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SPECIAL ISSUE - REVIEW

Neurorobotic and hybrid management of lower limb motor disorders: a review

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Abstract A neurobot (NR) is a mechatronic wearable robot that can be applied to drive a paralyzed limb. Through the application of controllable forces, a NR can assist, replace, or retrain a certain motor function. Robotic intervention in rehabilitation of motor disorders has a potential to improve traditional therapeutic interventions. Because of its flexibility, repeatability and quantifiability, NRs have been more and more applied in neurorehabilitation. Furthermore, combination of NRs with functional electrical stimulation/therapy constitutes a trend to overcome a number of practical limitations to widespread the application of NRs in clinical settings and motor control studies. In this review, we examine the motor learning principles, robotic control approaches and novel developments from studies with NRs and hybrid systems, with a focus on rehabilitation of the lower limbs.

Keywords Neurorobot · Exoskeleton · Functional electrical stimulation · Gait · Neurological diseases

1 Introduction

Loss of motor function is a hallmark consequences of neurological diseases. A study compiles the 12 most common neurological diseases in the U.S. Among them, those neurological diseases that can affect lower limb motor function are cerebral palsy in children, sclerosis, Parkinson, Stroke, amyotrophic lateral sclerosis, and spinal cord injury (SCI). Estimated prevalence for cerebral palsy was 2.4 per 1,000 children. In the general population, per 1,000, the 1-year prevalence for multiple sclerosis was 0.9. Among the elderly, the prevalence of Parkinson disease was 9.5. For diseases best described by annual incidence per 100,000, the rate for stroke was 183,101 for major traumatic brain injury, 4.5 for spinal cord injury, and 1.6 for amyotrophic lateral sclerosis [45]. Some others studies have been focused on one of those neurologic diseases, the ones with more incidence. For example, stroke prevalence has been estimated in other review in 2.9%, estimating that a new stroke attack occurs every 40 s [28]. Another study done in SCI showed that world annual incidence rates in traumatic SCI varied from 12.1 to 57.8 per million [94]. In the case of Parkinson disease, the world incidence has been established in 10–18 cases per million, with a prevalence of among 0.3–3% [35], mainly in the elderly population.

Neurologic motor rehabilitation is directed toward the re-learning of motor skills. Behavioral experience can cause dendrites to grow and regress, synapses to change in efficacy, vasculature and glia to be modified, and, sometimes, neurons to be added or lost [56]. Task-oriented repetitive movements can improve muscular strength and movement coordination in patients with impairments due to neurological disorder that leads to motor control abnormalities, weakness and spasticity. During the last decades, there is a trend in rehabilitation practices among practitioners that focus on the functional movements to recover gait [62, 95]: task-specific physiotherapy (standing on parallel bars, training of equilibrium), bracing, manual supported over ground gait training, manual bodyweight-supported treadmill training and robotic treadmill training, among others.

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Neuroprosthetic (NR) and neurorobotic (NR) management of motor disorders emerges as a promising technique that blends together technologies, actuation and rehabilitation principles that could overcome the performances of each independent approach. For the purposes of this review, we describe the application of principles for motor recovery with current state of the science on efforts on neuromuscular electrical stimulation and robotic technology. We highlight developments building bridges that will allow for combined NP and NR management of the impaired movement, with a focus on rehabilitation of the lower limbs, but also evoking examples of experiences for recovery of the upper limb function when informative. The review is organized as follows: Section 2 provides an overview of the basic training paradigms that are applied to retrain gait, Section 3 examines the neurorobotic devices for control of movement, and Section 4 describes hybrid approaches to gait retraining.

2 Training paradigms for gait recovery

Human gait is a typical repetitive functional movement. For example, weight-supported treadmill training has been shown to improve gait and lower limb motor function in patients with motor disorders, as SCI [4, 5, 13, 15, 16, 30, 33, 42, 43, 63, 68, 80, 86, 97, 99, 100], stroke [13, 42, 43, 63, 86, 97], multiple sclerosis, Parkinson and traumatic brain injury [68, 80, 100]. There is a growing evidence that locomotion in humans is based on the functional activity of neuronal circuits within the spinal cord, (the central pattern generator, CPG) [14]. Besides, neural plasticity, a rather broadly used term, addresses mechanism that involve a reorganization of neuronal circuits, e.g., as occurs during motor learning, and after a neurotrauma at both cortical and spinal level [12]. Therefore, strategies for recovering gait ability are based on intensive training strategies directed to the stimulation of CPG [14, 65]. Also, intensive training is beneficial while it provides an improvement on muscular tone and coordination among muscular groups. Neural plasticity, improvement in muscular tone and coordination, and changes on functional strategies to achieve walking (not due to neurological changes) are the main mechanism that contribute to improve locomotion [95].Therefore, the rehabilitative interventions have to promote such mechanisms through a certain training paradigm. On SCIs, there is no consensus on what are the most adequate intervention programs for rehabilitation of gait [62, 101], although there is a trend in rehabilitation practices among practitioners that focus on the functional movements to recover gait [62, 95]: task-specific physiotherapy (standing on parallel bars, training of equilibrium), bracing, manual supported over ground gait training, manual bodyweight-supported treadmill training and robotic treadmill training, among others.

