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29 Technology of the Robotic Gait Orthosis Lokomat

Laura Marchal-Crespo and Robert Riener

Abstract

Rehabilitation robots allow for longer and more intensive locomotor training than that achieved by conventional therapies. Robot-assisted gait training also offers the possibility to provide objective haptic, visual, and auditory feedback to the patients and/or therapists within one training session and to monitor functional improvements over time. This chapter provides an overview of the technical approach for one of the most widely used systems known as "Lokomat" including features such as hip abduction/adduction actuation, cooperative control strategies, assessment tools, and augmented feedback. These special technical functions may be capable of further enhancing training quality, training intensity, and patient participation.

Keywords

Exoskeleton · Actuated gait orthosis · Gait rehabilitation · Cooperative control · Augmented feedback · Lokomat

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29.1 Introduction

A major limitation of manual-assisted, body weight-supported treadmill therapy (BWSTT) is that a training session relies upon the ability and availability of physical therapists to appropriately assist the patient's leg movement through the gait cycle. Robotic devices can eliminate this problem through the use of a mechatronic system that automates the assistance of the leg movement [1, 2]. This chapter presents the technological steps in the evolution of the design and development of Lokomat, an internationally well-established robot for gait therapy.

Manually assisted BWSTT involves therapists' assistance, while the patient practices stepping movements on a motorized treadmill with simultaneous unloading of a certain percentage of the body weight. Manual assistance is provided as necessary (and as far as possible) to enable upright posture and to induce physiological leg movements associated with physiological

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human gait. Over the last decades, there has been growing supporting evidence for the use of this technique in neurorehabilitation programs for stroke survivors and subjects with spinal cord injury (SCI). A large randomized clinical trial, known as the LEAPS study, has confirmed that walking training on a treadmill using body weight support and practice overground at clinics was superior to usual care in improving walking, regardless of the severity of initial impairment [3]. Yet, it has to be noted that in the LEAPS study, body-weight-supported treadmill training did not lead to superior results when compared to a home program of flexibility, range of motion, strength training, and balance of the same duration.

Whereas evidence demonstrates improvement in locomotor function following manually assisted treadmill training, its practical implementation in the clinical setting is limited by the labor-intensive nature of the method. Specifically, training sessions tend to be short because of the non-ergonomic physical demands and time costs placed upon the therapists' resources. This resource constraint yields significant limitations upon access to the therapy and, ultimately, to the effectiveness of the therapeutic approach with patients, as it limits the intensity of the training, resulting in a hindrance of functional gains in the lower limbs [4–6]. Particularly, in individuals with limb paralysis and/or a high degree of spasticity, appropriate manual assistance is difficult to provide; these patients require more than two therapists, which increases the already high cost and further limits training time [7]. The success and promise of BWSTT and the limitations and resource constraints in the therapeutic environment have inspired the design and development of robotic devices to assist in the rehabilitation of ambulation in patients following a stroke or SCI.

The research team of the Spinal Cord Injury Center of the University Hospital Balgrist in Zurich, Switzerland, an interdisciplinary group of physicians, therapists, and engineers, began to work on a driven gait orthosis in 1995 that would essentially replace the cumbersome and exhausting physical labor of therapists in the administration of locomotor training [1]. The "Lokomat" (commercially available from Hocoma AG, Volketswil, Switzerland) consists of a computer-controlled robotic exoskeleton that moves the legs of the patient in adjustable conjunction with a body weight support system (Fig. 29.1). It is the most widely used rehabilitation robot worldwide, with about 1000 installed devices until February 2020.

Later on, other exoskeletal systems were developed including the "AutoAmbulator" by Healthsouth Inc. (USA). Like the Lokomat, the AutoAmbulator is a four degrees-of-freedom (DOF) treadmill-based rehabilitation device, which consists of actuated robotic orthoses that guide the patient's knee and hip joints within the sagittal plane. In Europe, the device is sold as "ReoAmbulator" (www.motorica.com). Another treadmill-based robotic exoskeleton is LOPES (lower-extremity powered exoskeleton) [8]. It combines an actuated pelvis segment with a leg exoskeleton. The pelvis can move in translational directions, whereas the legs have two active rotary DOF at the hip (flexion/extension and abduction/adduction) and one active DOF at the knee (flexion/extension). The leg joints of the robot are actuated with Bowden cable-driven series elastic actuators resulting in a lightweight and compliant robotic system. The lateral pelvis translation is equipped also with the same actuation principle, whereas the anterior/posterior motion is driven by a linear actuator. A new version, LOPES II, uses an end-effector structure approach with parallel actuation that facilitates the alignment of human-robot joints [9]. Another gait rehabilitation robot is the active leg exoskeleton (ALEX) [10]. The so-called walker supports the weight of the device, and the orthosis incorporates several passive and actuated DOF with respect to the walker. The trunk of the orthosis (connected to the walker) has three DOF, namely, vertical and lateral translations and rotation about the vertical axis. All the DOF in the trunk are passive and held in position by springs. The hip joint of the orthosis has two DOF with respect to the trunk of the orthosis allowing actuated hip flexion/extension and passive abduction/adduction movements. A final

