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Human-robot interfaces in exoskeletons for gait training after stroke: State of the art and challenges

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Abstract. Robotic rehabilitation of CVA (stroke) survivors is an emerging field. However, the development of effective gait rehabilitation robots used to treat stroke survivors is and remains a challenging task. This article discusses existing approaches and gives an overview of limitations with existing wearable robots. Challenges and potential solutions are being discussed in this article. Most difficulties lie in the implementation of physical and cognitive human robot interfaces. Many issues like actuation principles, control strategies, portability and wearing comfort, such as correct determination of user intention and effective guidance have to be tackled in future designs. Different solutions are being proposed. Clever anthropometric design and smart brain computer interfaces are key factors in effective exoskeleton design.

Keywords: BCI, exoskeleton, lower extremities, rehabilitation, state of the art, stroke, top-down approach

1. Introduction

Since a couple of decades cerebrovascular accident (CVA), also known as stroke, is on the increase. Implications in stroke survivors range from loss of functions over cognitive symptoms to motor control problems. Motor control problems have an impact on muscle strength, joint coordination or proper timing of different muscles amongst other. Most stroke survivors are hemiplegic and show asymmetrical gait pattern. A common method used to improve gait is repetitive gait rehabilitation training over several months. It could be proven that task-specific repetitive training in conventional rehabilitation therapies is beneficial [23].

Rehabilitation not only improves autonomy, which is an important quality of life, but amongst other also improves the condition of the cardiovascular system, maintains muscle strength and prevents bone deterioration induced by a lack of motor activity. [lagoda 2010] Gait recovery has been stated as a major achievement for increased quality of life in stroke survivors [31, 34]. This article focuses on rehabilitation of lower extremities in order to improve gait pattern in stroke survivors.

Recently new technologies in the field of robotic rehabilitation have been developed. There are some robotic systems available to rehabilitate upper extremities but only few to be used for the rehabilitation of lower extremities. These systems can be designed to be used whether stationary (non-ambulatory) in combination with a treadmill and a bodyweight suspension system, or ambulatory where the system is completely attached to the user thus allowing for level-ground walking. Most commercially available systems for gait rehabilitation work are non-ambulatory and up to this date the authors are not aware of ambulatory

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gait rehabilitation systems designed for stroke survivors. The design of ambulatory exoskeletons requires lightweight but in the same time powerful systems. These contradictory requirements might be the reason why no commercially available systems are available yet. Furthermore, it is not clear which one of a set of possible treatments is the optimal one to restore gait function in non-ambulatory conditions.

Originally rehabilitation robotics for gait training have been designed to allow for repetitive training over longer therapy sessions. However, no persisting improvements in gait pattern could be detected. At the beginning of the training the patient could improve gait pattern, but after a couple of weeks the performance stagnated or even worsened. The main problems have been identified to be due to the passive role the patient was given during training, the lack of task-specific training in ambulatory conditions or even at home and the user's evanescent motivation and thus concentration during therapy.

Rehabilitation robotics have been adapted and tried to counteract these problems, mainly by allowing the user to deviate from predefined trajectories, providing visual and force feedback, and assisting as needed which means that in phases of gait where the user does not require assistance the robot would behave in a passive manner. Still real breakthroughs in rehabilitation results failed to appear.

The inadequateness of providing effective results in rehabilitation could be explained by the difference of the user's intention and the robots predefined trajectory, and the occasional absence of the user's focus on his lower limb motion during gait. Concerning the intention evaluation, different methods have been tried, e.g. online force measurement during gait but could not show significant improvements. A new way of providing an effective rehabilitation robot would be to "look" into the user's neural activity to assess the intention and then apply an adequate action at the robot's end-effectors that not only might allow the patient to walk in a more efficient way but also result in increased activation of the cortical areas engaged in neural recovery. The user's lack of attention should be identified and the therapist should advert the user to focus on training. Effective walking does not necessarily imply that impaired persons will gain a natural normal walking as in unimpaired persons. The newly learned gait pattern might resemble normal gait pattern but is adapted to the abilities and needs of the impaired person.