Along intensive training interventions, an effective rehabilitation activity must be accomplished with an effective user involvement in the task [81]. It is hypothesized that CPG's are under the control of the brainstem: voluntary commands have to interact with the CPG in order to change, for example, the direction of gait. This mechanism enables a subject to voluntarily circumvent obstacles without loosing postural stability [14]. Patient-cooperative robot-aided gait training on incomplete SCI patients has shown an improvement on functional outcome of the therapy when compared with position-controlled gait training [21]. In stroke survivors, behavioral improvements, neuronal structural plasticity, and brain functional changes can be driven by targeted post-stroke behavioral rehabilitative therapies in humans and animal models as reviewed previously [10, 57, 74]. For example, targeted training of the impaired upper extremity in motor skills enhances motor map reorganization near cortical infarcts and improves motor function [74]. Even in stroke survivors with severe paresis who are well beyond the acute stage of recovery after stroke, intensive and repetitive task-related practice leads to changes in motor function that are associated with normalization of brain function [6].

Manual assisted training has several major limitations. Hands-on traditional techniques, such as active-assist exercise, are advocated in practice guidelines and standard texts and are labor-intensive. Therefore, training duration is usually limited by personnel shortages and therapist, rather than by patient fatigue. Furthermore, therapists often experience back pain because the training is performed in an ergonomically unfavorable seating or even standing posture. Consequently training sessions are shorter than may be required for an optimal therapeutic outcome. Finally, manually training lacks repeatability and objective measures of patient performance and progress.

3 Neurorobotic control of movement

Robotic technology could partially automate movement training following injury to the central nervous system. Robotic devices, because of their programmable force-producing ability, can replicate some features of a therapist's manual assistance, allowing patients to semi autonomously practice their movement training. However, robotic devices can also implement novel forms of physical manipulation that are beyond the capabilities of therapists in terms of speed, sensing, strength, and repeatability of the mobilization exercises. The evolution of therapy with electromechanical devices is possible by, for example, varying the force, decreasing assistance, increasing resistance and expanding the movement amplitude. Pilot studies suggest that an advantage of electromechanical and robotic devices, as compared with conventional therapies, may be an increase in repetitions during arm training due to an increase of motivation to train and also the opportunity for independent exercise [79].

A systematic review evaluated the efficacy of body-weight-supported treadmill training of walking in stroke patients, in which is concluded that treadmill training or body-weight support did not affect functional outcome as compared with conventional overground gait training [70]. A study compared four different body-weight treadmill training approaches in chronic motor incomplete SCI: treadmill with manual assistance, treadmill with electrical stimulation, over ground with electrical stimulation, treadmill with assistive robot. All training approaches were associated with improvements in gait quality regardless of training approach [73]. Pilot studies done on upper limb rehabilitation robots, suggest that an advantage of electromechanical and robotic devices for rehabilitation, as compared with conventional therapies, may be an increase in repetitions during arm training due to an increase of motivation to train and also the opportunity for independent exercises [79]. However, there is no evidence that the use of electromechanical assistive devices in rehabilitation settings may improve activities of daily living. Also, robotic training is at least as effective as other interventions for people with stroke when improving activities of daily living is the aim. There is also evidence that arm function and strength may improve [93]. Also further research in robotic training algorithms for the upper limb is need.

3.1 NR exoskeletons in physical therapy

NR control use volitional commands for controlling a (mechatronic) wearable robot (WR), typically shaped as an exoskeleton, which, in turn, applies controlled forces to drive paralyzed limbs. Such NRs are person-oriented robots used to supplement a function of a limb or to replace it completely. NRs can be used to either assist weakened muscles, to preserve and protect human joints or to rehabilitate people [41]. The former are typically used for functional substitution.

Such wearable NRs offer more versatility as to the implementation of diverse motor actions: (1) precise kinematics and impedance control is readily available, (2) biomimetic control architectures, e.g., CPGs, internal models (model-based feed-forward control) and reflexes, can be readily applied, and (3) built-in artificial proprioception (limb awareness) and vestibular sensors can be used to drive non-volitional motor actions, e.g., control of balance.

NR can be configured as exoskeletal devices to assist the treatment of patients suffering from neurological damage that led to mild or severe motor disorders, such as CVA, SCI, or pathological tremor. All these conditions lead to altered sensorimotor capabilities and one of the most disabling sequels is diminished locomotion capability. Such pathologies frequently result in diminished sensorimotor capabilities that can be at least partially restored by manual or robotic training.

