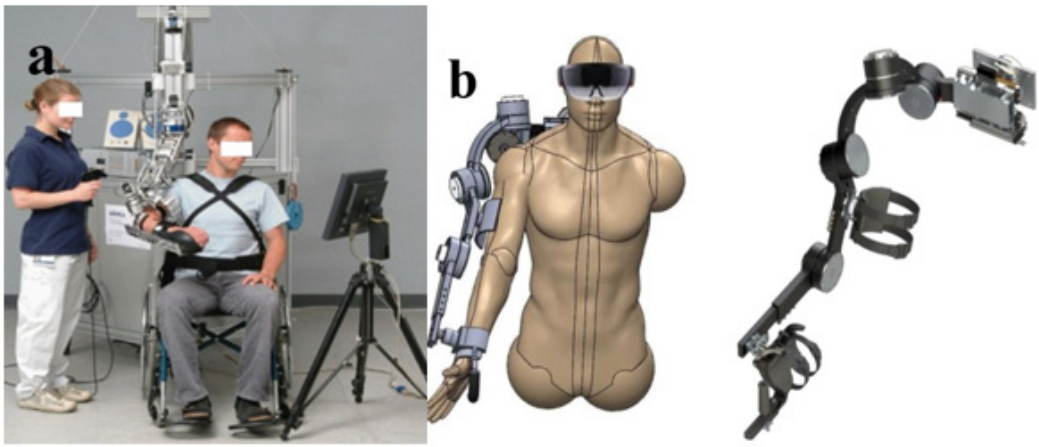
ARMin

ARMin is a rehabilitation robot with six degrees of freedom that allows movement in three planes: flexion, abduction and rotation of the shoulder, elbow, forearm and wrist (Figure 3). The device, which provides control in movements against gravity, enables to perform purposeful tasks that can provide video game integration (Nef et al., 2006).

CLEVERarm

The CLEVERarm rehabilitation robot has six degrees of freedom in the shoulder and elbow joints and two degrees of freedom in the wrist joint, which can passively perform flexion and extension and ulnar and radial deviation movements (Figure 3). It is a compact and lightweight device thanks to its carbon fiber material design. The device also supports virtual reality and augmented reality applications (Zeiaee et al., 2022).

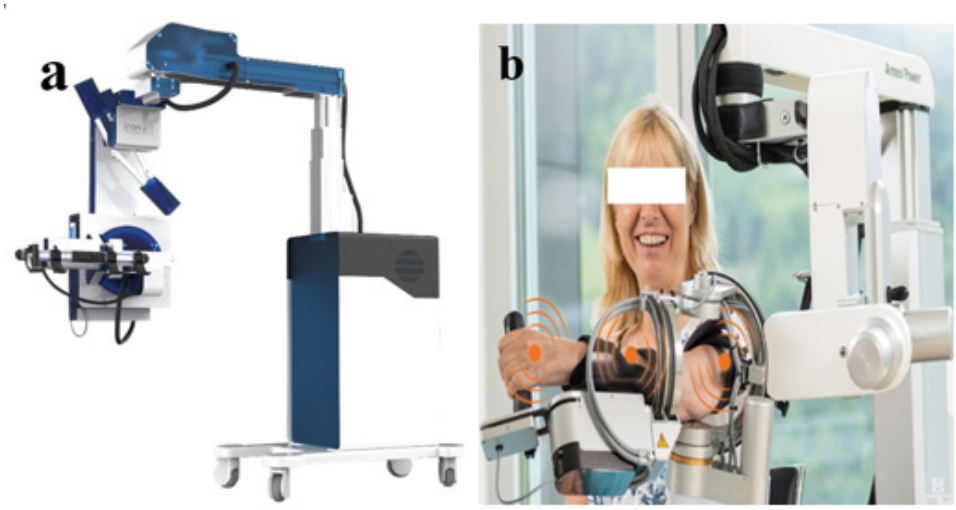
Figure 3.
a.ARMin (Nef et al., 2006), b. CLEVERarm (Soltani-Zarrin et al., 2017)



Asist On

Asist-On was developed by Patoglu et al. at Sabancı University in Turkey between 2006 and 2014 (Figure 4). In addition to supporting all upper extremity joints and performing all movement patterns, it also supports scapulohumeral rhythm. The device has seven degrees of freedom as it supports all upper extremity movement patterns. Made of lightweight material, the device is designed as a new-generation upper extremity rehabilitation robot with easy-to-wear features (Ergin & Patoglu, 2012).