2. Approaches in wearable biomechatronic exoskeletons for rehabilitation

In this section a few existing rehabilitation exoskeletons will be analysed, whereas in the next section open issues and possible solutions will be discussed. There are many more exoskeletons in research. Our goal is to discuss possibilities for improvements in existing and future designs based on the analysis of the most relevant and promising approaches. Basically wearable robots can be divided into two main categories: human enhancement technology (HET) and robotic rehabilitation devices. The latter can be used to whether assist weakened muscles, to preserve and protect human joints or to rehabilitate people, as the name implies [22].

In gait rehabilitation different physical human-robot interface systems are used. These systems can be end-effectors [52, 24], anthropomorphically [14, 60] or non-anthropomorphically [47] shaped wearable robots. A wearable robot (WR) is a mechatronic system that is designed around the shape and function of the human body in order to perform different tasks. An anthropomorphically shaped robot, worn by a user in order to assist and to work analogous to the user's movements, is referred to as a wearable biomechatronic exoskeleton (WBE).

In general robotic rehabilitation systems can be classified into physical human robot interaction (pHRI) and cognitive human robot interaction (cHRI).

A cognitive human robot interface (cHRi) supports the bidirectional flow of information between the human and robot, originating from interaction with the external world. Information is any type of variables (e.g. electrical signal, proprioception, visual perception) required for control and feedback of the WBE [44].

A physical human robot interface (pHRi) supports bidirectional flow of mechanical power between the human and robot in order to interact with the external world. Any type of force interaction or motion must be possible without impeding or endangering each other [44].

2.1. cHRi

Robotic therapy in post-stroke rehabilitation promotes motor learning that is relevant for recovery. It is well known that the efficacy of the human-robot interactions that promote learning depends on the sequence

of actions either imposed or self-selected by the patient. There are two main challenges in current AAN strategies: on the one hand, the adequate definition of the desired limb trajectories that the robot must generate to assist the user in space and time during exercise. This problem has been partially solved in some robotic rehabilitation systems with the use of so-called supervised learning approaches that pre-determine reference trajectories [64]. On the other hand, improved biofeedback methods are required to inform the degree of participation of the patient with more reliability.

Recently, force-based biofeedback methods had been proposed in a gait rehabilitation robot [36] in which biofeedback values per each gait cycle are used to characterize the degree of activity of the patient. Relying exclusively on the robot's sensors to extract the interaction forces for the biofeedback has a number of drawbacks, e.g. low sensitivity. Force sensors at the location of the interaction forces are not suitable as a number of forces are not detectable. It is unknown if sensitivity can be increased by increasing the number of sensors. Forces applied by the patient might be absorbed by the exoskeleton and are not detectable by the force sensing.

2.1.1. AAN

Since a couple of years some rehabilitation devices are based on the assist-as-needed (AAN) strategy [10, 11]. This strategy requires the user actively participate and the robotic device only assists or corrects the motions of the user. The AAN strategy is intended to lead to simultaneous activation of efferent motor pathways and afferent sensory pathways [18]. This is a prerequisite for cortical reorganization and thus the cornerstone for successful learning during gait rehabilitation.

In [18] it is looked into AAN as an optimization problem of a controller for gait training. The main goal is to retrain the swing-phase while minimizing the deviation of a reference trajectory and assistive force during training. An intelligent controller has been developed, capable of adapting automatically to the user's magnitude of assistance required during the whole rehabilitation process [18]. The assumption is made that the human resists applied forces by internally modelling the force and then counteracting appropriately to it. It is hypothesized that the human thereby uses an error-based learning controller. In robotic control it is tried to copy this adaptive strategy. The robotic controller takes the form of an error-based learning controller with a "forgetting factor" comparable to the human motor controller. Regarding AAN gait training, the "forgetting factor" reduces assistance in function of the measured trajectory error. The robotic controller is able to adapt to varying gait profiles and tune levels of assistance. One way of implementation is the use of impedance control [28]. The stiffness and the position of the actuator's output will be chosen in function of the current position error or can be manipulated manually by the therapist [60]. In case the patient wants to move freely the output impedance is set to zero, referred to as zero-impedance control mode. This type of control has been implemented in several devices [17, 53, 59, 60].