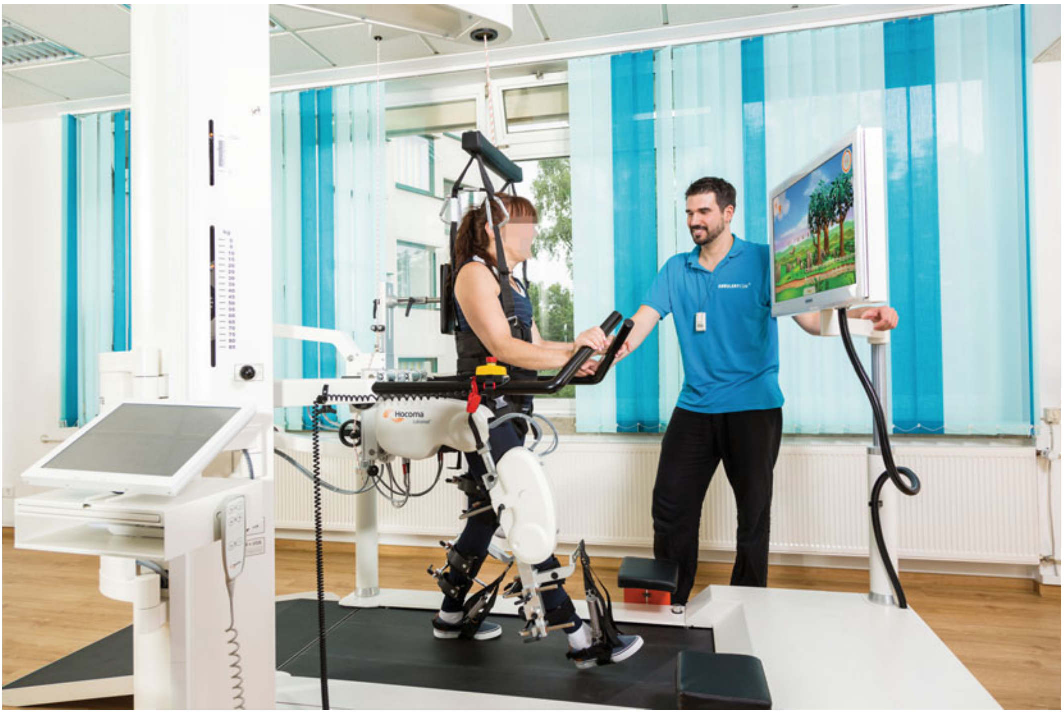

Fig. 29.1 Current version of the Lokomat system with a spinal cord-injured patient (Printed with permission of Hocoma AG, Volketswil)

example of a pioneer robotic device exoskeleton is the pelvic assist manipulator (PAM), a six DOF pneumatically operated device developed at the University of California Irvine that assists the pelvic motion during human gait training on a treadmill [11] and "POGO" (pneumatically operated gait orthosis), which moves the patient's legs with linear actuators attached to a frame placed around the subject [12].

Recent efforts have been made into developing wearable exoskeletons that allow overground walking. Although initially designed to assist SCI subjects in their daily ambulation, recent research highlights their potential also for gait rehabilitation [13]. Wearable robotic exoskeletons promote active participation of the user—crucial to driving brain plasticity and recovery [14]—as they require the user's active participation for both swing initiation and foot placement [15]. Several powered exoskeletons are already commercially available, such as the Ekso (Ekso Bionics, USA), the ReWalk (ReWalk Robotics, Israel), and the hybrid assistive leg (HAL) (Cyberdyne, Japan).

The interest in robot-assisted gait training has increased exponentially in the last years. This is reflected in the considerable number of reviews published within the last decade. Here we only presented some examples of hardware solutions. A detailed comparison between different gait-assisted devices can be found in e.g., [13, 16, 17].

An alternative to exoskeletal systems is end-effector-based systems, which connect the patients' leg (usually at the foot level) to the robot end-effector. One of the first footplate-based systems was the Gait Trainer [2], currently commercialized by Reha-Stim, Switzerland. The Gait Trainer operates like a conventional elliptical trainer, where the subject's feet are strapped into two footplates, moving the feet along a trajectory that is similar to a gait trajectory. As the Gait Trainer moves each leg only in one degree of freedom (DOF), Hesse and colleagues from the Fraunhofer Institute IPK developed a more complex device, called the “HapticWalker” [18]. The device comprises two end-effector-based platforms that move each foot in three DOF. Based on the knowledge gained with Gait Trainer and HapticWalker, Hesse et al. [19] developed the G-EO robot (EO is Latin meaning “I walk”), which is commercially available by the company Reha Technology AG in Switzerland (www.rehatechnology.com). As in the HapticWalker, the G-EO consists of two footplates, which move each foot with three DOF in the sagittal plane and enable the training of freely programmable tasks such as stair climbing. More recent examples of commercial end-effector systems include, e.g., Lokohelp (Woodway, USA), and THERA-Trainer lyra (medica Medizintechnik GmbH, Germany).