Figure 4.
a.Asist On ('AssistOn-Arm', n.d.), b. Armeo Power ('Armeo®Power', n.d.)



Armeo Power

It is a rehabilitation robot device with six degrees of freedom by the Hocoma company. It can work as active, resistive or passive according to the patient's needs (Figure 4). The robot, which can be integrated with virtual reality technology and has additional materials for grasping functions, is one of the most advanced robotic devices. There are also different upper extremity robotic rehabilitation devices called Armeo Spring and Armeo Senso designed by Hocoma company (Grimm et al., 2021).

Upper Limb End Effector Robots

Arm Guide

The Arm Guide can allow four and six degrees of freedom controlling the shoulder, elbow and wrist (Figure 5). The device, manufactured at the Chicago Rehabilitation Center, is effective on tonus and muscle spasticity while controlling movements against gravity (Reinkensmeyer et al., 1999, 2000).

Figure 5.
a.Arm Guide (Hidler et al., 2005), b. InMotion Arm ('InMotion® ARM', n.d.)



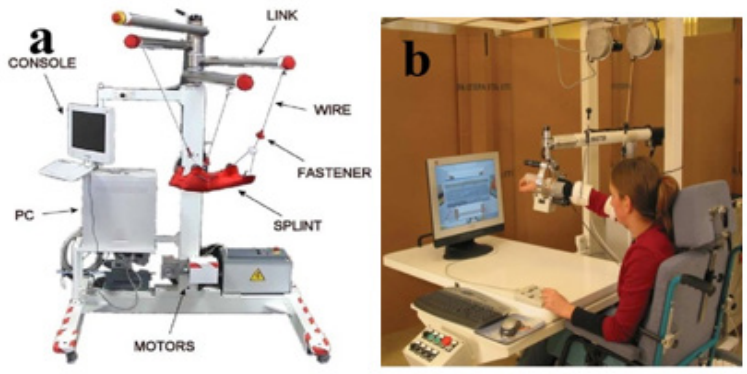
InMotion Arm

The InMotion Arm rehabilitation robot allows for practicing elbow and shoulder joint movements (Figure 5). The device, which is easy to wear and use, improves joint movement, coordination, strength and speed in activities. It can work together with virtual reality technology (Duret et al., 2019).

NeReBoT

NeReBoT is used as a rehabilitation robot with three degrees of freedom, allowing movement in the frontal and sagittal planes in the shoulder joint, while supporting rotation movement in the forearm (Figure 6). The device contributes to the patient's activity control and motivation with visual and auditory feedback during movements (Rosati et al., 2005).

Figure 6.
a.NeReBoT (Rosati et al., 2005), b. GENTLE/S Haptic Master (Harwin et al., 2006)



GENTLE/S Haptic Master

The GENTLE/S rehabilitation robot has three degrees of freedom, allowing movements in the shoulder, elbow and wrist joints (Figure 6). It is reported to improve upper extremity function in both chronic and acute neurological rehabilitation patients. It consists of a table, chair and computer and device-specific equipment (Hawkins et al., 2002).

