CHAPTER

Exoskeletons for upper limb rehabilitation

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INTRODUCTION

Motor recovery after stroke with consequent regain of function is promoted by physical therapy and exercise, thanks to the changes in cortical reorganization according to residual neuroplasticity. Four main factors are considered as the major determinants of motor recovery: early intervention, task-oriented training, amount and scheduling of practice, and degree of participation [1,2].

Stroke rehabilitation is being vastly improved through advanced robotic and neuroscience technology. As the entire rehabilitation process is time-consuming and labor-intensive, robots function as an alternative and a supplement to the one-to-one therapy.

There are two options available for upper-limb rehabilitation: on one side simpler devices, that is, one or two DOF, that can be used to train specific function or single-articulation movements, for example, elbow or hand planar movements, and on the other side multi-DOF robots that can train spatial and more complex movement. In this second category, exoskeletons represent the most advanced robot as they drive not only the end effector of the human arm, that is, hand, but also the full kinematic chain, that is, providing single-joint robotic assistance during movement execution, and so, they can be specialized and tailored to patient's needs.

However, the field of robotic exoskeleton technology remains in its infancy, since rehabilitation-robot markets at $221.4 million in 2015 are anticipated to reach $1.1 billion by 2022, with an exponential growth (source WinterGreen research), of which the current share of upper extremity is 13% and expected to grow up to 18.3% in 2021. Exoskeletons alone represent a share of 15% now and expected to reach 17.9% in 2021.

We can define upper-limb robotic exoskeletons as wearable robots characterized by suitable shape, kinematic, and weight factors that can be worn on the patient's arm [3,4]. In order to accomplish this function, the exoskeleton kinematics is characterized by multiple points of connection between the human limbs and robot-exoskeleton links so that often the exoskeleton kinematics is defined as isomorphic to that of human arm and it appears like an outer structure covering the human arm ("exo-", prefix,

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as used for naming insect exoskeletal structure). In this way, exoskeletons can provide a tailored assistance to patient's needs, providing selective joint control at the level of human articulations and acting in symbiosis with human movement. In order to accomplish this function, it becomes evident how appropriate kinematic constraints should be satisfied. Moreover, since exoskeletons are intended to be used for the rehabilitation of patients, with particular reference to neurological patients, it is clear that they should also exhibit a smooth, low friction, dynamic behavior, with overall requirements for the actuation similar to those adopted in the design of haptic devices [5].

In this chapter, we will deal with the main design issues of upper-limb exoskeleton for rehabilitation both in terms of mechanical design from kinematic, actuation, and control point of view in Section "Design of Exoskeletons" and we will analyze their clinical application in stroke rehabilitation in Section "Clinical Evidences of Upper Limb Rehabilitation With Exoskeletons."

DESIGN OF EXOSKELETONS

Upper-limb exoskeletons are typically used for rehabilitation of arm and hand function [6]. Another field of application of robot exoskeleton is human-power augmentation where a number of powered exoskeletons have been already developed [7] such as the Hercule by RB3D, the NASA X1 Exoskeleton [8], the XOS 2 exoskeleton by Sarcos, or the Body Extender from PERCRO, SSSA, Italy [9].

As shown in Fig. 1, there is a large variety of technologies used for exoskeletons. Rehabilitation and human power-augmentation exoskeletons make use of different actuation solutions, such as geared solutions, tendon drives, hybrid solutions (screw and cable actuators), or variable-impedance actuators.

We will briefly analyze in the following sections some of the main issues concerning the kinematics and actuation issues in rehabilitation exoskeleton design.

KINEMATIC ISSUES IN EXOSKELETON DESIGN

In order to accomplish training of motor function, upper-limb exoskeletons should be accurately designed from an ergonomic and biomechanics point of view. In particular, since exoskeletons are thought to act in symbiosis with the human operator, the kinematics is not less relevant than actuation. The following issues need to be properly analyzed: (1) nonideal equivalence of human joints to simple kinematic joints, (2) need of adjusting exoskeleton dimensions to human arm size, and (3) joint implementation should take into account the bulk of human arm.