29.2 Orthosis Design

29.2.1 Mechanical Aspects

The Lokomat® is a bilaterally driven gait orthosis that is used in conjunction with an active body weight support system [1]. The Lokomat moves the patient’s legs through the gait cycle in the sagittal plane (Fig. 29.1). The device's hip and knee joints are actuated by linear drives integrated into an exoskeletal structure. Passive foot lifters support ankle dorsiflexion during the swing phase. The orthosis is fixed to the rigid frame of the body weight support system via a parallelogram construction that, originally, only allowed passive vertical translations of the orthosis while keeping the orientation of the robotic pelvis segment constant, and thus, restricting the gait pattern to a two-dimensional trajectory in the body sagittal plane. Newer versions of the Lokomat (from 2014) also incorporate lateral translation and transverse rotation of the pelvis (Fig. 29.2; FreeD Module, Hocoma, Switzerland). These two movements are mechanically coupled and actuated through a linear actuation on the new pelvis module. With the FreeD addition, the pelvis is now movable in the frontal plane to a lateral translation of up to 4 cm (per side) and in the transversal plane to a pelvic rotation of up to 4° (per side). Additionally, the legs cuffs can passively move laterally. This promotes a more natural gait pattern as the new module allows the natural lateral pelvis displacement as well as weight shifting during walking, and thus the excitation of more physiological sensory information from cutaneous, muscular, and joint mechanoreceptors and the possibility to train balance.

The linear drives on the orthoses are equipped with redundant position sensors as well as force sensors. The angular positions of each leg are measured by potentiometers attached to the lateral sides of the hip and knee joints of the orthosis. The hip and knee joint trajectories can be manually adjusted to the individual patient by changing the amplitude and offsets of a predefined gait trajectory. Knee and hip joint torques of the orthosis and pelvis module are measured by force sensors integrated in series with the linear drives. The signals from the force sensors may be used to determine the interaction torques between the patient and the device, which allows the estimation of the voluntary physical effort produced by the patient. This important information may be optimally used for various control strategies as well as for specific biofeedback and assessment functions.

The patient is fixed to the orthosis with straps around the waist, thighs, and shanks. The Lokomat geometry can be adjusted to the subject’s individual anthropometry. The lengths of the thighs and shanks of the robot are adjustable via telescopic bars, so that the orthosis may be used by subjects with different femur lengths ranging between 35 and 47 cm. A special version of the Lokomat was designed and developed in 2006 to accommodate pediatric patients with shorter femur lengths between 21 and 35 cm (equivalent to body heights between approximately 1.00 and 1.50 m). The width of the hip orthosis can also be adjusted by changing the distance between the two lower limbs. The FreeD module accommodates pelvic widths between 29 and 51 cm (between 17 and 28 cm in the

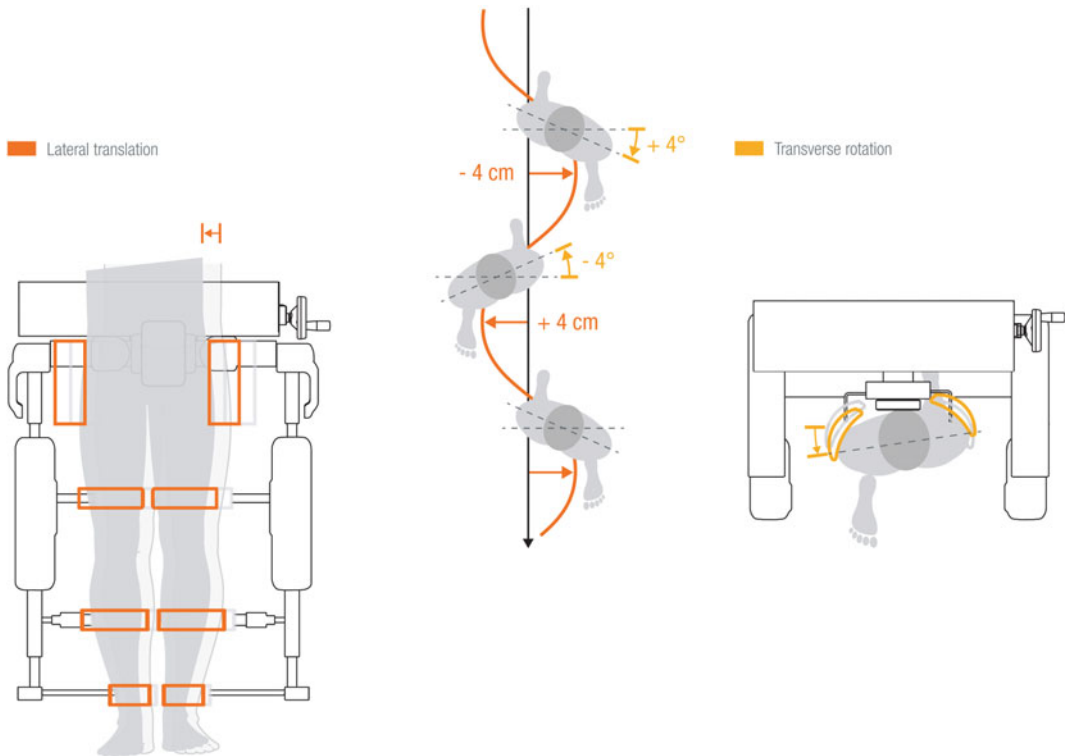

Fig. 29.2 Lateral translation and transverse rotation of FreeD. Left: Coupled lateral pelvis movement and rotation during physiological walking. Middle: Possibility of lateral pelvis and leg translation with the new FreeD. Right: Possibility of pelvis rotation with the new FreeD. Images with courtesy of Hocoma AG