Rehabilitation NRs have been mainly developed to allow a large number of task-specific repetitions. Available devices include the MIT-Manus, Bi-Manu-Track (Reha-Stim Co., Berlin, Germany), or the Lokomat gait orthosis (Hocoma), Gangtrainer (Reha Technologies), HAL (Tsukuba University), Cyberthosis (EPFL) among others. In the context of neural rehabilitation, these NRs are an attractive but yet not fully explored technique to reinforce the effect of the basis for rehabilitation: neural feedback. When acting actively through its actuators, and demanding an active intervention from the patient, muscle coordination patterns might be restored or more accurately and effectively be substituted through NRs [55]. At this time, with regard to stroke rehabilitation therapy, interventions driven by such NRs have demonstrated to be at least as effective as conventional therapy [16] but there is not yet a consensus with respect to effectiveness [17] at chronic or acute stages after stroke.

3.2 Motor learning principles and robotic control approaches

Robotic intervention in rehabilitation of neuromotor disorder is intended to promote motor learning that is relevant for recovery. The efficacy of the human–robot interactions that promote learning depends on the sequence of actions either imposed or self-selected by the patient. Applied strategies mainly can be distinguished to promote effort and self initiated movements. Such control approaches are thought to (a) allow a margin of error around a target path without providing assistance, (b) trigger assistance in relation to the amount of exerted force or velocity, (c) enabling a compliant at level of the joint, and (d) detrend the robotic assistance by means of what has been proposed as a forgetting factor [67], comparable to the human controller. The assist-as-needed control concept has emerged to encourage the active motion of the patient. In this approach, the goal of the robotic device is to either assist or correct the motions of the user. Under this approach, patients are trying to move along a gait trajectory while the robot provides only as much assistance as necessary. The amount of assistance depends on the magnitude of deviation of the desired trajectory, which is generated for each patient and gait scenario separately. The assist-as-needed approach is intended to manage simultaneous activation of efferent motor pathways and afferent sensory pathways during training [24]. A main challenge in current assist-as-needed strategy is the adequate definition of the desired limb trajectories that the robot must generate to assist the user in space and time during exercise. Some robotic rehabilitation systems have attempted to solve this issue with the use of so-called supervised learning approaches that pre-determine reference trajectories [48].

The assist-as-needed approach has been applied to the control of walking. In one scheme, the NR controller is able to adapt to varying gait patterns and levels of support, implementing control of mechanical impedance [46]. The stiffness and the position of the actuator's output can be set as a function of the current position error or can be manually tuned by a therapist [96]. Zero-impedance control mode has been implemented in diverse devices in order to allow free movement of the segments [21]. Other efforts on patient-cooperativeness have been focused on advancing the classical impedance control in order to overcome the disadvantage of imposing timing of movements to the limbs of the patient. The idea of a virtual tunnel [7] to allow some range of free movement was introduced with the MIT-Manus [61] and tested with stroke patients in the lower limb exoskeleton ALEX [55]. Likewise, an algorithm was proposed for the Lokomat exoskeleton that allows users to move actively along a spatial path of a defined walking pattern, which is referred to as *path control*. In [21], the *path control* strategy was reported to result in larger temporal variability more active EMG recruitments in tests performed with a group of incomplete spinal cord injury subjects.

Contrary to assistive strategies, challenge-based robotic strategies are aimed at rendering the task more challenging. Challenge-based strategies can be either resistive, based on evidence that kinematic errors are key neural signals driving motor adaptation [25], or intended for error-amplification, relying on the evidence that resistive exercise demanding higher effort can help improve motor function [98].

The above mentioned controlled approaches for NRs are mainly applicable to non-ambulatory solutions for training and recovery of motor function. When NRs are thought for functional substitution, robustness in dynamic conditions together with wearability and ambulation, are critical requirements. Advanced wearable NRs have been shaped around elastic structures with appropriate elasticity and energy recovery elements (e.g., powered prostheses during the stance phase of walking [85], intelligent stance-control orthoses during the swing phase of walking [103]) combined with active or dissipative actuators that allow for a more physiological movement. The former type of NR controllers rely upon fixed force–angle state relationships, obtained from measurements of intact humans walking at specific velocities and across known terrains. Novel controllers with the ability to adapt are required. Neuromuscular models with feedback reflex schemes as basis of control are emerging for the new generation of NRs for substitution [64]. An adaptive muscle-reflex controller of the ankle joint is proposed to determine the physical torque to drive a robotic ankle-foot prosthesis [23]. By modeling the reflexive muscle response due combination of afferent signals (muscle spindles and Golgi tendon organs), it has been demonstrated the importance of including such neuromuscular controllers to deliver the required adaptiveness NRs for substitution.