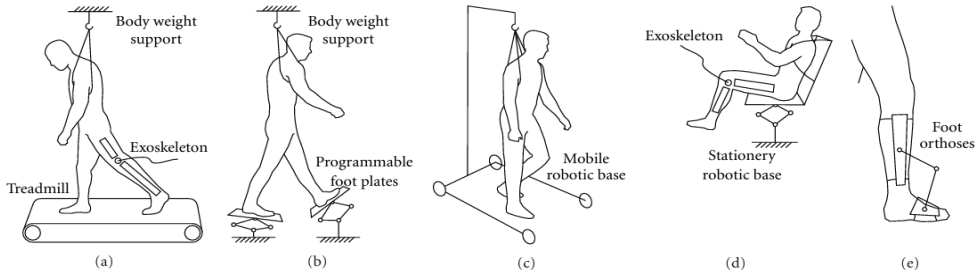
Lower Extremity Rehabilitation Robots

Exoskeletons used for lower extremities can have different degrees of freedom ranging from two to eight. They are mainly used for gait training, balance training and clinical evaluation. There are also body weight support systems in the devices used for lower extremities (Roy et al., 2007, 2013).

End effector robots used for lower extremity rehabilitation have force and torque sensors and are mostly used for walking and stair-climbing training (Low, 2015). In addition, data enabling the evaluation of gait performance can be obtained. It allows the physiotherapist to provide gait training safely and with minimum effort against the risk of falling, especially in neurological and geriatric individuals (Hesse et al., 2012; H. Schmidt et al., 2005).

Systems used in lower extremity robotic rehabilitation;
a) Treadmill-assisted rehabilitation device,
b) Programmable foot plane-assisted rehabilitation device,
c) Moving surface rehabilitation device,
d) Fixed surface walking device,
e) Foot orthoses,
are grouped as (Figure 7).

Figure 7.
Robotic system types for lower-limb rehabilitation: (a) treadmill gait trainers, (b) foot-plate-based gait trainers, (c) overground gait trainers, (d) stationary gait and ankle trainers, and (e) active foot orthoses. (Díaz et al., 2011)



Lower Extremity Ambulatory Robots

Ambulator robots are one of the technologies that can provide the patient with the opportunity to walk on a mobile floor by carrying body weight with a harness mechanism. They are robotic rehabilitation devices developed as an alternative to static walking training (Iyigun, 2018).

The KineAssist (Kinea Design LLC, USA) device has a movable floor and provides partial body support. The torso and pelvis mechanisms allow the patient's torso to move in all directions, with the ability to slow and stop the patient. In this way, the patient feels safe during walking.

WalkTrainer (Swortec SA, Switzerland) has six degrees of freedom. It has a robotic structure that controls the patient's pelvic movements. By design, the device prevents movement of the hip in the abduction direction.

The Hybrid Assistive Limb - HAL (Cyberdyne Inc, Japan) robot is available in different versions (full body, double leg and single leg). Since it has an exoskeleton structure driven by electric motors, it cannot provide adequate support for the trunk and pelvis. Therefore, it is not suitable for use in patients with severe impairment (Cao et al., 2014; Díaz et al., 2011; Iyigun, 2018; Pennycott et al., 2012).

Figure 8.

a. KineAssist (del-Ama et al., 2012), b. WalkTrainer ('KineAssist - Enabling Advanced Recovery', n.d.), c. Hybrid Assistive Limb – HAL (The World First Neurologically Controlled Wearable Cyborg - HAL Lower Limb, n.d.)



Lower Extremity Exoskeleton Robots

Lokomat

Lokomat is a robotic rehabilitation device developed by the Swiss company Hocoma (Figure 9). It consists of a walking belt, partial body weight support, and a robotic walking orthosis. The gait orthosis works in synchronization with the speed of the gait belt. The gait orthosis is controlled by motors connected to a computer that directs the movements of both hips and knees in the sagittal plane during walking. There are two types, LokomatPro and LokomatNano. The device can work by giving auditory and visual feedback with virtual reality integration (Kose, 2021).