pediatric version). The fixation straps, available in different sizes, are used to safely and comfortably hold the patient's limbs to the orthosis.

29.2.2 Drives

Ruthenberg and coworkers [20] reported the maximal hip torque during gait to be approximately 1 Nm per kilogram of body weight and an estimated average torque of approximately 35 Nm. In the Lokomat, hip and knee joints are actuated by custom-designed drives with a precision ball screw. The nut on the ball screw is driven by a toothed belt, which is in turn driven by a DC motor. The nominal mechanical power of the motors is 150 W. This yields an average torque of approximately 30 and 50 Nm at the knee and hip, respectively. Maximum peak torques are 120 and 200 Nm, respectively. This design has been demonstrated to be sufficient to move the legs against gravitational and inertial loads and, thus, to generate a functional gait pattern required in a clinical environment and suitable for most patients, even those with severe spasticity.

29.2.3 Safety

Whereas the mentioned peak torques are required to move the patient's joints in the presence of considerable interaction forces produced at the joints (e.g., due to spasticity) or between the patient's feet and treadmill (e.g., due to minor deviations of robot and treadmill speed), they can pose an inherent risk to the musculoskeletal system of the patient. To minimize this risk, various measures of safety were implemented into electronics, mechanics, and software. The electronic and mechanical safety measures follow principles of medical device safety regulations and standards (e.g., galvanic insulation). Additionally, passive back drivability and mechanical end stops avoid human joints getting overstressed or blocked in case of actuator malfunction. The software safety measures manage the proper operation of the device through the monitorization of nominal ranges of force sensors and the use of redundant position sensors. The software safety layer also checks the plausibility of movement and stops the device as soon as the movement deviates too much from the predefined desired gait trajectory. Another important safety feature is realized by the existence of the body weight support system, where the patient can be brought to a safe state when all drives have to be deactivated, e.g., when stumbling, or when spasticity causes the interaction forces to exceed the given threshold values. A wireless sensor system tracks the therapist's presence and regularly prompts input from the therapist to ensure the therapist's attention, and thus, improve the patient's safety. Furthermore, several manual emergency stops enable the therapist and/or patient to cause a sudden stop of movement whenever desired.

29.3 Body Weight Support System

Body weight support systems enable patients with leg paresis to participate in functional gait therapy, both on the treadmill and overground walking [21, 22]. The simplest system consists of a harness worn by the patient, ropes and pulleys, and a counterweight used to partially unload the patient. However, these simple systems do not ideally accommodate the wide range of conditions a patient with sensorimotor deficits encounters in gait therapy. The supporting vertical force varies mainly because of the effect of inertia that is induced by the vertical movement components performed during gait [23]. The lack of transparency of simple BWS solutions, the support force vector direction, and attachment to the harness influence the quality of the gait patterns during gait neurorehabilitation [24].

A mechatronic body weight support system called "Lokolift" has been developed to allow more precise unloading during treadmill walking. The Lokolift combines the key principles of both passive elastic and active dynamic systems [23]. In this system, at unloading levels of up to 85 kg and walking speeds of up to 3.2 km/h, the mean unloading error was less than 1 kg, and the maximum unloading error was less than 3 kg. This system can perform changes of up to 20 kg in the desired unloading within less than 100 ms. With this feature, not only constant body weight support but also gait cycle-dependent or time-variant changes of the desired force can be achieved with a high degree of accuracy. More recently, a spring-based (passive) system has been developed that allows similar results to the Lokolift system [25]. With the addition of the FreeD module, a new actuated degree of freedom was included in the Lokolift to allow for the pelvis lateral movement.

29.4 Control Strategies

In early clinical applications, the Lokomat was only used in a position control mode, where the measured hip and knee joint angles were fed into a conventional Position-Derivative (PD) controller. In the position control mode, the Lokomat does not systematically allow for deviation from the predefined gait pattern. However, rigid execution and repetition of the same pattern are not optimal for learning [26] and might lead to a reduction of patients' effort [27], and therefore, limit the therapeutic efficacy of the training [28]. In contrast, movement variability and the possibility to make errors are considered essential components of practice for motor learning [29]. Bernstein's demand that training should be "repetition without repetition" [30] is considered to be a crucial requirement. This is supported by recent advances in computational models of plasticity and motor learning to predict recovery [31]. More specifically, the study by Lewek et al. [32] demonstrated that intralimb coordination after stroke was improved by manual training that enabled kinematic variability, but was not improved by position-controlled Lokomat training, which reduced kinematic variability to a minimum. Another study performed with transected spinal rats also showed that kinematic variability facilitates spinal learning [33].