3.3 Neural signals, biofeedback, and BNCI

The cognitive interaction with the NR refers to the support of the flow of information between a NR and a human user. Information coming from the NR to the human is used to implement feedback strategies. On the contrary, information coming from the human to the NR might be basically used for commanding the device. Motor intention and execution can be extracted along the diverse stages in the motor planning-execution process that takes place in the nervous system. Brain–Neural Computer Interfaces (BNCIs), as multimodal interface to the humans' neural system, are becoming promising systems that combine available sources of neural activity to drive exoskeletal rehabilitation and functional substitution robots [104].

Brain–Neural Computer Interfaces are called to improve current assist-as-needed strategies for NR-based training and substitution. BNCIs, among other, include methodologies that enable: (1) passive monitoring (valid to assess motor intention without generation of real-time feedback); (2) assessment of peripheral nervous signals, directly related to muscle activation; and (3) indirect measures of neural activity at the skin surface (sEMG). Brain signals measured non-invasively with EEG electrodes can provide features to analyze information of motor planning. For example, low frequency cortical potentials, might be related to movement preparation, initiation and finalization, and can be used to design switches to volitionally drive a NR-device during training. Furthermore, the comparative analysis of cortical and muscular neural firings during execution is another potential technique to distinguish upper-level from lower-level neuromotor mechanisms, e.g., assessment of motor execution through measures of EMG–EEG coherence during a repetitive task [83]. Event related desynchronization in EEG activity has been demonstrated to provide insight on how the brain manages actual, intended, and perceived movements [36]. Such features are potentially useful to increase the robustness of NR response.

3.4 Neurorobotic feedback training for rehabilitation

It is widely accepted that during human walking the spinal cord has the potential to generate the basic locomotor patterns that synchronize lower-leg muscle recruitment required to perform the movement [14, 22]. Controllable orthosis or exoskeletons have demonstrated to be able to induce modulations in the muscle recruitment after training with such devices. Induced alterations of EMG activities have been explored with orthotic devices or robotic exoskeletons, triggered or preprogrammed to induce a certain locomotor pattern [69, 71]. Stance-control of the knee joint with a controllable exoskeleton has demonstrated short-term modification of timing and amplitude of the gastrocnemius muscles in healthy subjects after training to walk [69]. The former gait adaptation mechanisms where revealed when selectively imposing two levels of stiffness during walking. Intense orthotic gait training has demonstrated induced modulation of EMG activities in the ankle soleus muscle in patients with clinically complete SCI in [71]. Also, in their study, assessment of the soleus EMG activity in stretch flex tests was performed during orthotic gait. The result gave support to the hypothesis that spinal locomotor networks contribute to such adaptations. In [54], a robotic ankle exoskeleton used during gait training in healthy subjects has been used to analyze the role of the soleus H-reflex during powered walking.

Novel NR devices are required to encourage the level of intensity of the exercises in stroke and SCI patients, enabling the maintenance of the therapeutic methods in daily activities [47]. Ideally, it would be expected to progress toward compact, autonomous orthosis/exoskeleton that can provide both assistance and therapy during the wearer's everyday life [17]. Also, enhanced NR devices have to be designed to manage training with more and more knowledge of the neural mechanisms that are involved during recovery, such as the nature of reflex activation or the role of proprioceptive feedback. In this regard, design approaches are required in which the NR-device exerts physical stimulation at the periphery as a function of targeted neural activation patterns. Such novel NRs could be used to promote recovery by providing online control of movement with artificial controllers that take into account the activity of the intact and affected neural circuits.

EMG signals can be used to constitute active rehabilitation approaches to control NRs. During the application of task-oriented exercises, locomotor training can be supported by a NR according to the residual myoelectric activity. Feedback triggered by residual volitional EMG is thought to promote the recovery of proprioceptive feedback, and therefore, enhance the motor relearning [51]. Although there are few rehabilitation NR devices that have been reported using EMG, recent available evidence of improved motor control is marking the future of devices thought to amplify residual intention. Soleus electromyography has been used to control the amount of plantar flexion assistance from a robotic ankle exoskeleton [29]. Subjects significantly reduced their soleus activity to quickly return to normal gait kinematics. A computational algorithm that computes control commands (muscle force prediction) to a NR wearable robot has been proposed [92]. In this way, desired muscle activation pattern for target muscle forces can be induced.

Robotic feedback training has been proposed to train the paretic ankle of persons with chronic stroke. In a study with stroke survivors, the approach was tested in joint mobilization training, providing assistance only as needed and allowing subjects to reach targets unassisted if they are able [34]. Training with a feedback-based gait monitoring knee brace has been proposed to assess the neuromuscular effects of auditory feedback in post anterior cruciate ligament injury. It has been shown that particular short-term neuromuscular adaptations emerge, such as rate of loading and proprioceptive acuity, from such type of intervention.