Similar patient-cooperative control strategies have been developed, called "force-field control" [4] or "path control" [17]. Both methods use a virtual environment to influence the timing and impedance of the limb movement [4, 17]. The user tries to follow a path whereas the motions are executed in a "virtual tunnel", superimposing the original path. This tunnel limits the path error by increasing the impedance or an assistive force to push the limb back to its original path [5, 10, 17]. At the moment these strategies are being tested in different studies [4].

2.1.2. Biofeedback

Visual feedback has been integrated into the driven gait orthosis (DGO) Lokomat [7]. In the past the Lokomat used to move the patient passively. When acting passively, muscle activity is reduced during rehabilitation and thus neuro-plasticity is not triggered.

Now the magnitude of robotic assistance of the DGO is regulated via force measurements on the lower limbs during gait. Biofeedback values are displayed on a screen to show the patient's degree of participation. The visual feedback together with the adapted assistance shall motivate the patient to participate actively during rehabilitation sessions. It has been shown that visual feedback correlates well with the degree of activity of the patients. Patients prefer to have visual feedback compared to not have it.

Some researchers use ground reaction forces as a biofeedback source [25, 26]. The centre of pressure is determined during gait and used to adjust the assistance during the rehabilitation procedure.

EMG is most often used to investigate which muscle groups are active during rehabilitation. Beside of HAL 5 [21], no rehabilitation device has been reported using EMG to control the exoskeleton. However, relying only

on EMG signals with stroke patients is not a reliable method as spasms will induce strong EMG signals. Thus the system is not able to differentiate between voluntary and involuntary motion.

Human physiology and biomechanics are still not completely understood. Generating models of the sensory motor system is therefore rather difficult. This might also be the reason why robotic controllers for rehabilitation devices do not rely on "artificial" intelligence yet.

2.2. pHRi

For the pHRi several aspects have to be taken into account. When starting to design a wearable robot it has first to be looked into which joints of the robotic structure shall be articulated passively or actively. Thereafter it can be looked into suitable actuation principles. A next step would be the anthropometric design of the exoskeleton suit. Alignment of joints, body fixations and quick donning and doffing are major issues. During the design process it has to be looked at the right power to weight ratio, low inertia and low weight of the exoskeleton frame in order to allow for maximal portability.

2.2.1. Physical DoF/RoM

When designing a WBE, the first question that needs clarification is which joints and how many degrees of freedom (DoF) need to be covered by the exoskeleton. The Lokomat [14, 33] and the Reoambulator [38] are non-ambulatory exoskeletons which offer four DoF, i.e. hip and knee flexion/extension on each leg. The four DoF on the leg are actuated. In addition they offer two DoF for vertical and sideways body motions to compensate for pelvis tilt moving the body up and down. Additional DoF are unsupported or completely blocked.

Non-commercial exoskeletons like the LOPES [59, 60] or ALEX [1, 5, 6] offer more DoF. In addition to the hip and knee flexion/extension, those devices offer DoF for hip abduction/adduction and 3D pelvis motion. ALEX also offers a passive DoF for plantar/dorsal flexion of the ankle.

A second issue is the correct range of motion (RoM) for the covered DoF. Existing rehabilitation exoskeletons provide a similar RoM as found during natural gait at normal walking speeds, which is a logical choice.