In response to this important finding, “patient-cooperative” control strategies were developed that “recognize” the patient’s movement intention and motor abilities by estimating the patient’s physical effort and adapting the robotic assistance to the patient’s contribution, thus giving the patient more movement freedom and promoting more movement variability than during position control [34, 35]. It is recommended that the robotic control and feedback strategies should behave as qualified human therapists, i.e., they assist the patient’s movement only as much as needed and inform the patient about how to optimize voluntary muscle effort and coordination to achieve and/or improve a particular movement.

The first step towards more movement freedom is to allow a variable deviation from a predefined leg trajectory by means of compliant control, such as impedance control. Impedance control allows a variable deviation from the predefined joint trajectories while an adjustable assisting torque is applied depending on the deviation between the current and desired joint trajectories, which depends on the patient’s effort and behavior (e.g., measured using force/torque sensors). This assistive torque is usually defined as a function of angular position and its derivatives and is more generally called mechanical impedance [36]. More recent compliant controllers (e.g., path control) also include a deadband—i.e., a volume around the desired trajectory in which no assistance is provided—or the amount of impedance force varies with space and time [10, 35]. Figure 29.3 depicts a block diagram of an impedance controller [34].

An impedance controller was initially tested with the Lokomat in several subjects without neurological disorders and several subjects with incomplete paraplegia [34]. In the impedance control mode, angular deviations increased with increasing robot compliance (decreasing impedance) as the robot applied a smaller amount of force to guide the human legs along a given trajectory. It was found that inappropriate muscle activation produced by high muscle tone, spasms, or reflexes could affect the movement quality and yield a physiologically incorrect gait pattern, depending on the magnitude of the impedance chosen. In contrast, subjects with minor to moderate motor deficits stated that the gentle behavior of the robot feels good and comfortable.

The disadvantage of a standard impedance controller is that the patient needs to retain sufficient voluntary effort to move along a physiologically correct trajectory, which limits the range of application to patients with only mild lesions. Furthermore, the underlying desired gait trajectory allows no flexibility in time, i.e., leg position can deviate only orthogonally but not tangentially to the given time-dependent trajectory. Therefore, the original impedance controller

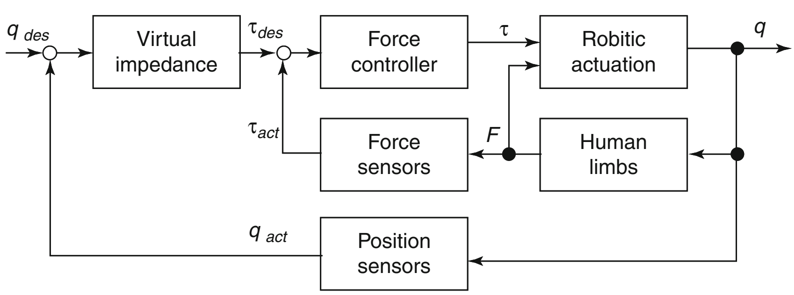

Fig. 29.3 Example of an impedance control architecture for the compliance of rehabilitation robot [34]. Symbols: q is the vector of generalized positions or joint angles; τ is the vector of generalized joint torques; F is the interaction force between robot and human; index “des” refers to the desired reference signal; index “act” refers to the actual, measured signal

has been extended to a so-called path controller [35], in which the time-dependent walking trajectories are converted to walking paths with free timing. Furthermore, the impedance along the path can vary to obtain physiological satisfactory movements, especially at critical phases of gait (e.g., before heel contact) [35]. This is comparable to fixing the patient's feet to soft rails, thus limiting the accessible domain of foot positions calculated as functions of hip and knee angles. Along these "virtual rails," the patients are free to move. Supplementary to these *corrective* actions of the Lokomat, a *supportive* force field of adjustable magnitude can be added to provide extra support to patients along the path. Depending on the actual position of the patient's legs, the supportive force act in the direction of the desired path. The support is derived from the desired angular velocities of the predefined trajectory at the current path location. Compared to the more simple impedance controller, the path controller gives the patient more freedom in timing, while she or he can still be guided through critical phases of the gait. The path controller has been evaluated in several single-case studies [37–39]. Most stroke patients improved their gait performance after several weeks of training with the path controller.

New trends in robot-based motor learning and neurorehabilitation suggest that challenge-based controllers—i.e., controllers that make movement tasks more difficult or challenging [40]—might enhance recovery by, e.g., strengthening the muscles by opposing the movement (e.g., resistive methods [41]), facilitating the detection of tracking errors (e.g., error augmentation methods [42–44]), and increasing movement variability (e.g., force perturbations [45]). These challenge-based control strategies might lead to improvements in recovery, especially in people in the late stages of neurorehabilitation or with mild impairments [41, 46–48].

