MODULE 1: STROKE REHABILITATION: FROM UNDERLYING BASIS TO ADVANCED REHABILITATION TECHNOLOGIES

Session 3: Introduction to new technologies in Physical and Rehabilitation Medicine (PRM). Neurophysiological basis and state of the art

Index

1 LEARNING OBJECTIVES

- To know the different technological solutions available that can be used as a support to traditional rehabilitation therapy.
- To learn the different categories of devices developed for helping the recovery from several motor function impairments affecting, in particular, stroke survivors.
- To know that different solutions are included within each category, which are based on different approaches, even to reach similar rehabilitation goals.
- To know that some technologies imply a physical interaction with the patient (e.g. robotic-based training) while others provide less tangible interactions (e.g. virtual reality-based devices), even though both approaches are more frequently combined.
- To learn the main technological tools that can be specifically applied to improve function of either upper-limbs or lower-limbs.
- To know that technological support can be provided through either workstations with robotic mechanisms or wearable devices, such as electromechanical orthoses and exoskeletons.
- To know that technologies supporting rehabilitation that imply a physical interaction with the patient are mostly based on some biomechanical approach.
- To learn the characteristics of specific robotic systems known as "gait trainers", and how some of them work to assist walking restoration.
- To know that some important aspects of rehabilitation -as patient motivation and training duration- can be further improved by combining virtual reality tools and perhaps "serious gaming".
- To know which are the approaches used for robotic-based training and virtual reality tools, through a review of the most recent advances in these fields.
- To know that the technological approaches exploit training approaches traditionally used in rehabilitation.

2 INTRODUCTION

In this Session, we will give an overview of several technological solutions that can be used as a support to traditional rehabilitation therapy, with a special focus on the devices that are currently available for the rehabilitation of stroke survivors.

We will show that different categories of devices were developed for helping the physical therapists to improve the recovery from motor impairments due to stroke. A first attempt for differentiating such tools could be made according to the different aims that diverse devices seek to achieve. For instance, devices for recovering locomotion are obviously very different from those used to restore hand function. However, we will see that, within each category, different solutions exist that may be based on completely different approaches, even having the objective of reaching similar rehabilitation goals.

For the sake of clarity, we will separately focus on the two main categories of technological tools that can be defined according to whether they can be applied to improve function of either upper-limbs or lower-limbs.

From a technical point of view, a classification of rehabilitation tools can be made on the basis of their designs and mechanical characteristics. A description of some representative devices will be provided considering they can be grouped into stationary workstations, most of them implementing robotic mechanisms, and portable, wearable devices such as exoskeletons or electromechanical orthoses.

Obviously, not only the design and the electromechanical implementation of each system are relevant, but also how their use may affect other fundamental aspects of rehabilitation such as patient motivation, engagement and training duration. All these features can be increased, for instance, by combining virtual reality tools and serious gaming with the exercise training.

The entrance of the first technological devices in the rehabilitation field was boosted by the need to overcome some of the limitations of physical therapy. Thus, it is not rare that, from the beginnings of the application of robotic rehabilitation, most of the available devices strive to imitate rehabilitation methods based on principles of motor learning, which have evidence of associated cortical level reorganization. In effect, robotic training is based on task-specific training, also known as repetitive task practice, and constraint-induced movement therapy as well as task-related virtual reality techniques.

The link between the rehabilitation approaches used to treat post-stroke patients and the strategies underlying robotic- and virtual reality based training, will be more clear after reviewing the most recent advances in the field. We will include a description of specific robotic systems known as gait trainers, which were developed for assisting to restore locomotion in patients suffering from neurological diseases. Such devices combine treadmills and body-weight-support, two devices from the therapy practice, as well as virtual reality features.

A video related to this Session is also available to better illustrate some concepts and the categories of devices described here.

3 TECHNOLOGIES FOR STROKE REHABILITATION

In general, several technologies are used in the rehabilitation field, but considering the treatment of post-stroke patients, we can identify two main macro branches (Figure 1). The first branch includes all technological solutions based on electromechanical devices, generally dubbed robotic rehabilitation devices. This group includes all technologies that imply a physical interaction with the patient to provide a robotic-supported training based on a biomechanical approach. Instead, the second branch comprises all tools providing less tangible interactions with the patient, mainly including the devices based on virtual reality technologies. Actually, we will see that, after reviewing the most recent rehabilitation technologies, the boundary between these two branches is always less defined and many devices seek to exploit both physical and sensorimotor interactions to better support the rehabilitation process.

In the next sections, we will better define both robotic devices and virtual reality tools, and will describe the main features of some representative examples of both groups.

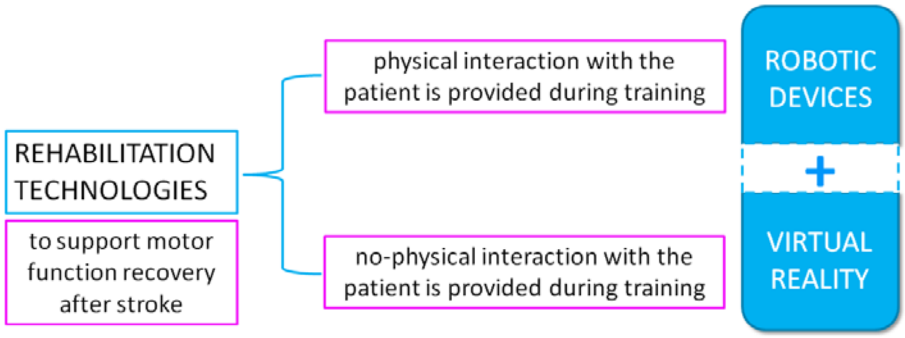


Figure 1 Rehabilitation devices for motor recovery- two main branches, whose features are frequently integrated in many available devices.

3.1 Robotic rehabilitation devices

In the rehabilitation field, robotic systems are the devices that automatically guide a patient through a series of specific motions, according to the orders given it by a physical therapist. By interacting with the patient in real-time, these devices should adapt their behaviour to patients' abilities in a transparent manner. A prescribed level of support should be maintained while restricting undesired or contraindicated movements, avoiding exercises that might cause any injury to the patient and, in general, preventing the patient from being exposed to any danger.

Certain types of robotic assistance could be limited to have beneficial effects for restoring certain types of tasks. However, it is always expected that the recovered features will remain even after robotic assistance is off and that robotic therapy will be beneficial in the long term.

To help the patient complete even simple movements, stroke rehabilitation typically advances toward active-assistive movements, in which a clinician uses physical cues and graded support to assist the patient. Robotic devices are properly designed to assist the clinician during this phase, because of their ability to consistently perform repetitive tasks that can guide the patient through specific motions. They represent a reliable option to the skilled therapist for performing repetitive movements without fatiguing, while simultaneously providing a proper level of patient engagement that otherwise may be difficult to achieve when performing repetitive physical activity. To this goal, robotic devices may include on purpose-designed software, virtual reality enhancements (which will be described in detail in a following Module) and perhaps games that transform physical activity into challenges that keep patients motivated and engaged with the rehabilitation. Moreover, rehabilitation devices can simultaneously collect objective, quantitative data that may be used for patient assessment to follow the rehabilitation process.

Further reading Iosa 2016, Weber 2018

3.1.1 Robotic-based training: principles and strategies

Robotic-based training focuses on using sophisticated electromechanical devices to better assist the patients during rehabilitation, through the application of proper forces specifically defined for the restoration of even complex movements. For doing this, different strategies may be used to timely apply such assistance forces. For instance, during exercise training, patients may feel relatively free to move, without feeling the assistance forces from the robotic device. Oppositely, they may experience relatively higher forces, which are intentionally applied according to the differences with respect to desired ideal movements; and perhaps, even unexpected robotic forces may be exerted on the patients to deliberately disturb their movements during training. These main differences reflect different robotic training strategies. On the basis of such approaches, different robotic devices may have different control algorithms implemented in their internal controller, which together with the necessary actuators must both be designed according to specific rehabilitation training strategies. Such strategies, in turn, may depend on the task characteristics and have an influence on the effectiveness of the robotic training.