The next point to clarify is which of these DoF need to be actively controlled. Normally actively supported DoF are found in the sagittal plane as those DoF require most energy when looking at biomechanical data. In LOPES hip abduction/adduction is also actively supported. On the other side most exoskeleton designs omit active actuation of the ankle, even though biomechanical data shows the largest energy peak at plantar/dorsal flexion. If taken into account, as in ALEX, the ankle only plays a passive role in the sagittal plane at which its other DoF are blocked. The Lokomat and LOPES use straps around the foot and suspend it to the lower part of the exoskeleton in order to guarantee for foot clearance during the swing phase.

2.2.2. Ergonomics

The number of articulated joints and DoF in an exoskeleton does not require matching the number of joints and DoF in the human covered by the robot, but depends on the tasks, the exoskeleton shall fulfil. Another factor to determine the number of DoF is to assure that the human can move unconstrained. In addition force needs to be transferred appropriately. A WBE can be considered as a directly coupled mast-slave system. In master-slave configurations the number of DoF of the master should match the DoF of the slave for optimal control [50].

On the other side when designing for WBE, imitating human limb kinematics, human and robot joints must be aligned perfectly [44, 50]. However, aligning human and robot joints is a difficult task in order to guarantee for optimal function and to prevent discomfort, slipping skin sores and damage to human joints [44, 50]. One way to compensate for misalignments and its drawbacks is the use of flexible straps as applied in many devices. Good alignment of joints is still required as straps can only compensate for small misalignment.

The overall mass and inertia felt during motion are other aspects which have to be taken care of. Low inertia is important for zero-impedance control of the exoskeleton amongst other. The centre of mass (CoM) should be as proximal to joints as possible. These and other aspects have led to recent exoskeleton designs like the LOPES which tries to minimize the overall weight of the wearable robot and decreases inertia by displacing heavy components, e.g. actuators, from the frame to the environment.

2.2.3. Actuation approaches

In most existing exoskeleton designs, e.g. Lokomat, Reoambulator, electric direct drives and brushless

dc-motor gearbox combinations are mainly used. The ease of control and the possibility to create compact actuation principles are the main reasons for their popularity.

In some non-ambulatory exoskeletons, e.g. Gait Trainer [24] or Haptic Walker [51], a combination of linear electric drives coupled with slider-crank mechanisms and electric rotational motors simulate different gait pattern. These systems are extremely heavy-weighted and are not suitable for zero-impedance training due to their inertia.

Pneumatic actuators, e.g. pneumatic artificial muscles (PAM's), are being employed in many WR projects [15, 19, 57]. They offer a relatively large power to weight ratio of several kW/kg and are compliant. The major problems with PAM's is the valve control and the need for pressurized air which requires compressors, thus limiting portability [16, 58]. Moreover the accompanying noise during venting must not be underestimated, causing severe distraction of the user.

Hydraulic actuators offer large forces at a better power to weight ratio than pneumatics but in general need relatively heavy-weight compressors. For instance the BLEEX uses linear hydraulic actuators [12, 65, 66].

2.2.4. Actuator power

The actuation power requirements for human walking, especially for rehabilitation, can be estimated by looking at average lower limb gait data including torque, power and motion range plots [63]. The gait data serves as a base to characterise actuation requirements. Time integrals of the power curves are useful to establish phases of energy generation and absorption throughout the gait cycle.

2.2.5. Actuation control

The most predominant control approaches in rehabilitation devices are position control, impedance control or force-field control.

Position control used to be implemented in different rehabilitation robots. This method moved the user's limbs, leaving the user in a passive role. Due to this passivity no progress in gait rehabilitation could be determined and this control approach has been discarded.

In a directly coupled master-slave system like rehabilitation robotics most often impedance control is applied, e.g. Lokomat, LOPES. It is possible to adjust continuously the amount of support, in other words the actuator impedance, during training when the user follows a trajectory. Alternatively when the impedance is set to zero the robot simply follows the user's motion.

Impedance is the relation between actual trajectory position and actuator output force. Deviations from the actual trajectory position result in corrective forces. The magnitude of the force depends on the preset impedance and the extent of trajectory deviation [29].