Finally, adaptive controllers that provide tailored assistance or resistance based on real-time measurements of the users' performance (e.g., tracking error [49]) during gait training might be more effective in promoting motor learning than those that do not adapt the assistance to the patients' especial needs [50]. The controller adaptation might be done by modifying the parameters of a reference trajectory or the dynamics of a virtual compliant controller [9, 49, 51]. The Hocoma 2020 software release for the Lokomat, the LokomatPro Sensation, provides new therapy options that include intelligent algorithms which create a maximum challenge by personalizing the assistance based on patients' performance.

29.5 Assessment Tools

Using robotic devices in locomotor training can have more advantages than just supporting the movement, thus, increasing the intensity of training. Data recorded by the position and force transducers can also be used to assess the clinical state of the patients throughout the therapy [52]. The following clinical measures can be assessed by the Lokomat.

29.5.1 Mechanical Stiffness

Spasticity is an alteration in muscle activation with increased tone and reflexes. It is a common side effect of neurological disorders and injuries affecting the upper motor neuron, e.g., after brain or spinal cord injuries. Formally, spasticity is usually considered as "a motor disorder characterized by a velocity-dependent increase of tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of stretch reflexes" [53]. It appears as an increased joint resistance during passive movements. Sanger et al. [54] used a more functional rather than physiological definition describing spasticity as "a velocity-dependent resistance of a muscle to stretch." Most commonly, spasticity is evaluated by the Ashworth Test [55] or Modified Ashworth Test [56]. In both tests, an examiner moves the limb of the patient, while the patient tries to remain passive. The examiner rates the encountered mechanical resistance to passive movement on a scale between 0 and 4. However, such an evaluation is subject to variable factors, such as the speed of the movement applied during the examination and the experience of the examiner and interrater variability.

The mechanical resistance can also be measured with the Lokomat [57, 58], which is capable of simultaneously recording joint movement and torques. The actuation principle allows for the assessment of the hip and knee flexion and extension movements in the sagittal plane. The stiffness measurement can be performed immediately before and following the usual robotic movement training without changing the setup. To measure the mechanical stiffness with the Lokomat, the subject is lifted from the treadmill by the attached body weight support system so that the feet can move freely without touching the ground. The Lokomat then performs controlled flexion and extension movements of each of the four actuated joints subsequently at different velocities. The joint angular trajectories are squared sinusoidal functions of time replicating the movements applied by an examiner performing a manual Ashworth Test. Measured joint torques and joint angles are used to calculate the elastic stiffness as slopes of the linear regression of the torque-position plots. As the recorded torques also include passive physical effects of the Lokomat and the human leg, the measured torque is offline-compensated for inertial, gravitational, Coriolis, and frictional effects obtained from an identified segmental model of the orthosis including the human leg. Patient data comparisons with manual assessments of spasticity based on the Modified Ashworth Scale demonstrated that higher stiffness values measured by Lokomat corresponded with higher ratings of spasticity [57, 58]. A feasibility study with ten children with CP showed that the Lokomat is a feasible tool to measure stiffness, but it is not sensitive enough to detect small changes in muscle tone [59]. Assessment of spasticity is still in experimental status and needs further validation in future studies.

29.5.2 Voluntary Force

For some patients, maximum voluntary force is a measure of limiting factor for walking. In order to assess the maximum voluntary force in the Lokomat [57], the examiner instructs the patient to generate force in each joint, first in flexion and then in extension directions. The force is generated against the Lokomat, which is position-controlled to a predefined static posture, thus providing a quasi-isometric measurement condition. Simultaneously, the joint moments are measured by the built-in force transducers and displayed to the patient and the therapist. The maximum moments for flexion and extension are used as outcome variables. An improved version standardizes the computerized sequence and instructions and uses a time-windowed calculation for the output values [60]. It was shown that this measurement method has a high inter- and intratester reliability and can be used to assess the strength of the lower extremities [61]. It has also been shown that the recorded peak forces during isometric contractions could be employed as an outcome measure to monitor changes in muscle strength in incomplete SCI subjects following robot-aided gait training [62].

29.5.3 Range of Motion and Lower Limb Proprioception

In a manner similar to the conventional clinical range of motion assessments, the therapist moves the leg of the patient until the passive torque produced by the patient's joint reaches a certain threshold that is qualitatively predefined by the therapist based on his or her expertise. As the patient's legs are attached to the device with the anatomical and technical joint axes in alignment with each other, and the recorded joint angles correspond with the patient's joint angles, the passive range of motion is determined by the maximum and minimum joint angles measured. This parameter can be used for further assessments and training. The Lokomat measures the joint range of motion within values typical for human gait and may represent only a fraction of the patient's physiological range. This test provides important additional measures of the patient relevant to the gait and further conditions making contractures and other joint limitations (e.g., due to shortened tendons) quantifiable. These measures are directly relevant to activities of daily living.