Analogy between Robotic control and Human motor control

To better understand the principles underlying how robotic-supported rehabilitation work, it may be useful to draw an analogy between robotic control and human motor control. Some principles underlying the different robotic approaches are very similar to principles of human motor control. Human motor control is the process by which the central nervous system, by also including cognitive functions, controls the musculoskeletal system involved in the performance of every motor skill, from muscular activity to limbs coordination. The process of motor learning is thought to be controlled by two different mechanisms in the brain (Figure 2):

- feedback motor control,
- feed-forward motor control.

In the case of **feedback** motor control, the human motor system acts in response to sensory information about deviations from the planned movement, and modification of the ongoing movement and consecutive actions are adapted according to the errors or perturbations that were detected. As an example, the feedback control is typically used when continuous tasks are performed, such as walking or repeatedly reaching a target.

Similarly, robotic devices are equipped with different sensor typologies that detect patient's movement deviations and, consequently, provide feedback to their actuators to correct the patient movements.

Instead, **feed-forward** motor control responds in a pre-defined, predictive way according to internal information and possessed knowledge, which means that movement's adjustments are not error-based but are done according to the possessed knowledge that is used to predict the outcome of future actions. This control is typically adopted when discrete tasks are performed, which require fast movements and include well-defined postures at the beginning and the end of the task; for instance, tasks like reaching an object or standing up from a chair.

In this case, robotic devices have been programmed with predefined motion patterns- that can be customized in different manners-, and their actuators basically apply the necessary forces to move the patient accordingly.

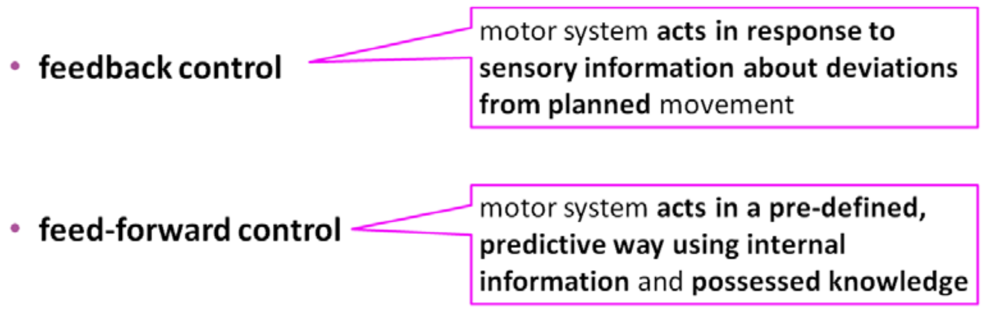


Figure 2 Main differences between both motor control approaches, which however may be adopted by combining characteristics of both processes, specially to reach an optimal level of movement control

Actually, optimal movement control likely involves a combination of both processes, and motor behaviours can occur along a continuum in the range from feedback to feed-forward. Also robotic control can also operate similarly, by integrating both pre-defined patterns and information from sensors to provide feedback about patient's movement. Moreover, since motor behaviours change during the course of skill acquisition, also robotic training strategies may adapt the support to the rehabilitation according to patient's needs.

It is important to point out that different brain areas have specific characteristics and may govern different motor control processes. Performing a task that requires mostly feedback motor control, or mostly feed-forward motor control, may require targeted training strategies to enhance the respective learning. To reach this goal, different robotic training strategies were developed.

Further reading Marchal-Crespo 2017b

Robotic training strategies

To force the re-learning process related to function recovery, some devices include advanced robotic training strategies, which were implemented to develop new rehabilitation paradigms.

The main robotic strategies used by many rehabilitation tools fall within the following two categories:

- No-Perturbation
- Error-modulating training strategies

No-Perturbation

When training with a no-perturbation strategy, subjects are free to move without feeling any disturbance or assistance force from the robot. A feedback control approach is used for the no-perturbation strategy, a "zero force" controller that minimizes the measured interaction forces between subjects and robot. The controller includes the compensation of the weight of the any robotic part that, interacting with the patient (for instance, an orthosis), may be perceived as a disturbance.

Error-modulating training strategies

In contrast, other strategies imply that some forces are intentionally exerted to affect the patient's movement, after they are being applied or perceived. Such strategies are called error-modulating strategies and, among other typologies, include the following two:

- **Error Amplification**

It is supposed that, when adapting a movement to a novel condition, the nervous system uses a process driven by movement error reduction (in this way, forces are anticipated according to an internal model of the environmental condition). The error amplification strategy is based on the hypothesis that motor learning could be accelerated by amplifying the differences related to this novel condition. A robotic system can apply this strategy by tracking the patient positions during movement; then, the differences between such measured positions and the desired patterns are used to generate new reference patterns by intentionally amplifying the previous tracking errors, aiming at accelerating the learning process.

- **Random Force Disturbance**

The idea behind the random force disturbance strategy is to force the patient away from the own "comfort zone" in such a way that the subject is always in charge of the generation of the movements necessary to correct the errors experienced because of the disturbances caused by the robotic device. The robotic control system applies unpredictable perturbing forces, while the patient is training, to create novel situations that otherwise would not been created. Such disturbing forces are randomly generated and last for very short time (tenths of second).

Further reading Marchal-Crespo 2017

3.1.2 Robotic rehabilitation systems - Robotic trainers - Robotic exercise devices

Many devices for robotic rehabilitation already exist, which can be either used as training exercise devices for restoring both upper and lower limbs or as assistive devices (in this case, they are also known as powered orthosis or neuroprosthesis).

We will focus on specific representative technologies to depict the diverse solutions implemented in different systems; therefore, this section is not intended as an exhaustive review of all available devices.

When available, the rationale supporting their clinical use for stroke rehabilitation will be reported to provide the trainer with an overall understanding of the field and its state-of-the-science.

Categories of Robotic rehabilitation devices

Most of the robotic rehabilitation systems used to deliver exercise-based treatments consist of relatively large workstation devices, which include an electromechanical part and integrated hardware and software for controlling it, as well as to provide visual feedback to the therapist and the patient.

According to the characteristics of their mechanical designs and, consequently, of the control methods used to operate them, the robotic workstations fall into the following two main categories (Figure 3 and Figure 4 some examples of each category, respectively for upper-limb and lower-limb rehabilitation):

- **end-effector** devices, rely on guiding the whole limb by applying needed forces through only one area of contact, located at the distal part of the limb, but always with the intention of moving the entire limb, if required to perform a desired motion. The first robotic technologies developed specifically for stroke rehabilitation were end-effector devices.
- **exoskeletal** devices, rely instead on directly controlling the movement of each segment of the limb by providing the forces needed to separately move them according to each independent component of the desired motion.

A further subdivision includes the **wearable** devices category; however, most of them can be included within the exoskeletal group, even though some others may act on one part of the limb only.