The impedance controller operates as the higher level controller which tries to control the impedance of the actuator. The actuator's output position is measured and an output torque is generated. The lower level controller, i.e. the torque controller, monitors and regulates the output torque. Hence the quality of the impedance controller depends on the accuracy of the position sensor and the bandwidth and accuracy of the torque sources [35].

The force-field control, which is based on varying impedance control along a predefined trajectory, seems to be a promising strategy in order to rehabilitate stroke survivors. A so-called "virtual tunnel" is created in which the user moves the lower limb. This force-field based tunnel provides sufficient proprioceptive feedback and is thought to improve the outcomes of gait rehabilitation [4].

3. Challenges in post-stroke rehabilitation robotics

3.1. cHRi

Previously it has been stated that there are three main challenges in robotic rehabilitation regarding cHRi at the moment. The first one is the adequate generation of an effective gait trajectory. This trajectory needs to be created for each user at different gait speeds, still allowing for deviations in space and time. The second challenge is the measurement of the user's attention, which gives information about the degree of volitional participation during each session. Looking at the amount of patient cooperation through, e.g. force measurements, does not directly give an estimate of the level of attention, which is related to the degree of cortical reorganization. However patient cooperation is an important factor and leads us to the third challenge: correct HR force interaction measurement. When trying to measure the force interaction it must be ensured that forces do not bypass sensors and crucial information is not available for control. Regarding

these challenges different approaches relying on Brain Computer Interfaces (BCIs) could be useful.

3.1.1. BCIs and robotic neurorehabilitation

BCIs might constitute new means to improve current AAN strategies for robotic-based gait training. BCIs are devices that translate direct measures of brain activity into messages or commands and provide the patient-end user with real-time feedback. Thus, BCIs have the potential to improve AAN controllers for gait training by demanding neural control within the involved cortical network. BCIs also include systems that rely on: passive monitoring (which might assess motor intention without providing real-time feedback); information derived from the peripheral nervous system (such as peripheral action potentials that might directly trigger muscle flexion); and indirect measures of neural activity (such as EMG).

Most BCIs rely on electroencephalography (EEG) to measure brain activity, while other imaging approaches have been used with BCIs, such as fMRI, NIRS, and invasive methods [64]. Invasive methods are not well explored, and entail serious drawbacks such as the need for neurosurgery or expensive, non-portable equipment, although early BCIs focused on simple applications like spelling or cursor control [64]. More recent work has clearly shown that BCIs can also control rehabilitation robots such as a wheelchair, orthosis, or robotic arm, [13, 20, 41, 42]. Due to those application successes it is thought that BCIs are a viable solution in exoskeleton control.

3.1.2. Detection of motor planning for motor control

Recent studies are revealing cortical areas which are crucial for the control of human gait, and evidences suggests the existence of a direct relation between performed movement (lower limb joint flexion/extension) and measured cortical activation [62]. Furthermore, the analysis of information of motor planning in slow cortical potentials might be related to movement preparation, initiation and finalization. In addition, the use of correlates between EMG-EEG activity (e.g. analysis of cortico-muscular coherence) can be regarded as a potential methodology to distinguish higher control mechanisms in bipedal gait, that can be useful to close AAN loops to correct involuntary or weak activation during training.

3.1.3. Measure voluntary/involuntary motion, ERD and compliance

Spasms do not produce the same EEG activity pattern as voluntary, planned movement intentions. Hence, if EMG activity indicates movement but EEG activity shows that this movement was unintentional, the patient may be having a spasm. Such information can be complemented with other information, such as joint kinetics and kinematics, in order to determine the degree of deviation with respect to a range of normal trajectories. The EMG-EEG activity then can be used to verify the nature of the spasticity (dominant frequency components) and to evaluate the temporal response of a filtering algorithm. This information could improve therapy in real time, and also provide more accurate information about real vs. unintended movements to improve control of rehabilitation robots and post hoc analyses of therapy.