Lower limb proprioception has also been listed as a relevant assessment in clinical practice [63]. Some attempts have been made to use the position sensors of the Lokomat for evaluating hip and knee joint proprioception. Joint position reproduction (JPR) was tested in healthy subjects and 23 incomplete SCI subjects [64]. The participants' legs were positioned at predetermined hip and knee angles and then displaced to a different (distractor) position. Using a joystick to control the robot, participants were requested to place their limb back at the remembered initial position and the error between the initial and remembered position was measured. Although the test-retest reliability in SCI participants was found to be between fair and substantial at the hip and knee respectively, the JPR score correlated well with the clinical assessment of proprioception. The ability to sense movement, i.e., the threshold to detection of passive motion (TTDPM), was also incorporated in a different study with healthy participants and 17 individuals with SCI [65]. The Lokomat was used to passively move the hip and knee joints at four different speeds (0.5, 1.0, 2.0, and 4.0 deg/s) in both flexion and extension. Participants were requested to press a button whenever a movement was felt. The measures showed high test-retest reliability and high correlation with several assessments of lower limb joint kinesthesia.

29.6 Biofeedback

Compared to manual treadmill therapy, robotic gait retraining changes the nature of the physical interaction between the therapist and the patient. Therefore, it is important to incorporate the features into the Lokomat system to assess the patient's contribution and performance during training and to provide necessary real-time feedback and instructions derived from precise measurements taken by the system. The patient may have deficits in sensory perception and cognition interfering with her/his ability to objectively assess movement performance and making it difficult to engage the patient and encourage active participation in the movement and training. With the feature of Lokomat, the technology of multisensory biofeedback has the potential to challenge and engage the patient in order to increase the benefit of motor recovery and neurological rehabilitation [66, 67].

The built-in force transducers can estimate the muscular efforts contributed by the patient's knee and hip joints. Incorporating this information into an audiovisual display can simulate the "feedback" the therapist usually gives to the patient during manual training, where the therapist estimates the patient's activity based on the effort required to guide the patient's legs.

The goal of the biofeedback function is to derive and display performance values that quantify the patient's activity and performance in relation to the target gait function such that the patient can improve muscle activity toward a more functional gait pattern. An early implementation of a force-biofeedback strategy for the Lokomat has been described [34, 68, 69].

To obtain relevant biofeedback values, the gait cycle is divided into the stance phase and swing phase. For each phase, weighted averages of the forces are calculated at each joint independently, thus yielding two values per stride per joint. Eight biofeedback values are available for each gait cycle from all four joints of the two lower limbs. Because of the bilateral symmetry, four weighting functions are required for the averaging procedure (hip stance, hip swing, knee stance, knee swing). The weighting functions were selected heuristically to provide positive biofeedback values when the patient performs therapeutically reasonable activities (e.g., active weight bearing during stance, sufficient foot clearance during the swing, active hip flexion during swing, active knee flexion during early swing, knee extension during late swing). The graphical display of these values has been positively rated by the patients and leads to an increased instantaneous activity by the patients [70, 71] and improvements in cognitive functioning and psychological well-being in patients with chronic stroke [72] and traumatic brain injury [73]. However, there is no direct clinical evidence showing that this training with computerized feedback leads to better rehabilitation outcomes or faster recovery compared to Lokomat training without feedback. In the Lokomat 2020 software release, the LokomatPro Sensation, a new assessment tool was incorporated to evaluate in real-time the patients' ability to walk. Using adaptive algorithms [74], the assistance provided by the device can be automatically adjusted at each gait step (i.e., the impedance of the joints and the unloading of the body weight) based on the patient's ability to follow a predefined gait trajectory [49]. Although not systematically evaluated in SCI and/or brain-injured patients, a first experimental evaluation of the assessment algorithm in eight healthy participants suggests that this method can be a promising tool to objectively assess walking function during training in clinical practice.

To further increase patients' engagement and motivation, virtual reality and computer game techniques may be used to provide virtual environments that encourage active participation during training (Fig. 29.4). A first feasibility study showed that the majority of subjects could navigate through a virtual environment by appropriately controlling and increasing their activity of left and right legs while walking through a forest scenario and other scenarios [75]. Wagner et al. showed how such kind of VR-enhanced Lokomat training activates premotor and parietal areas [76]. Calabrò et al. further showed that combining robotic-based rehabilitation with avatars animated in a 2D VR in chronic stroke patients may entrain several brain areas involved in motor planning and learning, resulting in enhanced motor performance [77].

Fig. 29.4 Walking through a virtual environment. Lokomat in combination with a virtual reality back-projection display system

More immersive VR visualization displays, such as large projections and off-the-shelf head-mounted displays (HMD), could also be employed to modulate motor behavior through the manipulation of the virtual environment [78]. The multisensory integration of visual and non-visual information (e.g., auditory, vestibular, and somatosensory information) allows the manipulation of the perception of the environment. This in turn can be employed to modulate the planning and execution of movements. For example, it has been shown that the walking speed is affected by changing the speed of the optic flow [79] and that visualizing avatars as self-representations of the users' own bodies can be exploited to induce changes in the gait pattern in healthy participants [80]. However, further research with patients is needed to unveil the real potential of more immersive VR in robot-aided rehabilitation.