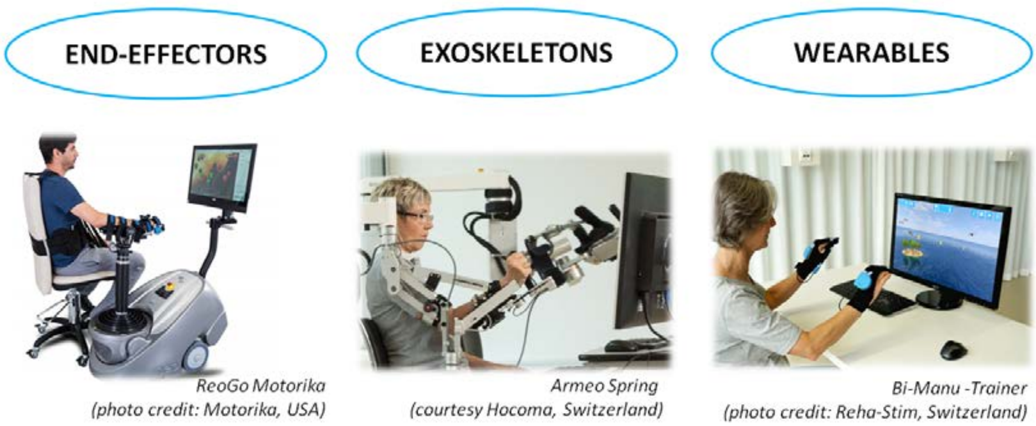


Figure 3 Some devices for restoring upper limb function, just to exemplify the different categories.

Both kinds of robotic devices exist for the functional restoration of either the upper limbs or the lower limbs in post-stroke survivors.

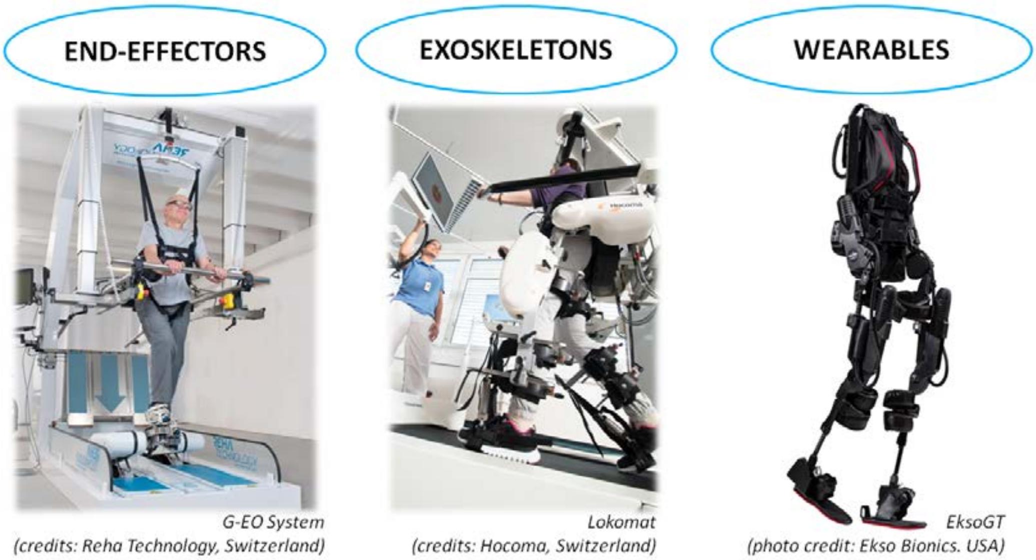


Figure 4 Some devices for restoring lower limb function, just to exemplify the different categories.

End-effector devices

An end-effector device for the rehabilitation of upper limb function may be fixed to the forearm with the aim of restoring elbow and shoulder joints movements. Because undue constraints of the limb segments are avoided, this approach allows assisting the arm motion in a more natural, unencumbered manner.

In general, end-effector solutions give the possibility to mechanically adjust the device to accommodate a range of patients in a simpler way.

Some practical aspects may hinder an end-effector robot to correctly support the limb movement, because of restrictions often present in neurologically-impaired limb, such as the presence of spasticity or joint contractures. In such cases, undesired compensatory movements often appear. For example, by moving forward the forearm to extend the elbow in a patient with severe spasticity or elbow contracture, an undesired compensatory flexion of the trunk may result instead of the desired movement.

More generally, freedom of movement provided by the end-effector design may be beneficial, but compensatory movement patterns may appear which may have a negative effect if not properly avoided.

Exoskeletal devices

In the exoskeletal devices, because a more precise control of multiple limb segments is possible, unwanted movement patterns are more easily restricted. However, to reach this goal, although the efforts made to design complex mechanisms and control algorithms, bulky mechanical parts are usually present. This is the case of the workstations currently used that implement an exoskeletal approach. These systems are large and unwieldy, and their moving parts have high mass and inertia, which may have an influence on movement fluidity and accuracy if compared with natural motions. To avoid these issues, wearable, powered exoskeletons are now being used also for the treatment of stroke survivors.

In the following sections, a detailed description of the technological solutions will be included, firstly for upper limb rehabilitation, then for the lower limb, including also gait trainer devices.

Further reading Weber 2018, Morone 2017

3.2 Technologies for upper limb rehabilitation

3.2.1 Devices for upper limb training

Concerning upper-limb function rehabilitation, robot-assisted exercises may be viewed as an alternative to therapist supervised training performed on a table top, except for the advanced features that technological devices offer, which create new opportunities that otherwise are not possible with conventional trainings.

There are several strategies employed by robotic systems to retrain movement after stroke. Some devices can either use simple games to encourage and guide movements, or integrate simulations of real-life tasks such as cooking or cleaning to create the perception of performing a functional task. An alternative strategy is to use wearable robotic devices to facilitate the performance of actual functional tasks. This can be conceived either as a training system to encourage restoration of motor abilities after removal of the device, or as an assistive device to assist the user on an ongoing basis. Devices designed according to this latter goal are sometimes termed powered orthosis, or also neuroprosthesis.

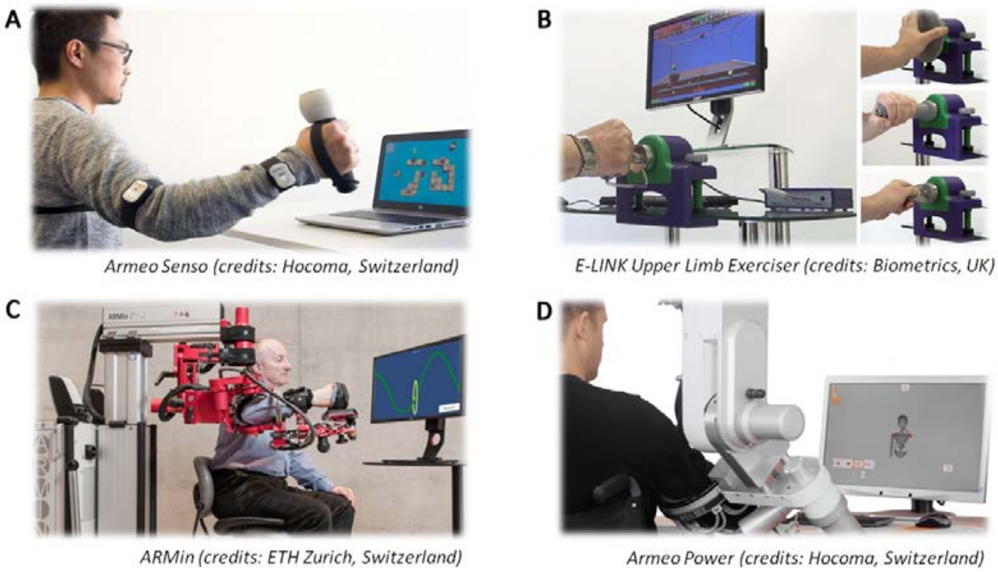
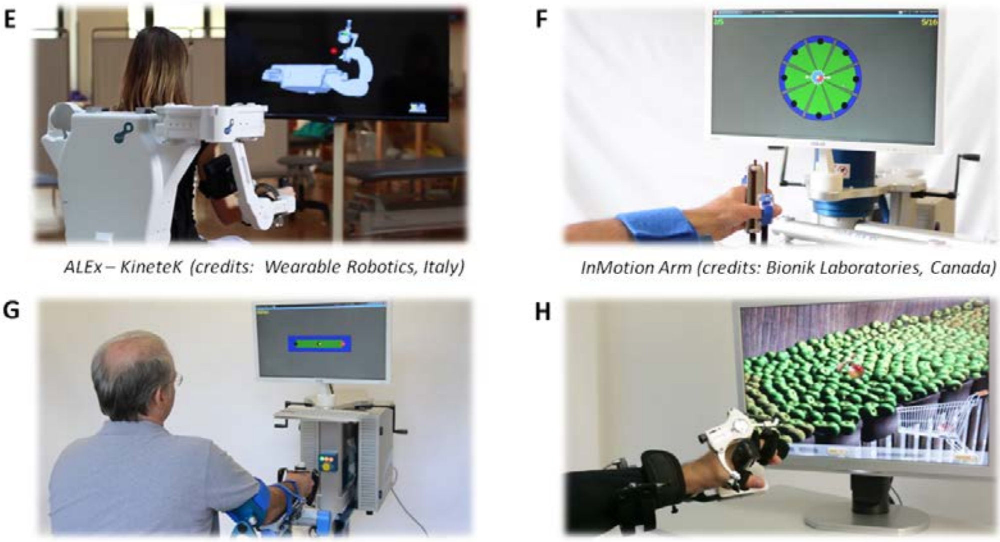


