13 Technology of the Robotic Gait Orthosis Lokomat

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Abstract

Rehabilitation robots allow for a longer and more intensive locomotor training than that achieved by conventional therapies. Robot-assisted treadmill training also offers the ability to provide objective feedback within one training session and to monitor functional improvements over time. This article provides an overview of the technical approach for one of these systems known as "Lokomat" including new features such as hip ab/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

13.1 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 article 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 therapist assistance while the patient practices stepping movements on a motorized treadmill and with simultaneous unloading of a certain percentage of body weight. Manual assistance is provided as necessary (and as far as possible) to enable upright posture and to induce leg movements associated with adaptive physiological human gait. Over the last two decades, there has been growing evidence of support for the use of this technique in neurorehabilitation programs for stroke and SCI subjects.

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V. Dietz et al. (eds.), *Neurorehabilitation Technology*,
DOI 10.1007/978-1-4471-2277-7_13, © Springer-Verlag London Limited 2012

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 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. 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 also limits training time [3]. 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 the rehabilitation of ambulation in patients following 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 an adjustable conjunction with a body weight support system (Figs. 13.1 and 13.2). Later on, other exoskeletal systems were developed including the "Autoambulator" by Healthsouth Inc. (USA); the "Lopes" by the University of Twente, The Netherlands; [4] and the "ALEX" by the University of Delaware, USA [5].

An alternative to exoskeletal systems are end effector–based systems such as the commercially available Gait Trainer [2]. 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. Another research group at the Los Amigos Research and Education Institute, Downey, California (USA), developed the "PAM" (pelvic assist manipulator), which is a device that assists the pelvic motion during human gait training on a treadmill, and "POGO" (pneumatically operated gait orthosis), which moves the patient's legs with linear actuators attached to a frame placed around the subject [6].

13.2 Orthosis Design

13.2.1 Mechanical Aspects

The Lokomat® is a bilaterally driven gait orthosis that is used in conjunction with a body weight support system [1]. The Lokomat moves the patient legs through the gait cycle in the sagittal plane (Fig. 13.1). The Lokomat'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 leg motion can be controlled with highly repeatable predefined hip and knee joint trajectories on the basis of a conventional position control strategy. The orthosis is fixed to the rigid frame of the body weight support system via a parallelogram construction that allows passive vertical translations of the orthosis while keeping the orientation of the robotic pelvis segment constant. The patient is fixed to the orthosis with straps around the waist, thighs, and shanks.

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 amplitude and offsets. Knee and hip joint torques of the orthosis are measured by force sensors integrated into the orthosis in series with the linear drives. The signals may be used to determine the interaction torques between the patient and the device, which allows estimation of the voluntary muscle 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 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 new Lokomat

Fig. 13.1 Current (2007) version of the Lokomat system with a spinal cord–injured patient (Printed with permission of Hocoma AG, Volketswil)

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 may also be adjusted by changing the distance between the two lower limbs. The fixation straps, available in different sizes, are used to safely and comfortably hold the patient's limb to the orthosis.

13.2.2 Drives

Ruthenberg and coworkers [7] 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