NRs have also been applied as unique tools that enable the study of motor learning in intact and injured humans. Two basic working principles can be identified in the literature: (1) A NR in parallel to the limbs is used to induce a perturbation that in turn should reflect a short or mid-term adaptation, [54]; (2) a NR in parallel to the limbs is used to determine the amount of volitional control of joint torque and its relation to a specific function post injury, e.g., when rehabilitation involves the practice of joint mobilization exercises [49]. These conclusions are guiding discovery of unsolved underlying principles. NRs are more and more considered as instruments to determine the degree of effectiveness of novel neurorehabilitation paradigms.

4 Hybrid approaches to gait retraining

Neuromuscular electrical stimulation refers to the electrical stimulation of lower motor neurons to cause muscle contraction. It constitutes an alternative approach to rehabilitate motor function. The term functional electrical stimulation (FES) refers to the use of neuromuscular electrical stimulation to directly accomplish functional tasks such as standing, ambulation, or activities of daily living. Devices that provide FES are also referred to as neuroprostheses, NPs.

The idea of compensating for paralyzed function using electrical stimulation was introduced as early as the 1960s [102], and has been widely explored for gait compensation in SCI subjects, in which the own muscles of the user are stimulated by electrical impulses, previously configured, to generate joint movement [77]. There is some evidence that FES-assisted walking can enable walking or enhance walking speed in incomplete SCI or complete SCI. Also, regular use of FES in gait training or activities of daily living can lead to improvement in walking even when the stimulator is not in use [62]. However, the FES also imposes challenges that prevent the widespread use for gait compensation, as the rapid fatigue in muscles and poor control of joint trajectories [87]. Closed loop control strategies of FES may help to prevent those phenomena.

Clinical applications of neuromuscular electrical stimulation in stroke rehabilitation provide both therapeutic and functional benefits. Therapeutic applications include upper and lower limb motor relearning and reduction of post-stroke shoulder pain. There is growing evidence that neuromuscular electrical stimulation, especially those approaches that incorporate task-specific strategies, is effective in facilitating upper and lower limb motor relearning [11, 31, 66, 77]. FES can enhance the recovery of upper extremity function during early stroke rehabilitation in patients with mild/moderate paresis more than task-oriented training without FES [1, 2]. In post-stroke patients, bilateral upper limb training with FES has been described as an effective method for upper limb rehabilitation [9]. Also the intensive training with FES has been identified as a factor that promotes motor function [60]. Overall, the literature suggests that surface neuromuscular electrical stimulation is effective in reducing motor impairment. However, the effect on upper limb-related activities remains uncertain [8, 66].

The combination of FES technology and active orthoses emerges as a promising technique that blends together technologies, actuation and rehabilitation principles that could overcome the performances of each approach, either for gait compensation or rehabilitation. The addition of FES to an exoskeleton system can take advantage of the muscle power generation, reducing the power demand of the exoskeleton and allowing less powerful joint actuators, leading to a less heavy and power-demanding system. Also, the combination of FES and exoskeleton technologies can increase the time of use of the neuromuscular electrical stimulation, and therefore, increasing the benefits derived of FES-induced gait: muscle strength and cardio-respiratory fitness [11, 40, 62, 72]. Besides, ambulatory hybrid exoskeletons promote daily training of functional abilities during gait, increasing user involvement in the task. As a result, it may be beneficial to promote neural plasticity better than other standard practices, such as treadmill training, due to the intensive, community-based, gait practice. Muscle fatigue due to FES can be counterbalanced by exoskeleton's design and hybrid control, aimed to be used for longer periods of time.

In the context of this article, we define hybrid exoskeletons as those systems that are aimed to compensate or rehabilitate gait in real scenarios, by means of delivering and controlling power to the lower limb joints, in which the net joint power results from combination of muscle activation with FES and electromechanical actuation at joint level, see Fig. 1. The concept of hybrid exoskeletons was first introduced by Tomovic et al. [91], but until 1989 was not reported the physical construction and preliminary results [76]. In subsequent years different systems have been proposed with diverse actuation and control principles. In order to give a more meaningful explanation, we have split into three main categories: (1) semi-active hybrid exoskeletons, (2) hybrid exoskeletons with energy storage, and (3) active hybrid exoskeletons.