Figure 5 Examples of rehabilitation systems for restoring upper limb function. A) Portable device with wearable sensors. B) Compact tools with different manipulators. C) and D) Stations equipped with multi-segmental robotic arms.



E — ALEx – KineteK (credits: Wearable Robotics, Italy)

F — InMotion Arm (credits: Bionik Laboratories, Canada)

G — InMotion Wrist (credits: Bionik Laboratories, Canada)

H — Manovo Spring (credits: Hocoma, Switzerland)

Figure 6 Examples of rehabilitation systems for restoring upper limb function- Cont. E) Robotic system. F) Modular system for arm and hand grasping, G) Modular system for wrist training, H) Modular tool for training grasping and release.

In Figure 5 and Figure 6, some examples of available devices are shown. In this section, some of them will be described with the aim to illustrate some of their characteristics that may be helpful to better understand the rehabilitation technologies in general. Among the end-effector devices, we included the commercial version of MIT-Manus, because it is one of the best-studied end-effector robots for the upper limb (namely the InMotion modular series InMotion ARM, HAND and WRIST, Bionik Laboratories Corp, Canada) and the ReoGo (Motorika Medical, Israel). Instead, as an example of exoskeletal workstation, a description of the Armeo Power and Armeo Spring (Hocoma, Switzerland) will be included.

Although being used for research purposes, other devices exist that exploit different paradigms. As an example, we will show a system using mirror therapy to restore upper limb function in stroke people, namely the Mirror-Image Motion Enabler (MIME).

3.2.1.1 InMotion ROBOTS (Bionik Laboratories Corp, USA)

The InMotion is a suite of robotic rehabilitation products, which are the result of research and development carried out at the Laboratory for Biomechanics and Human Rehabilitation at the Massachusetts Institute of Technology. The InMotion ARM MIT MANUS is a modular system that consists of proximal and distal components, which can be used individually or combined for upper limb training. It includes a module for elbow and shoulder movement in the horizontal plane, shoulder and hand grasp in the vertical plane, and wrist movement in all planes. The device may use an assist-as-needed paradigm: by continually sensing the motion of the limb, movements can be initiated or completed to achieve a high number of movements according to predefined simulated tasks.

It is able to exploit a property of robotic devices very useful in neurorehabilitation, which is the capacity for measurement and immediate interactive response. In this case, by sensing the patient movement, this robot guides the training treatment accordingly, in response to the continually-changing ability of the patient. When the patient is unable to move, the robot gently assists the patient to perform the movement towards specific targets, which change according to the task to be restored. Moreover, in the case of coordination problems, the robot always guides the patient movements towards the targets, making certain that the training movements will be correctly practiced. As the patient gradually gains movement control, the robot will reduce the assistance, in order to continually challenge the patient. Meanwhile, the system is able to provide quantifiable feedback on treatment progress and patient performance.

3.2.1.2 ArmeoPower

The ArmeoPower (Hocoma, Switzerland) is a robotic exoskeletal workstation device for the rehabilitation of upper limbs (it is the commercial version of the ARMin device, as it was formerly called in published scientific works, developed by ETH Zurich, Switzerland). The device is a large workstation with an exoskeleton enveloping the arm of the patient, which can be adjusted for shoulder height and limb length. The device provides arm weight support, which offsets the weight of the device and a designated proportion of a patient’s limb weight.

The device may be used in various ways and with different control modes. For instance, an assist-as-needed mode can be selected to provide an optimal level of challenge during the different recovery phases. It offers both planar and 3D mobilization modes and functional training in the form of simulated activities of daily living or engaging games, to promote repetitive movement. Additionally, it is possible to stabilize specific joints during exercise, when a modular treatment approach is indicated.

The appropriate challenge level for each patient can be select by controlling the complexity of the visual field, defining the range of motion required, or changing the pace of gameplay.

3.2.1.3 ArmeoSpring

The ArmeoSpring (Hocoma, Switzerland) consists of an upper-limb exoskeleton for the repetitive training of goal-oriented movements, which guides the movements of the patient arm while providing a variable amount of weight support. The exoskeleton consists of a mechanism integrated with springs, which allows the rotations about 3 joints, having a total of 6 degrees of freedom. Thus, after being individually adjusted to the patient, it enables simultaneous arm and hand training in an extensive 3D workspace, even though safety zones can be created. This mechanism also supports the movement of the arm against gravity. The level of arm weight support can be adapted in order to enable the patient to correctly perform many repetitions of a task without using compensatory movements.

Several training exercises can be performed according to specific rehabilitation goals, especially to train activities of daily living. Movements are always initiated by the patient, who in this way is challenged to use its remaining motor function and facilitated by the device to repeat a higher number of movements.

Integrated software controls the exoskeleton and different parameters can be adjusted according to the therapeutic goal of each patient. Functional exercises are supported by game-based trainings that include virtual-reality environments. Moreover, several built-in sensors measure the patient's performance and provide a feedback to the patient. By recording the active movements at each joint during the rehabilitation session, an assessment of motor function and coordination of patient can be also performed to monitor the rehabilitation outcomes.

3.2.1.4 Mirror-Image Motion Enabler

The device Mirror-Image Motion Enabler (MIME, designed in the framework of a collaborative effort between the U.S. Dept of Veteran Affairs and Stanford University) is a "manipulator", a robotic arm that produces planar or 3D forearm movements for mechanically assisted exercise training of elbow/forearm.

Actually, this device exploits an industrial robotic arm properly modified to interact with the patient arms in a consistent manner. The forces applied by the end-effector device to guide upper-limb movements can be controlled by the patient through bimanual, mirror-image therapy: the manipulator mirrors the movement of the unaffected arm to the affected one. In a patient with hemiparesis, the robotic arm is attached to the affected upper limb by means of a forearm splint, which is connected through a force-torque sensor that measures the interaction forces between the forearm and the device during motion. Instead, the contralateral arm is attached, by means of another splint, to a digital position sensor able to detect the unaffected arm position that is used to control the movement of the robotic arm, properly mirrored in order to correctly move the affected arm.

Training exercises can be also performed unilaterally. In this case, the movements of the robotic arm can be controlled in different manners. The patient arm can be controller along many different trajectories, either passively (asking the patient to relax the paretic arm) or actively, the patient's attempts to move the paretic arm are assisted by the robotic forces, which can be applied to stabilize the limb or to complete reaching movements. Finally, in a different operation mode, the robotic arm can also provide some amount of resistance to the movements performed by the patient across the workspace. Several predefined tasks can be adjusted according to the rehabilitation goals and the recovery progression.