Many BCIs rely on event related desynchronization and synchronization (ERD/ERS), which are changes in rhythmic brain activity that reflect movement imagery. Such types of BCIs might be useful for controlling robotic stroke rehabilitation systems. Due to research with ERD-BCIs, scientists now have a fairly good understanding of how the brain manages actual, intended, and perceived movements [40]. EEG measures can distinguish movement preparation vs. execution, identify which part(s) of the body someone is thinking about moving, and measure the intensity of movement imagery. Studies have shown that ERD/ERS activity can be recorded in stroke patients and even used to control orthoses or other devices [9]. It should be possible to use EEG measures to assess compliance during robotic stroke therapy by determining whether patients are indeed focusing on movement imagery and making a strong effort to follow a given trajectory.

Finally training with ERD activity may also help assess and predict the effectiveness of stroke therapy [43]. ERD measures can reveal hidden partial recovery at brain level that can be useful to motivate and reengage an unmotivated patient. Furthermore, if therapy is not effective, ERD measures might provide a better understanding of what is wrong and thus help therapists identify changes that could improve therapeutic outcomes.

3.1.4. HR force interaction

The correct position and implementation of force sensing in exoskeletons remains a challenge. One

way to solve this problem could be to partly shift the cooperation measurement problem from a force measurement-based approach on the exoskeleton frame to a force-based measurement triggered by position differences between the human limb and the exoskeleton limb. This can be implemented by using force sensors directly on the joint. Forces, originating from position differences, cannot be bypassed. One example of application is SEA. This force measurement system is relatively easy to implement and sources of error can be reduced to a minimum. For rehabilitation purposes direct interaction force measurement is not required in order to estimate if the user follows a trajectory. Direct force measurement might only remain important during ground contact. Detection of ground reaction forces is less problematic than human robot interaction forces. In this case the term human refers to the user or the therapist.

3.2. pHRi

3.2.1. DoF and RoM

Kinematic compatibility is a crucial factor in designing wearable robots. The number of articulated joints and DoF in an exoskeleton does not require matching the number of joints and DoF in the human covered by the robot, but depends on the task the exoskeleton shall fulfil. Another factor to determine the number of DoF is to assure that the human can move unconstrained. In addition torque or force needs to be transferred appropriately. In master-slave configurations the number of DoF of the master should match the DoF of the slave for optimal control [50].

The ankle joint is one of the most important joints in rehabilitation. The foot provides significant feedback during stance. The pressure on the foot tells the human if the body is balanced. Furthermore different gait cycle phases might be triggered by proprioception and ground reaction force feedback. Rehabilitation with body-weight compensation, resulting in no ground reaction forces, is proven to be inefficient [32]. It is crucial to train the ankle actively, at which the user learns to stabilize the foot. The ankle should be taken into account when designing exoskeletons.

The constraints imposed by the lower limb exoskeletons should not limit those degrees of movement that enable error signals that are crucial for the recovery.

3.2.2. Ergonomics in anthropometric designs

Regarding the alignment of joints, this problem could be solved by increasing the number of DoF. The DoF must be larger than the number of DoF in the human limb. Thus this redundant system can compensate for misaligned joints. On the other side controlling all DoF and transferring loads will become problematic.

This problem can be avoided by increasing the number of DoF. The DoF must be larger than the number of DoF in the human limb. A system with a redundant number of DoF can compensate for misaligned joints. In [56] a double-parallelogram mechanism is presented which allows torque transmission between two segments of a limb while the involved HR joints can be misaligned. Another option would be the use of stretchable materials in combination with a mechanism which together could compensate for the misalignment of both joints. The disadvantage of such systems is that a flow of force to the environment (the floor) will not be possible, in order to exchange forces during push-off and for exoskeleton weight compensation.

Quick and accurate alignment of joints remains a problem in future exoskeleton designs, even though elastic straps can dynamically compensate for some misalignment.