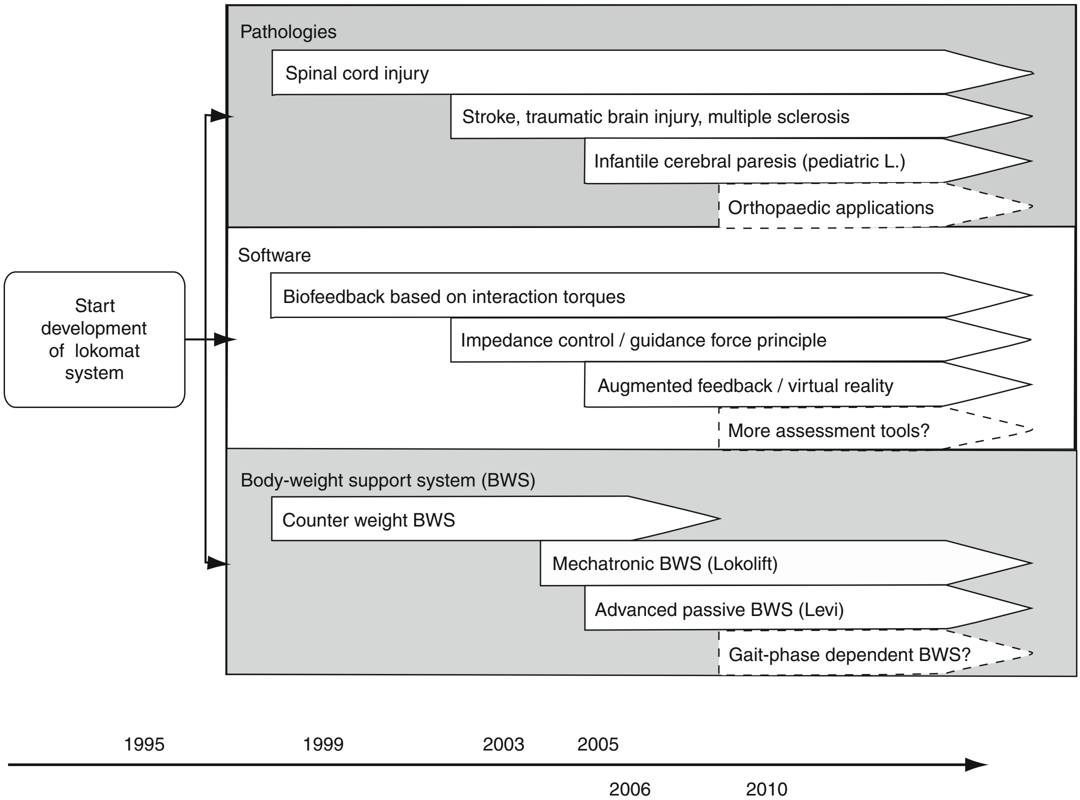

Fig. 13.2 Rough timeline and outlook of features of the Lokomat system (From: Riener et al. [31]. Used with permission)

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.

13.2.3 Safety

Whereas the mentioned peak torques are required in order 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. In order 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 endstops avoid incidents that human joints get overstressed or blocked in case of actuator malfunction. The software safety measures manage proper operation of the device through control of nominal ranges of force sensors and also through the use of redundant position sensors. Software also checks plausibility of movement and stops the device as soon as the movement deviates too much from the known 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 situation, when all drives have to be deactivated, e.g., when stumbling, or if spasticity causes the interaction forces to exceed the given threshold values. A wireless sensor system tracks the therapist's presence and prompts input from the therapist in order to ensure therapist's attention and to improve patient safety. Furthermore, several manual emergency stops enable the therapist (or patient) to cause a sudden stop of the movement whenever desired.

13.3 Body Weight Support System

Body weight support systems enable patients with leg paresis to participate in functional gait therapy, both on the treadmill and in overground walking [8]. A simple 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 will encounter 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 [9]. A mechatronic body weight support system called "Lokolift" has been developed to allow a more precise unloading during treadmill walking. The Lokolift combines the key principles of both passive elastic and active dynamic systems [9]. In this system, at unloading levels of up to 60 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 new system can perform changes of up to 20 kg in desired unloading within less than 100 ms. With this innovative feature, not only constant body weight support but also gait cycle–dependent or time variant changes of the desired force can be realized with a high degree of accuracy. More recently, a spring-based (passive) system has been developed that allows similar results like the Lokolift system [10]. A chronological overview of the different developmental stages of the Lokomat system is given in Fig. 13.2.