Further reading Burgar 2000, Gassert 2018, Hidler 2005

3.2.1.5 ReoGo

The robotic-assisted device ReoGo (Motorika Medical Ltd, Israel) was developed specifically for neuromuscular training of the upper limbs in patients dealing with the effects of neurological or orthopaedic conditions. It is a portable platform with a motorized end-effector robotic manipulator, which facilitates three-dimensional movements of the forearm or the whole arm, inducing the mobilization of shoulder and elbow joints. The training can be practiced in standing position or when the patient is seated in a special chair, which is provided with straps to be tightened around the trunk, for increasing stability, and over the affected shoulder, for preventing the patient from using compensatory movements.

This robotic manipulator can be used with different ergonomic supports for forearm, wrist only, or through a handgrip, including a mechanism (gyroscope) that allows for the combined rotations of wrist and forearm about three functional axes, making it possible to perform several kinds of exercises more naturally.

Its treatment modality is based on repetitive, guided neuromuscular training to enhance patient learning and promote functional recovery. Patient-specific exercises and engaging games are featured allowing the patient to restore movement through measured repetitive motion and biofeedback. The purpose of such exercises is to reach some objectives displayed on a screen, while providing visual and audio feedback. During such goal-directed movements, the range of the movement can be modulated according to the patient's range of motion. The supporting forces exerted by the device can vary from completely passive to completely active, according to the force level exerted by the patient on the robotic arm. The patient is instructed to actively reach predefined points by moving a pointer into each target displayed on the screen. When the patient is not able to reach a target point, the manipulator dynamically applies the assistance force necessary to lead the affected forearm towards this point. Target, directions, and patient's success are always displayed to provide visual and auditory feedback to the patient.

Further reading Siedziewski 2012, Bovolenta 2009, Treger 2008

3.3 Technologies for lower limb rehabilitation

In this section, after describing the rationale underlying the use of robotic-based rehabilitation, some examples of commercially available devices will be described, including both exoskeletal stations (also known as driven gait orthoses) and end-effector devices. Recently, wearable devices for lower limbs became also available, and are being utilized to support retraining locomotor function.

Among the examples of end-effector robotic systems already used for automatic treadmill therapy of stroke survivors, we will describe the workstations G-EO System (Reha Technology, Switzerland) and LokoStation (Woodway, USA). Instead, as an example of exoskeletal workstation, a description of the Lokomat device (Hocoma, Switzerland) will be included. Concerning wearable devices we will describe the EksoGT (Ekso Bionics, USA) and the Bionic Leg (AlterG, Inc, USA), both for recovering lower limbs function.

To conclude, we will give some details about known critical aspects of gait trainer systems and of the approach in general.

3.3.1 Rationale for Robot-Assisted Gait Training

Conventional treadmill training, by requiring the therapist to manually assist the patients, has several major limitations. Training duration may be limited either by clinical personnel shortage or by fatigue of the therapist -not by the fatigue of the patient-, because manually assisting the training is very labour intensive. To assist the movement of the lower limbs, prolonged unfavourable ergonomic postures are adopted by the therapist, usually leading to musculoskeletal discomfort and back pain. Moreover, when the patient movements are manually-assisted, the repeatability of the obtained pattern is low. Another limitation regards the lack of objective measures of patient performance, which are useful for assessing the rehabilitation progress.

Instead, by means of robotic gait trainers, consistent movements can be automatically imposed on the lower limbs which, in this way, can be moved according to predefined gait patterns, also customized to each patient. Movement consistency implies a better modulation of both the timing and the amplitude of muscular activity, activating appropriate afferent sensory input.

Robot-assisted training allows both the duration and the number of rehabilitation sessions to be increased. While improving the treadmill training for patients, a reduction of the workload and the number of therapists directly involved in each post-stroke patient treatment may be also achieved.

Further reading Riener 2005

3.3.2 Driven gait orthoses/Gait trainers (stationary workstations)

For retraining locomotor function, electromechanical robotic systems automate the assistance of the patient's leg movement during the gait cycle. Adequate afferent inputs are necessary to stimulate the locomotor centres within the central nervous system to activate the muscles that cannot be voluntarily moved. Optimal afferent inputs can be achieved if the limbs are moved in a rhythmical and reproducible, physiological manner. That is the reason why the assistance of leg movements during the training is of crucial importance.

Driven gait orthoses, and gait trainers in general, are a typology of stationary electromechanical system with a fixed frame, which appropriately assist the stepping movements performed by the patient on a treadmill or some foot-plates, overcoming the limitation of manually-assisted training that mainly relies on the ability and availability of physical therapists.

3.3.2.1 Lokomat

The Lokomat (Hocoma, Switzerland) is a stationary, driven gait orthosis, a device that applies automated locomotor training to patients with limited ambulatory abilities, allowing different parameters of gait and the degree of assistance of leg movements (namely, the forces and torques that are applied by the device to assist the movement of both legs) to be modified in order to properly influence the stepping training.

The main element of this system is an exoskeletal structure that is fixed to the lower limbs of the patient, which includes actuators to move the patient legs similarly to normal walking by applying the necessary torques, even in the case of spasticity and hypertonia.

More specifically, the structure of the orthosis consists of five rigid segments, namely, a pelvis and two limbs with two articulated segments each. In order to drive such exoskeletal structure, four motors, placed in correspondence with hip and knee joints, apply rotational motions in the sagittal plane only. The resulting torques at the knee and hip joints are measured by means of sensors integrated into the orthosis. Such signals may be used for controlling the limb movements, according to the interaction torques between the patient and the device, as well as for providing a feedback to the patient or for assessment purposes, allowing an estimation of the voluntary effort done by the patient.

This driven gait orthosis is used on a moving treadmill, which is integrated within the workstation, to take advantage of the moving belt. In effect, the motion of the treadmill belt controls the movement of the feet by providing the necessary forward propulsion during stance phase. Instead, dorsiflexion of the ankle joint during swing phase is achieved by means of a passive foot lifter (there are not active drives at the ankle joints).

The system also includes a harness for providing partial body-weight support. Moreover, it is provided with a pelvis supporting mechanism that ensures the stability of the upper body in the vertical direction during training. This supporting mechanism consists of a rotatable parallelogram that allows the upward and downward movements of the body that occur during walking while preventing tilting to one side. Because of this supporting mechanism, the patient does not feel the weight of the orthosis (about 20 kg).

The stepping movements are applied by controlling the legs in the sagittal plane only, and two control modes are possible. One control mode involves the guidance of the legs through predefined gait patterns in the range of physiological gait, and includes the possibility of adjusting both gait speed and step length. In the other control mode, guidance is provided by means of an adaptive algorithm that takes into account the patient forces to control the minimum torque needed just to keep the legs within a reference trajectory. By selecting the first approach, known joint motions are imposed, whose walking trajectories were recorded in a group of healthy subjects by means of motion capture methodologies. By changing gait speed and step length parameters, the training program may be optimized. Initially, satisfactory stepping movements were obtained mainly when the patients were unloaded by more than 40% of their body weight; otherwise, the affected leg usually touched the treadmill belt during swinging, even causing stumbling. To correct this issue, the original joint angles were changed to increase foot clearance during the swing phase. Updated trajectories were experimentally obtained while healthy subjects were walking with the orthosis over 3cm-height obstacles, considering in this way also the restrictions imposed by the orthosis during walking.

In stroke survivors, it is important to accommodate training for unilaterally affected limbs. The system provides the possibility to set separately the guidance for each leg. Asymmetrical settings may result in more complex effects due to the interlimb coupling, i.e. the activity of one leg depends on the guidance applied to the contralateral leg. So, specific neuromuscular activity in the ipsilateral leg may be regulated by the contribution of the contralateral leg.

In hemiparetic patients, unloading a part of their body weight during walking reduces unbalance and allows the patient to walk at higher speeds than overground.