An ergonomic connection between the robot and the human has to respect the properties of the human tissue. Some spots on the human limbs are very sensitive to pressure. It needs to be avoided to design exoskeletons which connect to those spots. Moreover shear forces on skin can become painful. The relationship between pressure and comfort is complex and has not been identified accurately yet [44].

The materials used to couple the HR system have to be soft and should not restrict the micro-climate on the skin. The use of breathable and "micro-climate friendly" materials is necessary.

It is also of interest to put the connections to the human limb as distal as possible in order to increase the moment arm for the mechanism, which makes it possible to decrease the actuator torque needed. Making connections non-rigid increases the comfort, but makes control difficult as stiff connections are required in order to determine the right force on the limb [58].

3.2.3. Actuation principles

Copying the human muscles-tendon system would be a straightforward way to create a useful actuation principle in order to assist or mimic gait. Mechanisms

integrating elements which mimic the roles of anatomical parts will increase the level of functionality and performance. For example tendons that assist powered accelerations or imitate the role of biarticular muscles in a limb [27].

A so-called biomimetic system can increase its level of functionality by increasing the level of system integration, consequently improving imitation of its biological ideal. Such systems are not easy to realize and a lot of research needs to be done in order to obtain a reliable high-performance system at relatively low energy consumption.

One example is electroactive polymers (EAP's), which have emerged during the last years and are considered as a new promising type of actuation. These are polymers that change their shape when a voltage is applied. There are two main types: dielectric and ionic EAP's. They offer integrated joint impedance, good controllability, are noise-free and anthropomorphic shapes can be developed easily [22]. Research is still in the early stages and only a few applications in other research areas can be reported yet.

State of the art actuator technologies must provide versatility and adaptability. This can be achieved if the design process is conceived in an integrated approach considering known technology limitations. Examples of this can be found in novel applications developed in the field of biorobotics, prosthetics and biomimetic designs which are based on relationships between experimentally achieved biomechanical parameters and verified biomechanical models.

Recently, series elastic actuation has experienced high popularity among researchers in the domain of prosthetics and orthotics. A Series elastic actuator (SEA), in general terms, is a drive in series with a compliant element [46, 48]. The advantage of such a configuration lies in its ability to act as nearly-perfect torque or force source, e.g. electrical motors are excellent in positioning but inaccurate for low force display. Using Hooke's law small forces and torques can be generated easily and measured with potentiometers [58]. Another advantage is the fact that energy can be stored in the compliant element. When the drive is turned off the SEA remains backdrivable to a certain amount and can absorb shocks, which improves safety for both, the human and the robot. On the other side the compliant element in the drive train decreases the bandwidth for larger forces and in general a SEA needs more power, disregarding the effect of energy storage in the compliant element. SEA technology has been proven to work efficiently in non-ambulatory exoskeleton designs such as the LOPES [60] and in wearable robotic orthoses and prostheses [3, 8, 39, 54, 61]. At the moment, SEA seems to be a feasible way to mimic properties of biological muscle-tendon units.

The development of SEA has been expanded to hydro-elastic actuators [45] and rotational hydro-elastic actuators (rHEA) [55].

An interesting approach can be found in a lately developed knee-prosthesis. The principle of SEA is expanded to an active series-elastic clutch (SEC) system [37]. In this robotic knee joint flexion/extension is realized with two motors, each of them driving a spring on a ball screw. Between both spindles a linearly moving carriage is coupled to the rotation of the knee joint. Both springs can move along with the carriage, move away from the carriage or can be used to block the carriage, hence blocking the knee joint. Stiffness of the joint can be regulated by the tension in each spring. This technology offers a good power-to-weight ratio and allows for optimal energy dissipation during gait. This series-elastic clutch principle could be incorporated into future exoskeleton designs.