AutoAmbulator

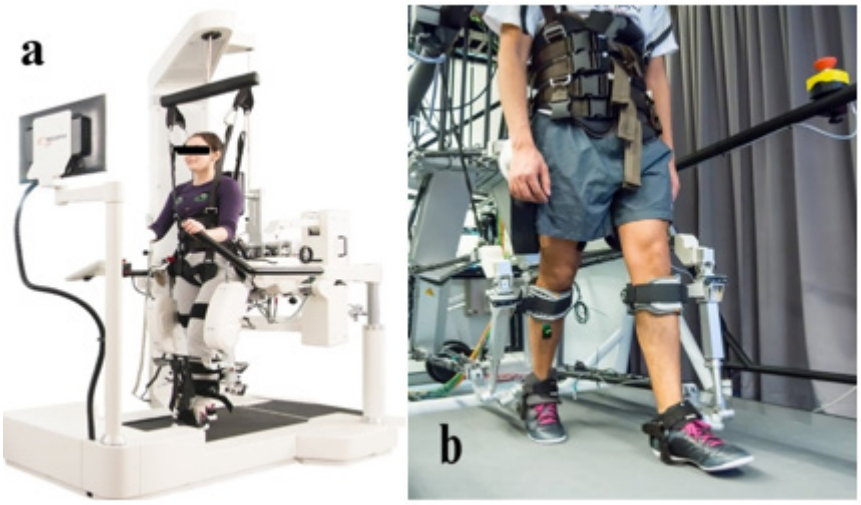
The treadmill consists of partial body weight support, and robotic arms. Robotic arms placed on the patient's lower extremity guide the gait pattern. This system, like the Lokomat system, allows movement in a single plane (sagittal) and the patient has little

influence on the gait trajectory (Cao et al., 2014).

Lower extremity powered exoskeleton (LOPES)

This rehabilitation robot, which is not yet commercially available, includes a gait belt and a robotic walking orthosis (Figure 9). This system allows translational movements of the pelvis and hip in both sagittal and frontal planes (Iyigun, 2018; Pennycott et al., 2012).

Figure 9.
a.Lokomat (*Lokomat® - Hocoma*, n.d.), *b. Lower extremity-powered exoskeleton (LOPES) (Zhao et al., 2019)*



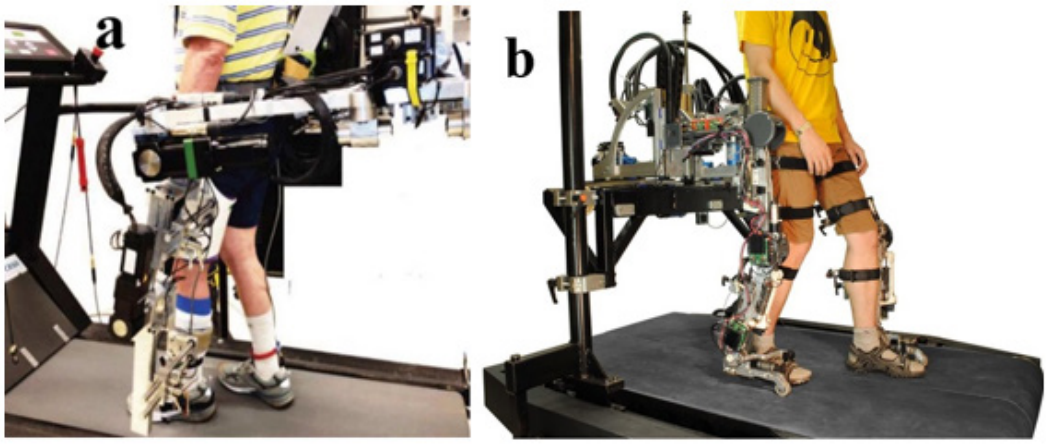
Active Leg exoskeleton (ALEX)

The ALEX, which is currently not in commercial use, includes a four-degree-of-freedom gait belt and robotic walking orthosis in the body (Figure 10). It allows movements in the sagittal and frontal planes of the hip, knee and ankle, but only actively controls sagittal plane movements (Díaz et al., 2011; Pennycott et al., 2012).

Actuated compliant robotic orthosis (ALTACRO)

The ALTACRO robotic rehabilitation device, which is currently not in commercial use, consists of a gait belt and a robotic walking orthosis (Figure 10). The device uses pneumatic artificial muscles to provide linear motion control, but only provides active assistance for knee movements (Cao et al., 2014; Iyigun, 2018).