4.1 Semi-active hybrid exoskeletons

Semi-active hybrid exoskeletons are built on the basis of a passive gait orthosis, adding controllable brakes at the joints. This design allows the use of FES as a power source to generate gait, controlling joint movements by closed-loop control of joint trajectory. This can be regarded as a semi-active solution to the problem of joint trajectory generated by FES [19]. In addition, placing joint brakes on the orthosis avoid the stimulation of muscles during stance phases of gait, which reduces stimulating duty-cycle at approximately 11% of the gait time when compared to walking with only a FES-gait system [26, 38]. The hybrid neuroprosthesis developed by Kobetic et al. [58] aims to improve flexibility, step length, and walking velocity compared to hybrid passive reciprocating orthosis, which

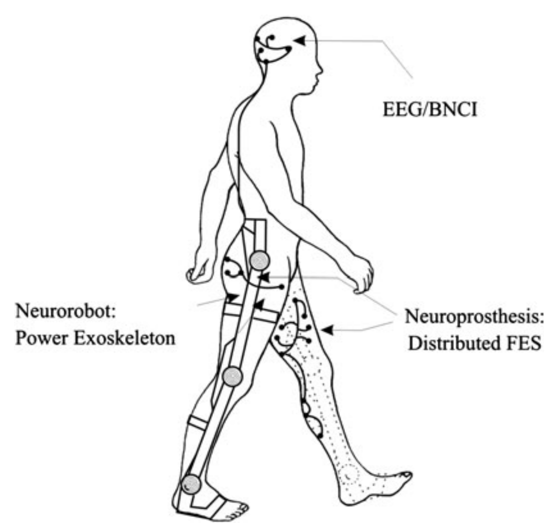

Fig. 1 Concept of a neurorobot and neuroprosthesis for the control of the lower limb. A powered neurorobot acting in parallel to a distributed neuroprosthesis constitutes a hybrid approach to accomplish functional tasks and promote recovery. A BNCI (e.g., based on EEG) can be applied to implement the cognitive interaction

are the main drawbacks of such systems. The orthosis comprises 26 intramuscular electrodes for mobilizing hips, knees, and ankles joints; and the hip and knee joints were controlled by spring clutches, releasing or blocking the joints during swing and stance phases of gait. Although step length and walking velocity were improved, the posture and stability of the user was compromised due to the hip control through the spring-clutch. Also appearance of muscle fatigue in hip extensors was reported. Therefore, in order to overcome those limitations related to the hip brake, a variable hip coupling mechanism was included in a new design, in which the coupling ratio between hip joints could be modified by means of a controllable hydraulic system [59, 88, 89]. This hydraulic hip mechanism provides trunk and hip stability and free or coupled hip movement during swing phase of gait. Although preliminary results in able-bodied subjects have shown both hip kinematics and kinetics closer to normal data, the weight of the system can affects walking velocity (decreased) and muscle activation (increased) [3] which comprises its applicability in patients.

A similar approach was followed for the robotic control of the joints in the development of the Controlled Brake Orthosis (CBO) with eight degrees of freedom and four FES channels [18, 38]. The orthosis hip and knee joints are controlled in flexion-extension movement by magnetic-particle brakes, whereas ankle was actuated by and elastic actuator which controlled the dorsal flexion to avoid drop foot. Also, CBO features free hip adduction-abduction, with a limited range of movement [18]. This configuration resulted in a relatively low-weight orthosis (6 kg) with highly backdrivable joint actuators (magnetic brakes). FES is applied to quadriceps and peroneal nerve to generate knee extension and withdrawal reflex respectively [39]. Therefore, knee joint is controlled in flexion and extension whereas hip joint is controlled in flexion only, which constitutes a difference with respect to Kobetic's hybrid system. Closed-loop control of joint position is achieved by the use of joint brakes, using the stimulated muscle as a source of power. Control strategy of CBO tries to actively control muscle fatigue, closing the FES loop with the information of braking torque. Position error is used to detect when the stimulation level is too low, whereas the brake torque is used to detect too high levels of stimulation. Both metrics are integrated on the basis of one step, and combined in a weighted difference. Amplitude of muscle FES was controlled as a function of trajectory and torque error, averaged in a step-by-step basis in order to stimulate the muscles with the amplitude necessary to achieve joint movement [38]. An evaluation with four subjects with paraplegia have shown a reduction in muscle fatigue and an improvement in trajectory control when compared to FES-only gait [39]

4.2 Hybrid exoskeletons with energy storage

The former hybrid exoskeletons can control joint trajectory and reduce muscle fatigue by means of brakes placed at the exoskeleton joints. Optimizing the stimulation strategy and the use of energy storage have been proposed to increase the performances of the system in terms of portability and muscle fatigue manage. By the combined use of an elastic element and a joint brake, it is possible to store energy form the quadriceps stimulation during swing, which is the less demanding condition for the muscle, and release the energy in other phase or joint. Therefore, the need of stimulating the muscles is reduced by the combined use of joint brakes for the stance phases of gait and the use of energy storage. Also stored spring energy could be used to replace stimulation of the hip flexors or withdrawal reflex, which has shown low effectiveness for eliciting hip flexion [39, 76].