In order to reduce power consumption different approaches could be thought of. With help of variable elastic stiffness elements in addition to the SEC principle a more versatile and energy efficient system could be developed. Another way of reducing energy requirements could be realized by making the SEC non-backdrivable by using self-impeding gears or adding brakes. For example, during stance phase the electric motor does not need to be active to lock the knee joints.

3.2.4. Actuator power

Looking at biomechanical data during walking at normal speed, the most demanding period of mechanical energy required is found at the ankle joint, during the push off phase. The peak energy is 2-3 times higher than for the joint knee. This might be another reason why active ankle support has been chosen to be omitted in existing exoskeletons. However, it is wrong to reason that an active ankle actuator requires the same amount of energy. When looking back into human gait function it can be noticed that the Achilles tendon is stretched by the bodyweight during the stance phase. During the swing phase 80–90% of the stored energy is released [49]. This means that most of the energy, as shown in biomechanical data analyses is not actively

but passively generated. Hollander et al. developed a powered ankle orthosis which recovers energy during stance phase and thus could reduce the energy demands of the actuator by 2/3 [30]. It can be concluded that the active ankle actuation can be implemented in rehabilitation exoskeletons, making it unnecessary to provide the full amount of ankle torque as shown in biomechanical data.

The ankle should be at least actively supported in the sagittal plane in order to assist the user. The frontal and transversal plane can be passive in order to keep the foot in a more or less natural position. Training too many DoF can distract and confuse the patient (Show prove source). It could be useful to make the passive assistance manually adjustable.

3.2.5. Actuator control

SEA's are preferably used with impedance control, as the compliant element is a robust, reliable and low-cost torque/force source. Simple potentiometers or encoders can be used to measure the deformation of the compliant element, which is a measure for the torque/force using Hooke's law. Those sensors can also be used to measure the actuator's output position. Hence very compact and reliable systems can be developed. On the other side serious problems with can be caused by the elastic element. Hysteresis in elastic elements and non-linear behaviour in the low force range, most often due to friction, require pretension of the spring. In addition the spring stiffness can change over time. Consequently the exact force cannot be correctly calculated as the compression rate changes because of varying spring stiffness. This limits control and could even lead to instability.

With a SEA the output torque is easily regulated by quantifying the elastic element's deformation with position sensors. The joint position is also quantified by position sensors. This makes dramatically increases the robustness of the control [2].

Control of lower level, state of the art actuation technologies might not be problematic at the moment. The challenge lies more in the correct measurement of the user's intention and thus the right level of assistance during training.

4. Conclusion

Looking at previous studies it can be concluded that effective rehabilitation is only possible when the user actively participates during gait training. Regular functional or task-specific rehabilitation excites sensory-motor pathways which stimulates neurological reorganization. Robotic rehabilitation triggers the learning-dependent neuro-plasticity.

Even though recent research results show that training with AAN paradigms causes cortical reorganization, long-term recovery is marginal and enduring improvements still need to be proven. One possibility to improve the AAN strategy is the implementation of a Top-Down approach where neural signals are correlated with myoelectric signals and fed back to the brain via visual or proprioceptive cues for instance.

The main difficulties lie in the detection of the right signals correlating with the motion intention of the user, their interpretation and the control of the exoskeleton. Different BCI tools, like EEG, EMG, NIRS, could help in solving the challenges. A combination of these systems together with real-time biomechanical data of the exoskeleton can result in improved cHRi, able to rehabilitate stroke survivors in an effective and safe way.

On the other side the trade-off between maximal torque and weight of an exoskeleton will remain challenging. The most logical thing to do in order to decrease the overall weight is the reduction of the actuator size. One way to achieve this could be the usage of smaller energy-demanding actuators capable of being adaptable to different gait situations and storing or harvesting energy. Another issue is the transfer of the joint torques between the human and the robot. Comfort, safety and donning/doffing time efficiency require special attention.

Regarding these issues it might be clear why effective robotic gait rehabilitation systems are not encountered yet, not to mention ambulatory rehabilitation exoskeletons.

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