Figure 10.
a.Active Leg exoskeleton (ALEX) (Srivastava et al., 2015), b. Actuated compliant robotic orthosis (ALTACRO) (Grosu et al., 2017)



Lower Extremity End Effector Robots

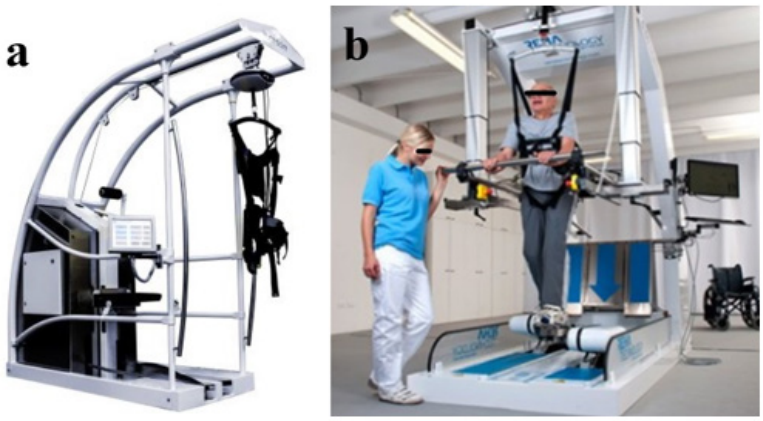
Gait Trainer (GT)

The device provides partial weight transfer during rehabilitation. Movement is provided by the individual capacity and speed of the patient (Figure 11). While the patient's balance is provided with the help of the harness system, walking is simulated with the help of foot connection plates. Gait trainer GT I produced by Reha - stim company was improved and Gait trainer GT II model was developed (Kose, 2021; Peurala et al., 2009; Surdilovic & Bernhardt, 2004).

G-EO Systems

The G-EO robotic rehabilitation device transfers movement from the sole to the patient. This device is used in combination with a harness mechanism that supports body weight (Figure 11). The gait system consists of a foot plane and a computer interface that can be programmed separately and independently for both feet. The hips and torso move freely according to the motion transmitted from the sole. The device also provides a different rehabilitation opportunity with a stair climbing program (Iyigun, 2018; Kose, 2021).

Figure 11.
a.Gait Trainer (GT) (Kose, 2021), GE-O System (GEO System, n.d.)



LokoHelp

The LokoHelp rehabilitation device includes a walking belt, partial body weight support, and foot pedals (Figure 12). The lower limb orthotic system is not moved by an external part but by the gait belt. With this system, the feet follow a specific trajectory, but no part guides the pelvis (Díaz et al., 2011; Iyigun, 2018).

Haptic Walker

The Haptic Walker robotic rehabilitation device provides partial body weight support (Figure 12). Programmable foot pedals accompany the movement. This system allows the simulation of walking on a slow and smooth trajectory (on flat ground and up and down stairs) as well as walking that requires a higher level of dynamics (on rough and slippery surfaces) (Díaz et al., 2011; Iyigun, 2018; Pennycott et al., 2012).

RoboGait

RoboGait, a device developed and manufactured by Bama technology company in Turkey, is a commercially available device (Figure 12). Structurally, it has the same features as other sliding floor-assisted robotic devices. Unlike its counterparts, there is no obligation to use separate units for adult and pediatric. Thanks to its adjustable structure, the same unit can be used in both adult and pediatric patients (Kose, 2021).

Figure 12.
a.LokoHelp (Díaz et al., 2011), b. Haptic Walker (H. Schmidt et al., 2007), c. RoboGait (Kose, 2021)



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About The Author

Muammer Corum works as a lecturer at Necmettin Erbakan University Seydisehir Vocational School of Health Services. In 2017, he graduated from Karabuk University School of Health, Department of Physiotherapy and Rehabilitation with the title of physiotherapist and completed his master's degree at Pamukkale University in 2019. He is still continuing his PhD education in the same field. His areas of interest are neurological and cardiopulmonary rehabilitation.
E-mail: muammercorum@gmail.com ORCID: 0000-0002-4619-3210

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