Of course, it is well-known that the real anatomy of human joints do not correspond to ideal rotational or spherical joints: if we restrict, for instance, to upper limb, the shoulder complex involves the glenohumeral, the sternoclavicular, the acromioclavicular, and the scapulothoracic joints, so the human shoulder complex can be considered only as a generalized spherical joint with a floating center.

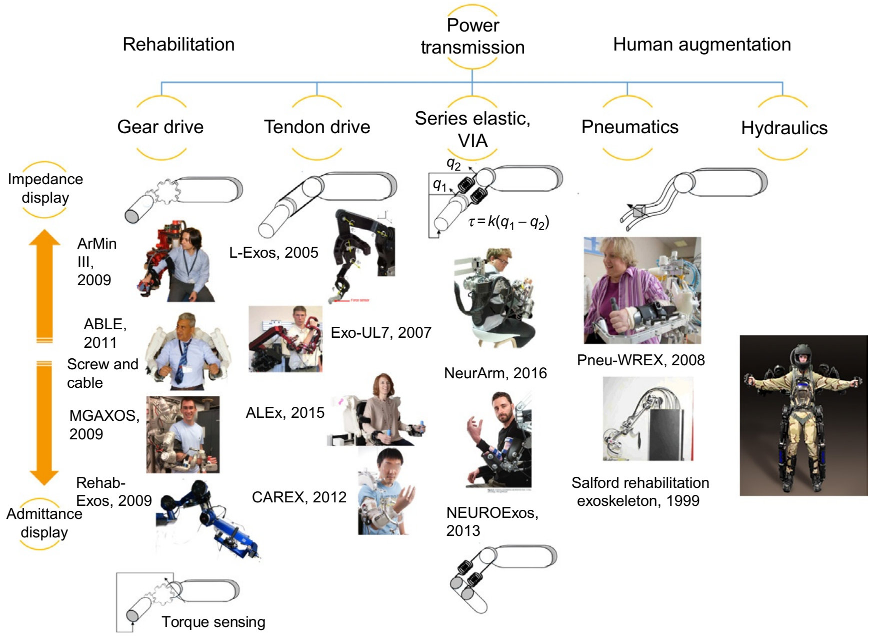

FIG. 1

Exoskeletons divided by category of actuation.

Pictures courtesy of Prof. Robert Riener for ARMin III; Prof. Craig Carignan for MGA Exoskeleton; Eng. Philippe Garrec for ABLE; Prof. Jacob Rosen for Exo-UL7; Prof. Sunil Agrawal for CAREX; Prof. Antonio Frisoli for ALEx, Rehab-Exos, and L-Exos; Prof. David Reinkensmeyer for Pneu-WREX exoskeleton; Prof. Nikos Tsagarakis for Salford Rehabiltation Exoskeleton; and NEUROExos to Massimo Brega. Right-most image used with permission from Sarcos Corp.

Axis misalignment can lead to undesired interaction loads (UI loads) that can render training uncomfortable. Moreover, the perfect alignment of joints requires that either to adapt robot-link size to human anthropometric dimensions or to use self-alignment mechanisms based on passive joints. A first systematic approach to the synthesis of self-alignment mechanisms was proposed by Jarrasse et al. [10] by studying the general problem of connecting two similar kinematic chains through multiple passive joints.

A further generalization [11] of this approach in terms of the type synthesis of self-adapting upper-limb exoskeletons considers the application of the mobility formula to multiloop linkages $\#F = \#f_{\text{active}} + \#f_{\text{human}} + \#f_{\text{passive}} - dl$ where l denotes the number of loops, equal to 2, for instance, for shoulder-elbow exoskeletons (one for shoulder and one for elbow complex), $d = 6$ for spatial case, $\#f_{\text{active}}$ indicated the active degrees of freedom of known joints (4 DOF), $\#f_{\text{human}}$ the human joints (4 DOF), and $\#F = 4$ degrees of freedom considering shoulder (3 DOF) and elbow (1 DOF). By solving for $\#f_{\text{passive}}$, it is easy to derive that eight passive degrees of freedom should be added to the kinematic chain as passive joints in a shoulder-elbow exoskeleton,