In the advanced control mode, guidance is provided by means of a feedback controller, namely an adaptive algorithm that applies a controllable torque to each joint to keep the legs on the reference trajectory; in this way, reduced levels of guidance are set, allowing the patient to increase the effort done. If the lower limb position deviates from the reference trajectory, correction torques are applied according to the amount of such deviation. The position deviation can be calculated from the known reference position and a measurement of the limb position at each instant. The applied torque is immediately adapted according to this deviation and pre-specified system parameters (defining the so-called “impedance” of the system), resulting in smaller torques are applied to move the legs toward the pre-defined trajectories.

The reproducibility of the optimal trajectories can be maintained while the walking speed can be increased by the therapists, who are still needed to supervise the training session, to evaluate training effectiveness and to monitor patient progress.

The angular trajectories of hip and knee joints can be manually adjusted to each patient by changing amplitude and offsets. Concerning the pelvis movement, an optional module allows both lateral translation (within a range of +/-4 cm) and the traversal rotation (within a range of +/-4°).

The orthosis has to be adjusted differently for the training of different patients. Before using the device with a different patient, an adjustment to the anatomy is necessary. Then, the limbs must be fixed to the orthosis, with straps around the waist, thighs and shanks, and with the foot lifters around the patient's shoes. To properly assist the patient movements, each lower limb joint must be accurately aligned with the corresponding centre of rotation of the orthosis.

Several parameters can be modified to achieve an optimal fitting of the orthosis to the patient. To fit individual requirements, the following orthosis adjustments must be done:

- width of the orthosis at the hip level, moving the two legs apart,
- vertical and horizontal position of a back pad fixed with a band around the breast,
- length of the orthosis thighs and shanks,
- size and position of the leg braces that connect the orthosis legs.

These devices produce high forces and torques that are acting directly on the patient limbs, so the developers ensure appropriate precautions were made to ensure that the patients would not be injured.

Further reading Riener 2010, Colombo 2000, Jezernik 2003, Weiland 2018

3.3.2.2 LokoHelp

The LokoHelp-LokoStation Automated Treadmill Therapy (Woodway, USA) is an electromechanical system for automated treadmill therapy. It consists of a modular device that is fixed on a motor-driven treadmill in such a way that a wheel leans over the treadmill belt (the complete workstation is called LokoStation). This wheel works like a passive drive-wheel that is directly activated by the treadmill belt movement. In turn, an internal mechanism transforms the wheel rotation into a close trajectory and activates two levers positioned on each side of the device. Two ankle-foot orthoses are attached to the side levers for moving the feet-shank complex; thus the device is acting as an "end-effector" robot. More in detail, the internal mechanism sequentially transforms the belt movement into two synchronized tracks, one for each foot, which are properly phase-shifted to respectively imitate the gait phases of each leg and a simulation of walking on place is achieved by the planar trajectory tracked by the levers. Because the movement occurs in the sagittal plane and each leg is set into the brace that maintains the ankle joint angle at 90°, this mechanism do not completely achieve the degrees of freedom of a natural limb.

While velocity and cadence can be set individually, step length is fixed by the mechanism and is kept constant at 0.4 m.

The workstation includes a treadmill, that has an impact-absorbing surface and the option to be inclined, handrails and a support system, which must always be used in conjunction with the gait trainer. By means of a harness, the patient can be secured and if necessary partially relieved from the own body weight, by an initial offload of up to 30% of body weight; this value can be constant or dynamically controlled and can be progressively reduced until no unloading is applied. The harness system allows to set the trunk in a straight position or to correct the trunk inclination not only forwardly or backwardly but also laterally to provide asymmetrical support, by adjusting the two hanging points of the suspension straps.

This system delivers active-assistance according to its end-effector principle; it proceeds to move the foot-braces, as the last segment of a kinematic chain, according to a trajectory-tracking control. By still allowing to activate the lower limb muscles, knee and hip extensions should be ideally controlled by the patient. Though this feature might facilitate a relatively passive use, the patient should not be moved passively but, instead, should work along with the machine as much as possible shifting the load from the swinging leg to the standing one and oppositely.

The initial position of the centre of mass of the patient is important for allowing a proper hip extension, and can be adapted by using elastic belts attached to the side and front bars and.

Because of its design, most part of the patient limb are accessible from all sides during training, and physical assistance may be administered according to patient needs, for example, for controlling knee or hip extension during the stance phase.

Further reading Freivogel 2008, Freivogel 2009, Zhang 2017

3.3.2.3 G-EO System

The G-EO System (Reha Technology, Switzerland) is an end-effector robotic device for robotic-based locomotion rehabilitation. It can be used not only for gait retraining but also for restoring slope and stair climbing and descending, being currently the unique robotic workstation that allows to simulate the corresponding movements.

A simulation of walking movements (also backward walking) is generated from physiological gait patterns acquired by means of motion capture techniques available from published works. Another feature that is unique for this system is the possibility to generate a specific phase of the gait cycle as isolated stance, pre-swing or swing phases. By performing such partial-movement exercises, it is possible to improve stepping, especially during the first stages of the rehabilitation process. The kinematical trajectories related to the phases of the gait cycle have been defined according to published data.

Three operations mode (passive, active-assistive, active) can be adjusted according to different levels of impairment. Adjustable settings allow also to modify gait cadence and velocity, step length, ankle angle, horizontal hip activation and centre of mass movement, as well as the amount of dynamic body weight support.

When used in an active-assistive mode, it senses the patient’s efforts to overcome a pre-selected level of resistance, requiring the patient to increase the effort necessary to initiate the step movement. This mode is available on level walking and stairs climbing only.

An active operation mode enables the patient to self-initiate the gait simulation by overcoming a pre-selected resistance level, allowing a higher engagement of the patient.

The system offers different therapy modules that can be adjusted to patients with different levels of functional ambulation capabilities (ranging from score 0 to 5). Among others, Functional Electrical Stimulation (FES) for the enhancement of muscle activation through different stimulation channels, knee support through additional knee stabilization during knee flexion and extension.

A Visual Scenario is integrated for enhanced visualization of patient performance along with additional therapy options.

Further reading Hesse 2012

3.3.3 Critical aspects of gait trainer systems in general

A gait trainer device is essentially a robotic implementation of body-weight supported training, conventionally performed with the manual assistance of physical therapists. However, some evidence suggests that this training paradigm may not be optimal for the rehabilitation of stroke survivors.

Moreover, workstation robotic trainers are in general insufficient to simulate other real environments or in a natural context.

Many workstations are practically restricted to clinical settings because a direct supervision by a clinician is required during their use, and remain costly in the near-term. Switching from patient to patient often requires adjustments of various parameters due to differences in limb length and dimensions.

3.3.4 Lower limb wearable devices

In general, a wearable exoskeleton for the lower limbs can be described as a lightweight frame actuated at the main joints, normally hips and knees. Wearable exoskeleton devices used in rehabilitation are able to offer variable assistance and to initiate ambulation by means of integrated sensors that detect forward motion of the trunk or other similar solutions.

Most of the wearable exoskeleton technologies for the lower limbs have their origin in the spinal cord injury population, as these first devices were intended to restore ambulation to people with paraplegia.

3.3.4.1 EksoGT

The EksoGT (Ekso Bionics, USA) is a wearable, powered, bilateral exoskeleton provided with on-board motors for controlling both legs, to assist the sagittal rotations of hips and knees while patient support is provided for overground walking training. A backpack component contains battery and controllers. Stepping initiation can be controlled by the patient by means of sensors placed in the foot-plates that are able to detect the weight transfer from one leg to another. The amount of support provided to each limb can be adjusted to accommodate the individual needs. A walker or crutches should always be used for balance, thus hemiplegic patients should have the necessary level of upper limb motor function in at least one arm.

A predefined walking pattern is reproduced by the exoskeleton but it can be customized according to the patient. Several gait characteristics, like step length, stance phase duration and velocity can be adjusted; however, a fine-tuning of the exoskeleton settings that account for the functional condition of the patient is fundamental to achieve the best force assistance. Research is being performed to automate such procedure by using the neuromuscular pattern of the lower limbs collected with the surface EMG.