13.4 Control Strategies

In early clinical applications, the Lokomat was only used in a position control mode, where the measured hip and knee joint angles are fed into a conventional 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 is not optimal for learning. In contrast, variability and the possibility to make errors are considered as essential components of practice for motor learning. Bernstein's demand that training should be "repetition without repetition" [11] is considered to be a crucial requirement and is also supported by recent advances in computational models describing motor learning [12]. More specifically, a recent study by Lewek et al. [13] demonstrated that intralimb coordination after stroke was improved by manual training, which enabled kinematic variability, but was not improved by position-controlled Lokomat training, which reduced kinematic variability to a minimum.

In response to this important finding, "patient-cooperative" control strategies were developed that "recognize" the patient's movement intention and motor abilities by monitoring muscular efforts and adapt the robotic assistance to the patient's contribution, thus giving the patient more movement freedom and variability than during position control [14, 15]. It is recommended that the control and feedback strategies should do the same as a qualified human therapist, i.e., they assist the patient's movement only as much as needed and inform the patient how to optimize voluntary muscle efforts and coordination in order to achieve and improve a particular movement.

The first step to allow a variable deviation from a predefined leg trajectory, thus giving the patient more freedom, can be achieved by an impedance control strategy. The deviation depends on the patient's effort and behavior. An adjustable torque is applied at each joint depending on the deviation of the current joint position from the trajectory. This torque is usually defined as a zero order (stiffness) or higher order (usually

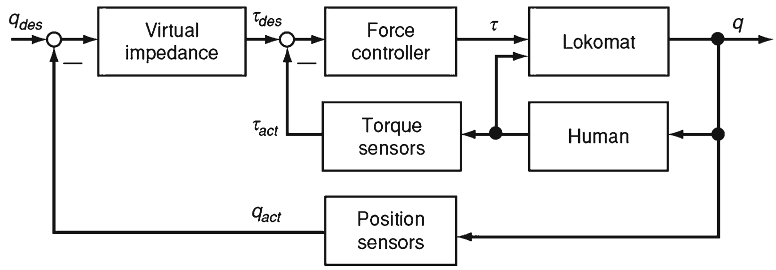

Fig. 13.3 Example of an impedance control architecture for the compliance of rehabilitation robot [14]. Symbols: q is the vector of generalized positions or joint angles; τ is the vector of generalized joint torques; index "*des*" refers to the desired reference signal; index "*act*" refers to the actual, measured signal (From: Riener et al. [31]. Used with permission)

first or second order) function of angular position and its derivatives. This torque is more generally called mechanical impedance [16]. Figure 13.3 [14] depicts a block diagram of an impedance controller.

The impedance controller was initially tested in several subjects without neurological disorders and several subjects with incomplete paraplegia [14]. 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. Inappropriate muscle activation produced by high muscle tone, spasms, or reflexes can affect the movement and may 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 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 gait trajectory allows no flexibility in time, i.e., leg position can deviate only orthogonally but not tangentially to the given trajectory. Therefore, the impedance controller has been extended to a so-called path controller [15], in which the time-dependent walking trajectories are converted to walking paths with free timing. Furthermore, the impedance along the path can vary in order to obtain satisfactory movement especially at critical phases of gait (e.g., before heel contact) [15]. 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. 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. Supportive forces make it possible to move along the path with reduced effort. Compared to the impedance controller, the path controller gives the patient more freedom in timing while he or she can still be guided through critical phases of the gait.

13.5 Additional Hip and Pelvis Actuation

The original Lokomat version restricts the gait pattern to a two-dimensional trajectory in the sagittal plane of the human body. This lack of lateral movement leads to a reduced weight shifting and, thus, to a lower load transfer between treadmill and supporting leg. It is assumed that this has a negative effect on the balance training and the excitation of the cutaneous, muscular, and joint receptors. Therefore, the Lokomat version installed at the Balgrist University Hospital has been extended by three additional actuated degrees of freedom. Two