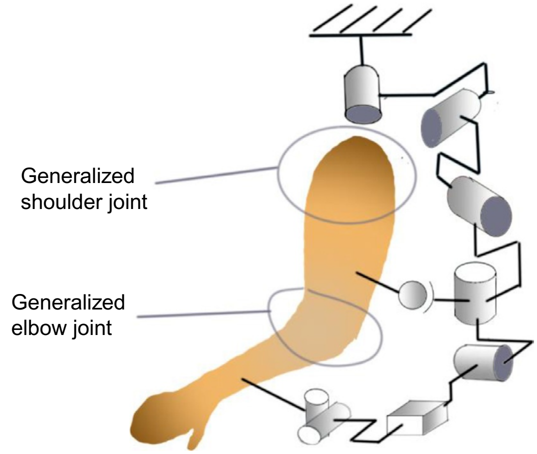

FIG. 2

Example case of an isostatic connection between human arm and shoulder-elbow exoskeleton.

with a distribution on shoulder-elbow # DOF subchains that can vary in the range of 3/5, 4/4, and 5/3. One example is reported in Fig. 2 where a $3R_a$-C-S chain is used for the shoulder and then a R_a-P-U chain is used for the elbow, where R, C, S, P, and U symbols stand, respectively, for rotational, cylindrical, spherical, prismatic, and universal joint kinematic pairs, while the subscript a indicates that the joint is actuated.

ACTUATION ISSUES

There are several technological issues to be taken into account in the construction of upper-limb robotic exoskeletons, of which a relevant one is the choice of the actuation principle.

Fig. 3 shows a summary map of the different technological options that are available to the design. First, the choice of the actuation principle represents a fundamental choice. Electric motors have several advantages; they are commonly used in the form of brushless DC motors to reduce the electromagnetic emission as required for medical devices.

Hydraulics has a better power density, but it poses problems in terms of safety due to the high pressure required by the oil circuit, and it is not always compliant to guarantee patient's safety.

Pneumatic actuation has been used in several designs; see, for instance, in the form of artificial pneumatic muscle [12] or for the actuation of shoulder and elbow in Pneu-WREX [13]. In this particular application, the inherent compliance due to air transmission might increase also the safety for a human-worn exoskeleton.

In fact, it has been already pointed out that for physical human-robot interaction, the risk of human injury in case of collision with a robot increases with the stiffness and mass of the moving parts of the robots [14]; so that in reducing the effective

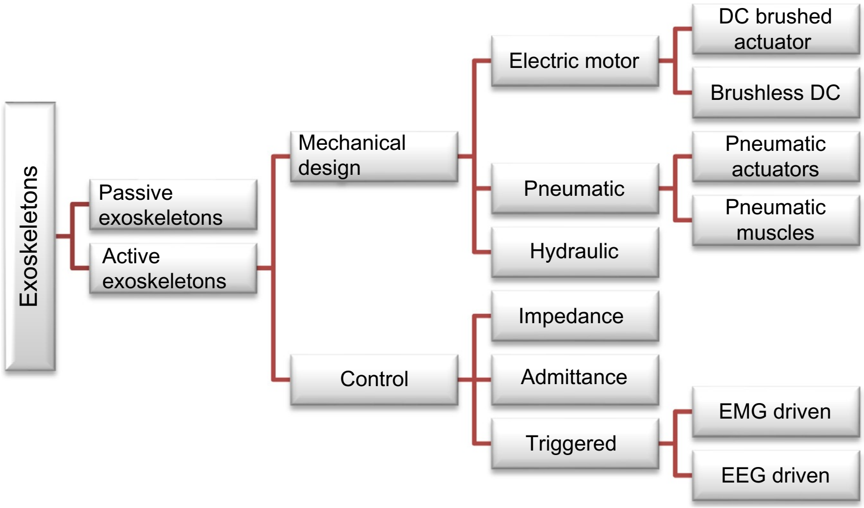

FIG. 3

Actuation and control solutions for design of exoskeletons.

impedance of the robot while maintaining high-frequency torque capability, it is possible to satisfy the competing design requirements of performance and safety.