29.7 Clinical Outcomes

Robotic technology is still very much in development, and there are a lot of new devices and technical features that might further enhance the potential of therapeutic training. Nevertheless, there have already been more than 200 clinical investigations applying the Lokomat technology to different patient groups. It was applied for the therapy of patients with SCI, hemiplegia after stroke, traumatic brain injuries, multiple sclerosis, Parkinson's disease, cerebral palsy, and other pathologies (see [81]). Most of these studies show positive outcomes with the Lokomat compared to conventional therapies or usual care.

Although robot-aided gait training with Lokomat has proved to be feasible in a number of pathologies such as iSCI [6], multiple sclerosis [82], and cerebral palsy [83], the majority of clinical studies have been done with stroke subjects. Often cited are the ones from Hidler et al. [28] and Hornby et al. [84], who applied the Lokomat on subacute and chronic stroke patients, respectively, and compared it with conventional gait therapy. Both studies showed that participants who received conventional training experienced greater gains in gait parameters such as walking speed, walking distance, or single limb stance than those trained on the Lokomat. Hidler et al. and Hornby et al. concluded that for stroke participants, conventional gait training interventions appear to be more effective than robot-assisted gait training. However, both studies included only ambulatory patients, although the Lokomat is recommended to be used primarily for nonambulatory patients. Furthermore, the Lokomat was used in most simple control modes (position controller or impedance controller with reduced guidance force), without any other features such as augmented feedback or biofeedback functions. Of course, this kind of mode cannot compete with the quality and gentleness of a trained therapist or more advanced robotic features, such as cooperative and self-adaptive control strategies. A more recent study is the one by Dundar et al. [85] who compared conventional physiotherapy and robotic training combined with conventional therapy on 107 subacute and chronic stroke patients. They found that robotic training combined with conventional therapy produced better improvement in a large number of different stroke scales.

A recent Cochrane report [72] analyzing 62 trials involving 2440 stroke patients revealed that people who receive electromechanical-assisted gait training, such as provided by the Lokomat or the Gait Trainer, in combination with physiotherapy after stroke are more likely to achieve independent walking than people who receive gait training without these devices. Specifically, people in the first three months after stroke and those who are not able to walk seem to benefit most from this type of intervention. The role of the type of device is still not clear.

Fewer studies have focused on evaluating the effectiveness of electromechanical-assisted gait training on cognitive function and quality of life in patients with walking disabilities, despite their importance in rehabilitation. There is initial evidence that training with the Lokomat together with virtual reality positively affects cognitive recovery and psychological well-being in patients with chronic stroke [73] and traumatic brain injury [86].

The current evidence suggests that future research should go into performing a large definitive, pragmatic, phase III trial to address specific questions such as: "What frequency or duration of electromechanical-assisted gait training might be most effective?" and "how long does the benefit last?" Importantly, due to the heterogeneity of the studied stroke population, future clinical trials should consider time post-stroke in their trial design.

29.8 Conclusion

Robotic rehabilitation devices such as the Lokomat become increasingly important and popular in clinical and rehabilitation environments to facilitate prolonged duration of training, increased number of repetitions of movements, improved patient safety, and less strenuous operation by therapists. Novel sensor, displays, and control technologies improved the function, usability, and accessibility of the robots, thus increasing patient participation and improving performance. Improved and standardized assessment tools provided by the robotic system can be an important prerequisite for the intra- and intersubject comparison that the researcher and the therapist require to evaluate the rehabilitation process of individual patients and entire patient groups. Some rehabilitation robots offer an open platform for the implementation of advanced technologies, which will provide new forms of training for patients with movement disorders.

With the use of different cooperative control strategies and particular virtual reality technologies, patients can be encouraged not only to increase engagement during walking training but also to improve motivation to participate in therapy sessions. Especially promising are adaptive controllers that can accommodate the patient's specific pathology and level of disability by identifying and reducing hindrances that could impede the recovery process, or by challenging more skilled patients. However, to date, there is a lack of standardized comparisons among control strategies to analyze the relation between control strategies and clinical outcomes [87, 88]. More immersive VR visualization displays that provide a realistic representation of virtual environments and avatars that mimic the patients' movements could potentially further enhance robot-aided rehabilitation by leveraging psychological factors such as motivation, presence, and embodiment [89]. Yet, more research is needed to unveil the real potential of immersive VR in robot-aided rehabilitation.

Several clinical trials have been performed showing that the application of rehabilitation devices is at least as effective as the application of conventional therapies. Further clinical studies are required to find predictors for the success of a Lokomat treatment in order to distinguish therapy responders from nonresponders. From such investigations, it is expected to figure out which choice of technical Lokomat features (controller complexity, number of actuated joints, kind of feedback, etc.) have to be applied to which kind of patient characteristics (kind of pathology, severity, and time since lesion, anthropometry, etc.) in order to obtain the best therapeutic outcome. New sensitive assessment methods, which include non-sensorimotor assessments such as cognitive ability and quality of life, will be required to better distinguish among the different patient characteristics and detect already small changes in the therapeutic outcomes.

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