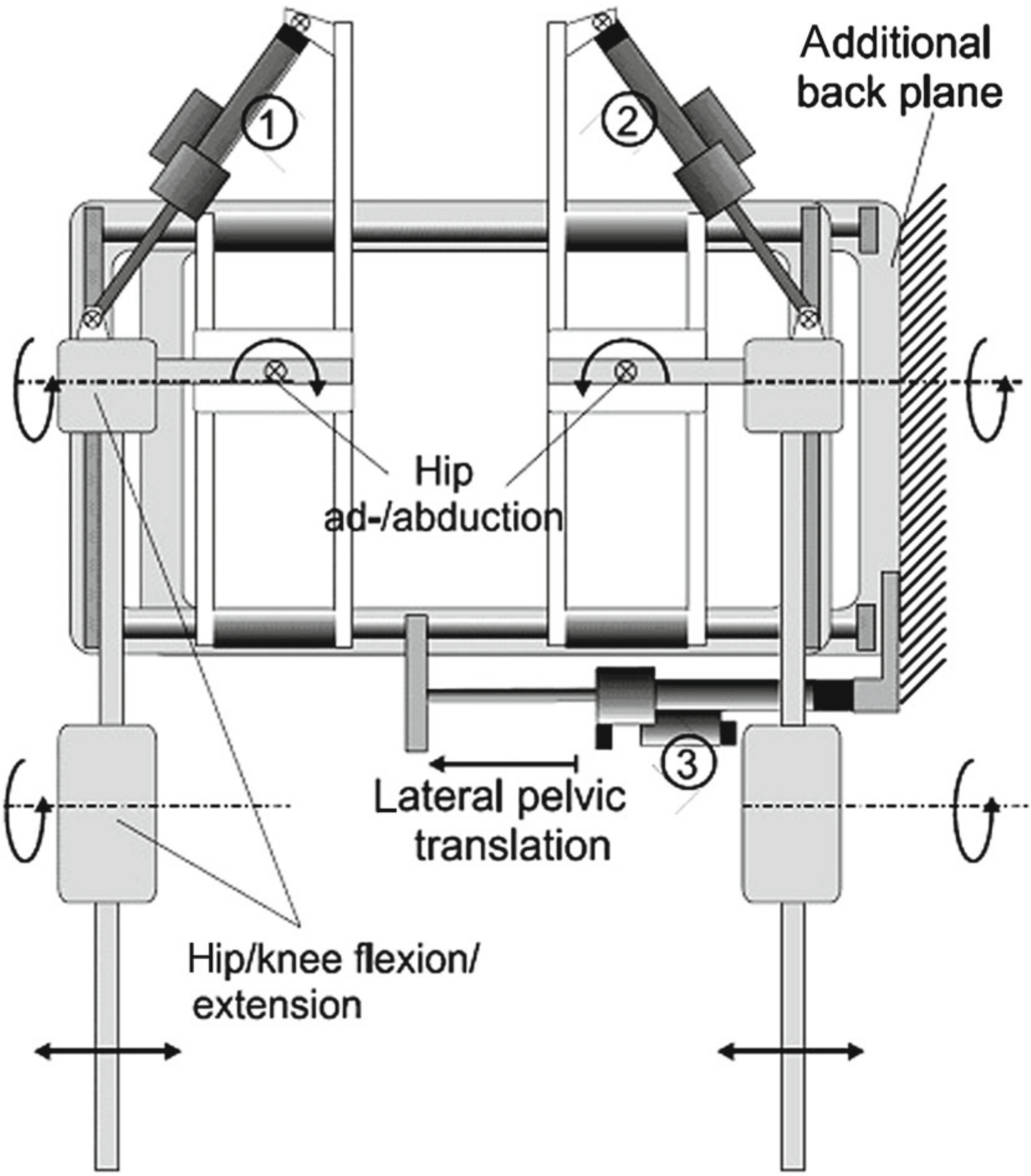

Fig. 13.4 Sketch of the front view of the extended Lokomat hardware

degrees of freedom perform hip ad/abduction, and 1° of freedom enables the Lokomat to accomplish a lateral pelvis displacement movement (Fig. 13.4). Three linear actuators have been added to drive the ad/abduction (No. 1 and 2 in Fig. 13.4) and the lateral pelvis displacement (No. 3). The linear drives are equipped with redundant position sensors as well as force sensors.