The spring brake orthosis [36, 37] only have two FES channels, for stimulating quadriceps muscles. The actuation strategy relies on flexing the knee after toe-off due to the energy released in a spring, which also causes the hip to flex due to gravity action. This combined action drives the hip and knee joints to a flexed equilibrium position [36]. At mid-swing, knee extension is achieved by quadriceps stimulation, at the maximum intensity safe and tolerated by the subject, to accelerate the shank until the knee reaches

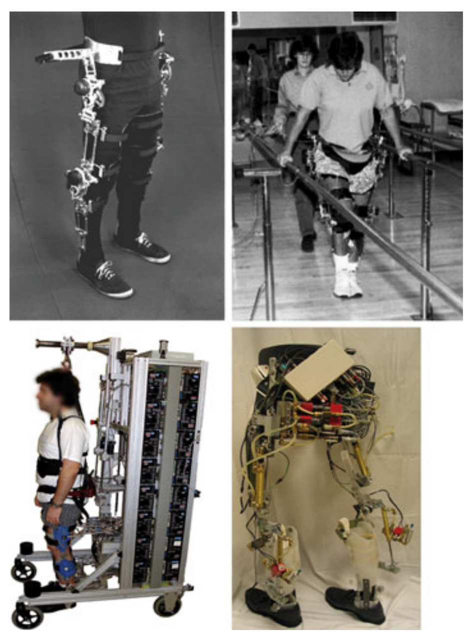

Fig. 2 Hybrid exoskeletons. From *left* to *right* and *top* to *bottom*: CBO exoskeleton [38], CBO on clinical trial [39], WalkTrainer [84], and VHCM exoskeleton [59, 89]. Image credits: Mr Michael Goldfarb, Vanderbilt Univ., Mr Mohamed Bouri, EPF Lausanne, and Mr Rudi Kobetic, Cleveland VA

full extension. Extension of the knee during this phase stores energy on the spring placed at the knee joint brake [37]. A fuzzy inference system determines burst duration to control knee joint kinematics, on the basis of knee joint position and velocity error [36], but recently a proportional-integral-derivative controller has been introduced [50]. Gharooni's FES control system is intended to achieve the limb's maximum acceleration in the shortest period of time, in order to minimize muscle fatigue, whereas hip and knee joint brakes are used to give support during stance phase [36].

Another orthosis developed following the elastic-energy storage concept is the Joint Coupled Orthosis [26, 27]. This system propose an unidirectional mechanical coupling between hip and knee joints, that is active during early swing. This unidirectional coupling is comprised by a spring that bias the knee and hip joints toward an equilibrium position in which both joints are flexed. Therefore, flexion of the knee generate hip flexion. As in the above systems, the exoskeleton also have hip and knee brakes which provide control of hip and knee joints during the stance phase and release after toe-off. As in the spring brake orthosis, two FES channels are used to stimulate quadriceps muscles of both legs at the peak of hip flexion, which fully extended the knee during the swing phase and also stores energy on the spring [26, 27]. However, contrary to spring brake orthosis, FES pulse parameters are fixed, and the stimulation timing is not controlled. Quantitative data have been provided in which muscle fatigue in non-disabled subjects is directly addressed by monitoring the knee range-of-movement (ROM). Data provided shows that knee ROM stabilizes after 15 minutes at 85% of the maximum value achieved at the beginning of the experiments [27].

Hip flexion in spring brake orthosis is achieved by gravity action, after the stored energy on the spring flex the knee. In the Joint Coupled Orthosis, hip and knee joints are mechanically coupled through a lineal spring, so that the energy stored at the spring causes knee flexion, which also causes hip flexion. However hip extension is not take into account, and is resulting from contralateral leg movement and body progression. In contrast, the energy-storing orthosis uses the energy-storing concept to decouple hip extension and flexion. spring brake orthosis have pneumatic cylinders placed at the hip and knee joints, and an pneumatic accumulator, and also elastic actuators to keep the hip and knee joints in a flexed equilibrium position [20, 52]. At the mid-swing the quadriceps are stimulated and the knee extends, storing energy in the pneumatic accumulator. Simultaneously energy is also stored in the elastic storage element at the knee joint. After full extension, the knee is locked and energy is released into the hip actuator and hip extends enabling forward progression and storing energy in the hip elastic storage element. Therefore, this pneumatic system allows decoupling control of hip and knee joints. Wrap spring brakes controls joint trajectory and give joint support during stance [20, 53].