An upgrade to the device software has been released, which includes other activities such as step in place, weight shifting and squats, but this exoskeleton is not intended for stair climbing. However, the exoskeleton is intended for supporting ambulatory functions in clinical settings under the supervision of a trained physical therapist.

Further reading Baunsgaard 2018, Gandolla 2018

3.3.4.2 Bionic Leg

The Bionic Leg (AlterG Inc, USA) is a wearable, unilateral, battery-powered, lower-limb orthosis designed for neurological and orthopaedic rehabilitation. Despite of being a knee-ankle-foot orthosis with active assisting technology, the knee joint is the only one to be actively controlled (for this reason, it is also referred to as Robotic Knee Orthosis). Basically, the device actively supplements quadriceps function on the patient affected limb. Such knee mobility assistance can be adjusted and is provided during either standing or the stance phase with an assist-as-needed approach; instead, during the swing phase it allows a free movement. Actually, it also provides an appropriate resistive adjustment for controlled knee flexion, useful for increasing resistance to flexion during stair descent and stand-to-sit transfer. Stepping is initiated by the patient movement, thanks to internal sensors at the foot and knee joint that detect movement intention according to a force threshold (that is, a minimum force that must be passed to initiate device assistance). Then, according to the pressure measured from a plantar sensor and the angular rotation from a sensor at the knee joint, the device responds with appropriate assistance during locomotion, not only during walking but also stair climbing and descent, as well as transfers.

By supplying an additional force that act against gravity according to the movement, this powered orthosis enables the patient to engage the affected limb while the therapist supervises patient performance, leg positioning, symmetry and weight bearing.

Further reading Louie 2016, Iida 2017, Byl 2012

3.4 Introduction to Virtual Reality in the field of Stroke Rehabilitation

Virtual Reality is the simulation of environments, conditions and situations, where virtual objects, acting similarly to real ones, are shown to the users with the aim to resemble both existent and no-existent ones, allowing not only the visualization of real-life or hypothetical things but also their manipulation (virtually or actually by means of some tools) and the interaction with them in a more or less believable, natural manner.

As robotics, also Virtual Reality has been introduced in the field rehabilitation, in many cases combined with electromechanical tools, finding interesting applications for the treatment of stroke survivors.

The main features of Virtual Reality will be explained in detail in Module 3. However, to give an introductory overview about its use in many neurorehabilitation applications, it is worth noting its capabilities to create graphic simulations, displayed with sounds and/or voices to engage the patient, and to provide the patient with the sensation of moving through a world (simulated environment) in which there is a motivating goal and a sense of accomplishment. In this way, the patient is encouraged to play an active role that engages both mind and body simultaneously, while remaining in a safe, supervised environment. For instance, the patient can feel the experience of walking down a city street, stepping over objects or performing other tasks, while actually being in a clinical setting, walking overground or on a treadmill, perhaps placed in a safe suspension harness, and watching the displayed environment on a screen placed in front of the patient at eye level.

Virtual reality can be regarded as a novel rehabilitation strategy, an alternative to enhance motor recovery after stroke.

Beyond the technological aspects (which will be described in the Module 3), there are some aspects we will introduce here to allow you better understand their importance within a Virtual reality-based treatment: a) presence, immersion and involvement, b) providing feedback to the patient, c) tracking patient movements

3.4.1 Presence, immersion and involvement

By increasing the level of isolation from the real objects surrounding the user, and the fidelity level of virtual objects, a feeling of "presence" may be perceived by the user. Considering these aspects, virtual reality may have a different level of "immersion", ranging from non-immersive to fully immersive. However, true immersion is a relative concept: actually, it is that feeling of "being there" that sets a fully immersive experience apart, allowing to distinguish virtual reality systems from other multimedia experiences.

For instance, a fully immersive environment can be achieved by advanced features, which allow an empty room (with only ground, walls and ceiling) to be virtually transformed in one or more different places (such as the interiors of a building or imaginary landscapes). In this environment, even animated things or other real, tangible objects may also be present for giving a more accurate depiction of the simulated scenarios or more complete situations to be experienced (creating what is known as mixed or augmented reality).

Nevertheless, immersion is different from involvement -the personal ability to become deeply absorbed into what one is doing or one's environment. Users must direct their attention on the virtual environment in order to subjectively feel present in the virtual world; they do not have to exclude of the real world but to be less aware of events occurring in the real world around the user.

In the clinical settings, involvement is even more important than immersion. Longer and more intensive trainings are possible when patients are properly motivated and are able to enjoy while performing physical exercises.

Regardless of the hardware and display format, the capacity of virtual reality technology to create controllable, multisensory, interactive 3D stimulus environments, within which human performance can be motivated, assisted and also measured, offers clinical and research options that are not possible using traditional methods.

3.4.2 Providing feedback to the patient

To provide the person with some amount of feedback, the body weight-support or the treadmill may be adjusted in real-time according to the personal performance achieved, the body posture or other relevant criteria during movement.

By means of special devices, not only the interaction of the patient with the rehabilitation system can be more effective but also a variety of other forms of sensory stimuli can be delivered to the user, including touch sensations through special (haptic) devices. In this way, users can become virtually immersed within a simulated scenario that changes more intuitively because not only real-time images are displayed but also the sensations of touching solid objects may be given.

By recreating the sense of touch, haptic devices apply forces or motions that provide to the user a “force-feedback” or the sensations of resistance to motion while actually some features of the simulated task are being performed in a computer-generated, simulated world.

In the frame of virtual reality rehabilitation, such features can provide patients with additional feedback during training, increasing their motivation and allowing exercise difficulty to be dynamically adjusted to the individual performance.

3.4.3 Tracking patient movements

Virtual reality can be considered a form of human-computer interface that allows the interaction with dynamic digital contents in a more complex manner than with standard input devices like mouse, joystick or keyboard. A complex interaction may be possible by naturally tracking user activity by means of special gloves, exoskeleton devices or instrumented treadmills. Specialized motion capture technologies are used to sense the position of the patient limbs and to track the performed movements; this information is then used for a real time update of the sensory stimuli that create the illusion of being immersed in the virtual environment.

3.4.4 Categories: virtual reality stand-alone vs. virtual reality integrated within other rehab devices

The main characteristic of virtual reality is not limited by any specific technological approach or hardware set up; nevertheless, the type of virtual reality environment generated depends on the equipment and software used. Two categories of devices can be identified according to the integration with other rehabilitation devices or their use as stand-alone rehabilitation tools. But also the interaction of the patient with the virtual content may reach high levels. In effect, differently from traditional interface devices used with computers and gaming products that require very small movements (e.g. mouse and joysticks), more complex interaction devices are used to track more naturally the patient movements, which may be integrated within robotic arms, gloves, treadmills or exoskeleton devices, perhaps allowing to deliver multisensory stimuli. Also different forms of visual display technology can be used to deliver the virtual environment that creates the immersion through a continuum of visual stimuli. Higher levels of immersion can be achieved by means of a head mounted display (HMD) and the so-called “cave” (also known by the acronym “CAVE” Cave Automatic Virtual Environment). A CAVE is an immersive virtual reality environment created by means of several projectors, usually positioned outside a cube, where 360-degree scene graphs are directed towards its walls, and perhaps floor and ceil. These projections are controlled real time by the movements from a user inside the cube, recorded by a motion capture system. A 360-degree graph represents a complete scene as viewed when fully rotating about a central position.

Head mounted displays and especial stereoscopic LCD glasses can also be used to convey 3D scenarios. At each instant, two images are generated, one for each eye, according to the user’s head position and orientation detected by the motion tracker. Because of each eye only sees the proper image, a stereoscopic 3D view of the virtual environment is created.