Several control strategies have been implemented and tested with the new hip–pelvis actuation. First, the new degrees of freedom have been position-controlled. For this purpose, gait trajectories of healthy subjects have been recorded, which then served as the desired trajectories for the PD position controllers. Later, a controller was developed that is able to emulate the viscoelastic properties of passive spring–damper elements. The integrated force sensors allow measuring the interaction forces between the patient and the Lokomat so that an impedance controller could be implemented. The interaction force has been controlled by a proportional force controller with feed-forward of the desired force value in order to display the virtual spring–damper element to the patient. The desired value depends on the angular velocity of the joint and the deviation from the desired angular position. In the meantime, further controllers have been derived that are based on the path controller that is performing the knee and hip joint movements in the sagittal plane.

This extended Lokomat version has been tested with several healthy subjects. All subjects agreed that gait training with lateral pelvis displacement and ad/abduction feels more physiological and comfortable than without. The optimal amplitudes of lateral pelvis displacement and ad/abduction are not only dependent on the subjects' heights but also differ due to individual walking behaviors. Therefore, the amplitudes of the new degrees of freedom were chosen to be adjustable.

13.6 Assessment Tools

Using robotic devices in locomotor training can have more advantages than just supporting the movement and, 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. The following clinical measures can be assessed by the Lokomat.

13.6.1 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 hyperexitability of stretch reflexes" [17]. It appears as an increased joint resistance during passive movements. Recently, Sanger et al. [18] introduced 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 [19] or Modified Ashworth Test [20]. In both tests, an examiner moves the limb of the patients 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 [21, 22], which is capable of simultaneously recording joint movement and torques. The actuation principle allows for 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 [21, 22]. Assessment of spasticity is still in an experimental status and needs further validation in future studies.

13.6.2 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 [21], 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 [23]. 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 [23].

13.6.3 Range of Motion

In a manner similar to 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.

13.7 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 his/her ability to objectively assess movement performance and making it difficult to engage the patient and to encourage active participation in the movement and training. With the new feature of Lokomat, the technology of biofeedback has a potential to challenge and engage the patient in order to increase the benefit on motor recovery and neurological rehabilitation [24, 25].

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 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 [14, 26, 27].

In order to obtain relevant biofeedback values, the gait cycle is divided into stance phase and swing phase. For each phase, weighted averages

Fig. 13.5 Walking through a virtual environment. Lokomat in combination with a virtual reality back-projection display system (From: Riener et al. [31]. Used with permission)

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 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 [28, 29]. 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.

To further increase patient's engagement and motivation, virtual reality and computer game techniques may be used to provide virtual environments that encourage active participation during training (Fig. 13.5). 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 virtual underground scenario [30].

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, display 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. Furthermore, 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 therapy sessions.

Acknowledgment This work was supported in parts by the US National Institute on Disability and Rehabilitation Research (NIDRR) under Grant H133E070013, the National Centre of Competence in Research (NCCR) of the Swiss National Science Foundation (SNF) on Neural Plasticity and Repair under Project P8 Rehabilitation Technology Matrix, the EU Project MIMICS funded by the European Community's Seventh Framework Program (FP7/2007–2013) under grant agreement n 215756, the Swiss Commission for Technology and Innovation (CTI) projects 6199.1-MTS and 7497.1 LSPP-LS, the Olga Mayenfisch Foundation, and the Bangerter Rhyner Foundation. Furthermore, we want to thank Katherine G. August for her support in the organization of structure and language of this manuscript.

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