4.3 Active hybrid exoskeletons

It has been shown that hybrid exoskeletons have proved that joint support and trajectory control can be achieved by the use of joint brakes. This also allows to delay muscle fatigue onset due to the avoidance of stimulating muscles during stance phases of gait. However, this control strategy is also its main drawback as those systems cannot provide full control of the joint since joint brakes are not capable of providing positive torque. Therefore, movement is performed only by the muscular action due to FES, and since most systems perform an open-loop control of FES, movement quality is low in terms of joint trajectory and velocity. In the case of closing the control loop of the FES, as in the case of CBO exoskeleton, although FES intensity can be adjusted in terms of muscle fatigue, this phenomena can not be counterbalanced by the system, and the insufficient joint power obtained, especially in the flexion withdrawal reflex, makes the system control ineffective [39, 76].

In contrast, active actuators placed at the exoskeleton's joint allow to deliver power at the joint, which in turn provides an effective way to counterbalance muscle fatigue and closed-loop control of joint movement. The first hybrid exoskeleton with active actuators, was developed by Popovic et al. [76]. It is based on a previous active orthosis, the self fitting modular orthosis, [90], which is a lightweight knee-ankle brace equipped with a DC servomotor and a motor-actuated drum brake coupled to the knee joint with a ball screw. The actuator is able to deliver power or providing externally powered and controlled extension and flexion, in addition to stiffness control from locked to free. Ankle joint is actuated by a spring mechanism to control dorsal flexion. The FES system consisted of six channels, acting on gluteus medius for balance, quadriceps for hip flexion and knee extension, and peroneal nerve for generating the flexion reflex, which allow knee, hip and ankle dorsal flexion. The stimulation parameters for each channel were fixed, based on a prior calibration with the subject. Hybrid control is performed by a finite-state machine which detects gait events. After event detection, a set of control rules are fired to activate or deactivate the FES system and the exoskeleton's actuators [76]. Data from a case study (C5/C6 incomplete tetraplegic) are reported, showing that the hybrid exoskeleton allow higher gait velocity and lower oxygen consumption when compared with only FES gait [76].

The concept of actively controlling hip and knee joints by means of actuators was also explored by Obinata et al., through the Hybrid Powered Orthosis, [75]. The HyPo exoskeleton is designed with the motors and gearboxes at the frontal part of the orthosis in order to allow the user to wear it from the back of the orthosis in a seated position. DC motors and gearboxes are implemented over the exoskeleton for control hip and knee joints of both legs. In this case the actuators are dimensioned to allow the generation of gait without FES, therefore, taking into account that muscle fatigue do not hinder the use of FES while walking. Hybrid control is realized by setting the FES in open loop, and controlling the joint trajectories and velocities by the actuators. No information was found on how the system is able to discriminate between stance and swing phase, thus, presumably the FES pattern and the joint trajectory reference are synchronized thorough an entire gait cycle, without discrimination of swing and stance.

Stauffer et al. proposed the hybrid exoskeleton WalkTrainer as a hybrid exoskeleton with closed-loop control of FES that relies on an estimation of the interaction forces between the leg and the exoskeleton [84]. The WalkTrainer exoskeleton actively controls hip, knee and ankle joints, and also the pelvis movement in six degrees of freedom. It is attached to a moving frame, which supports the exoskeleton and the user, via a weight bearing system, similar to treadmill training systems. This structure had motorized wheels that assist walking with the exoskeleton. The FES closed-loop controller have a combination of a feed-forward model of the torque-intensity characteristics of the muscle involved in the movement, as well as a classic proportional-integral-derivative controller for compensating the torque error, while the DC motors controls joint trajectories [82]. Joint torques exerted by the user are estimated based on measuring structural forces resulting from the interaction between the body segments and the exoskeleton. The system is intended to minimize such interaction forces through the modulation of muscle stimulation during walking.

The combination of FES and bodyweight-supported training has been also addressed by some groups, showing that the combination improves both gait endurance and velocity [31, 44, 78]. However, only a few studies have been found to compare the hybrid approach with conventional physiotherapy [78], resulting in improvements in both gait endurance and velocity. Also, two randomized controlled trials have shown no differences on treadmill training combined with FES when compared with other approaches [32, 73].

5 Conclusion

Exoskeletal robot technologies provide versatile control approaches as a framework to the design of optimal rehabilitation interventions and experimental motor control studies. In order for exoskeletal NRs to have a higher impact in the treatment of affected populations, improved transmission of motor actions to the human limbs, optimized control of the interaction efficient and compact solutions should be further researched. Exoskeletal NRs will increase their impact on rehabilitation outcome with more thorough investigation into the seemingly positive effects of the robotic interventions. Both NRs and MNPs are technologies that can be applied to restore or substitute motor function. MNPs have been extensively applied to restore function. Exoskeletal NRs can be driven by volitional commands to control movement of paralyzed or weak limbs. The potential of novel hybrid approaches (NRs and NPs) to both enable and rehabilitate motor function with repeatability and flexibility, makes them an attractive instrument to develop and evaluate novel neurorehabilitation concepts to manage motor disorders.

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