The ubiquitous presence of displays in computers and console games systems, as well as of commercially available interface devices primarily used in the domain of entertainment, has promoted the access to a form of non-immersive media, where a 3D graphic environment is displayed on a flat screen or projected on large panels and the user can navigate and interact. Although being less-immersive graphic worlds, this approach can be still considered a basic virtual reality environment.

3.4.5 Considerations for rehabilitation

Specialized virtual environments for stroke rehabilitation are designed according to some rehabilitation principle, as those of motor learning and task-specificity training, and more generally, for inducing brain plasticity and motor recovery.

In some cases, virtual scenarios reproduce typical environments that are relevant from a functional standpoint, also replicating key real-life challenges. For stimulating patients to sustain more intense and specific trainings -central aspects for neurorehabilitation-, patient’s attention and motivation are also important matters to increase the effectiveness of virtual reality-based therapies. It is important to note that their effectiveness is not necessarily related to the level of graphic realism of the virtual scenario or its degree of immersion; instead, interactivity, feedback on the own performance and perceived user control are most important features, necessary to create greater patients engagement. To this purpose, an avatar may be embedded within the virtual environment, which not only helps to engage the patient to play a more active role but also serves as a training companion. Moreover, encouragement or congratulatory messages after achieving certain milestones may also be helpful for the patient to feel a sense of accomplishment.

Virtual reality-based rehabilitation, as well as interactive gaming used for rehabilitation purposes, has some advantages over more traditional training approaches as they can give patients the possibility to practice activities that cannot be normally performed in a clinical setting. Moreover, the engaging features of virtual reality usually lead the patients to spend more time in rehabilitation training.

Current uses of virtual reality in rehabilitation require a clinician to be present, as its application should be viewed as another tool that expands the expertise of the therapist.

Though the potentials of this and other emerging technology, it should be avoided an overexploitation of new technologies and it is important to note that it cannot be viewed as the solution of all rehabilitation issues.

Some caution might be needed in the readaptation to the real world, which could cause some patients to operate differently from unimpaired people. After leaving a virtual reality session, perceptual after-effects induced by virtual reality may be experienced like impaired depth perception. Thus, adaptation methods should be developed to let patients be at their pre-exposure levels.

Further reading Saposnik 2016, Wiederhold 1998, Lange 2012, Walker 2010, Deutsch 2017, Laver 2015

3.4.6 Virtual reality and e-Rehabilitation (telerehabilitation)

The application of virtual reality within a telerehabilitation framework allows to deliver rehabilitation to patients at home or in remote locations for independent use under professional guidance and supervision. Virtual reality interventions delivered over the Internet through a connection between a remote client using the system and a primary server at a rehabilitation facility allow the quantified tracking and analysis of patient performance by the rehabilitation professionals in charge of monitoring the patient. Virtual reality-based telerehabilitation offers many potentials, yet clinical, technical and ethical complexities still need to be addressed, which are beyond the scope of this course.

Further reading Rizzo 2005

3.4.7 Game-Based Rehabilitation

The borderline between virtual reality-based and game-based rehabilitation is often thin. Beyond games available as consumer products, serious gaming tools are being developed for stroke rehabilitation. For optimizing the patient experience in the rehabilitation context, some particular aspects of game design are considered fundamental. Patient must be aware of the game goals, must also know what actions need to be taken in order to achieve such goals and if they are achieved or not. Meaningful, clear feedback should be always provided in response to each patient action. The level of challenge must be suitable to the patient skills, neither extremely difficult nor ineffectively easy; otherwise, the patient could become frustrated or bored. Thus, the level of challenge of rehabilitation games should be dynamically adapted according to the patient performance. Finally, because of the high likelihood that stroke survivors experience failures during gaming, especially those severely affected by motor impairment, it is important to handle failures in a positive manner to avoid patient feeling discouraged.

Further reading Burke 2010

3.4.8 Low cost- entertainment off-the-shelf consumer electronic- Kinect

In the last years, a variety of systems are being developed by the entertainment industry for home use (for non-immersive video-gaming), making this technology less costly and more accessible for potential rehabilitation interventions, also in the neurorehabilitation field.

The use of off-the-shelf video games as training tools has gained interest in the rehabilitation field. Clinicians are investigating the use of available gaming consoles, like Xbox Kinect and Nintendo Wii Fit as rehabilitation tools with the help of researchers, who are converting existing games or developing new ones, for improving functional recovery of stroke survivors. Several free games are being converted to rehabilitation applications after associating each game action with a selected patient movement, which are also variable for easily grading the challenge level of each game.

Further reading Lange 2010, Boone 2017

3.5 New frontiers- Soft robotics

Currently, robotic rehabilitation devices mainly rely on rigid materials, not only because of their physical strength, but also because of their predictable response. In order to match more closely the physical structures and the characteristics of the human body, the use of new compliant materials is being investigated because they might offer some advantages in terms of patient safety, fit and mobility. For instance, the use of soft robotic materials in the rehabilitation field may enable more human-like joint function and enhanced adaptability for precise functional tasks, such as hand function. However, different difficulties must still be overcome to be possible to use these materials, which are extremely difficult to control.

3.6 Appendix- Classification of rehabilitation technological devices

For the sake of clarity, we grouped the technological tools according to their application to improve function of either upper-limbs or lower-limbs. However, the classification of the technological solutions used in rehabilitation, and more specifically, of the robotic devices for retraining impaired function, can be based on other different criteria, such as the following characteristics:

1. Location of application of the body (end-effector for whole arm, forearm, hand, or lower limb)
2. Application domain (rehabilitation or assistive device)
3. Function (reaching, grasping, walking, among others)
4. Degrees of Freedom DoF (number of independent rotations allowed at each joint, active DoF controlled by an actuator, constraints imposed to block some motions)
5. Control method (passive, active, active assisted as-needed, force, impedance)
6. Underlying training approach (repetitive task, constraint induced, mirror therapy, virtual rehabilitation)
7. Weight support provided (no supported, partial body weight support, fixed, dynamically controlled while patient is moving)
8. Method of actuation (actuated with motors, springs or passive joints)
9. Power (battery powered or no)

All these characteristics may be relevant when selecting the most suitable solution for treating different patient's categories or patients at different stages after stroke.

4 KEY IDEAS

- Several technological solutions are available and already used as a support to traditional rehabilitation therapy to assist, in particular, the recovery of motor function impairments affecting stroke survivors.
- Different categories of devices can be defined according to several criteria. However, different solutions exist within each category, even to reach similar rehabilitation goals different devices may be based on different approaches.
- The technologies that imply a physical interaction with the patient are based on applying forces or movement patterns, which may be predefined according to some biomechanical approach.

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- In addition, virtual reality-based devices are able to provide another kind of interaction, especially if stand-alone systems are used without any robotic mechanism. However, most of the robotic-based systems currently include some sort of virtual reality-based technology, from displaying basic scenes to advanced systems, which are integrated to further support the rehabilitation process.
- Technological tools can be specifically applied to improve function of either upper-limbs or lower-limbs. Consequently, the application of each device is limited to support the restoration of specific motor function.
- Technological support can be provided through either workstations, with robotic mechanisms, or wearable devices, such as wearable electromechanical orthoses and battery-powered exoskeletons.
- The “gait trainers” are specific robotic systems designed to assist walking restoration. Some of them are based on electromechanical orthoses; others are based on end-effector approaches. However, both categories are optimized to perform a task-specific, repetitive training that can be adapted according to the patient’s rehabilitation needs.
- By means of virtual reality tools or serious gaming, other important aspects of rehabilitation, such as patient motivation and training duration, can be further increased with the aim to improve the treatment effects.
- While some technological solutions exploit training approaches traditionally used in rehabilitation, new paradigms may be also employed, also for research purposes to further improve the knowledge of some rehabilitation mechanisms.

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