Recently, we have assisted in the advances in the direction of new actuators for human-robot cooperation, and this is particularly relevant in the fields of exoskeletons, with the introduction of different solutions. We will focus mainly on the electric actuation, as this represents the most commonly adopted solution.

The simplest class of exoskeletons is the fully passive, where a system of springs or counterweights are used to compensate the weight of the patient's arm, reducing the role of abnormal synergies [15].

On one side, the requirements of transparency and high fidelity of forces, such as the concept of Z width [5], require that actuator solution is chosen to prevent anisotropic behavior and low perceived reflected inertias. If we consider that for a given gear ratio τ, we will achieve at the end effector an equivalent increase in terms of motor inertia I_m proportional to the square $\tau^2 I_m$.

Since in the case of electric actuation we need to adopt usually transmission systems to achieve the rate torque values, there are different approaches that have been developed to comply with this requirement (Fig. 4).

Gear drive designs

Direct-drive actuators are electric motors coupled with a transmission/reduction system; they can be classified according to the backdrivability and sensing system.

More commonly, joint torque solutions can be implemented by means of gear-drive designs, where Harmonic Drive speed reducers can provide important gear ratios for force amplification. The ArMin III exoskeleton [16] makes use of additional

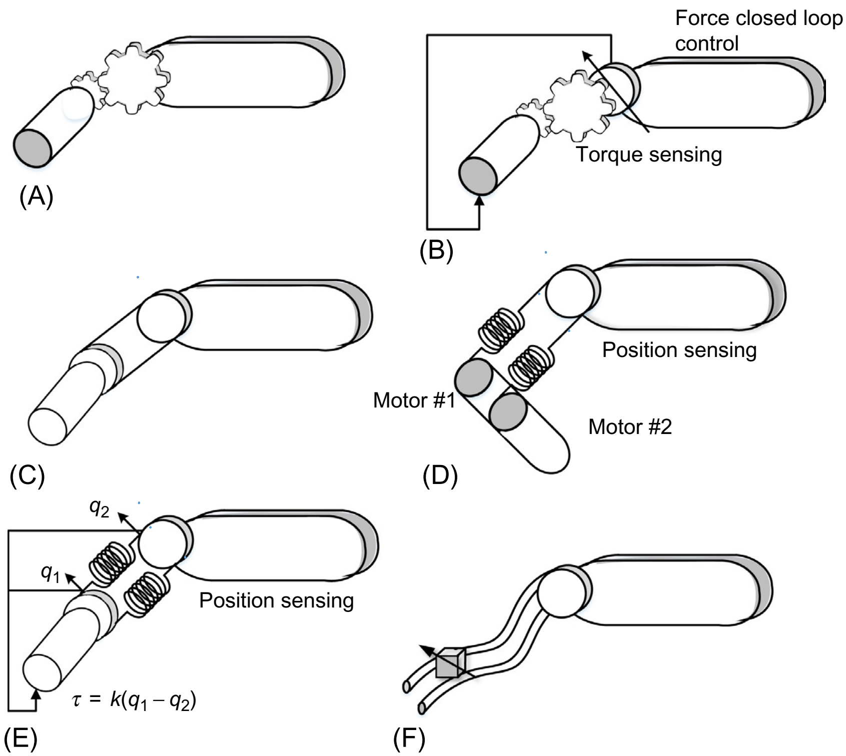

FIG. 4

Principles of actuation for exoskeletons. (A) Geared transmission. (B) Force sensorized joint. (C) Tendon transmission. (D) Variable impedance. (E) Series elastic. (F) Hydraulic-pneumatic.

passive degrees of freedom for compensating scapula elevation movement. In this case, actuators are located at joints and are composed of electric DC motors connected with Harmonic Drive (HD) gearbox with different reduction ratios according to joint location, while an open loop control can be used with feedforward compensation schemes for inertia and friction disturbances.

A hybrid approach successfully employed is a combination of ball-screw actuators and tendon actuation, such as in the case of ABLE exoskeleton [17]. In this case, the ball screw, thanks to the low friction, leads to an overall high backdrivability, while tendons are used for torque transmission at joints and motion conversion from linear to rotational.

Alternatively, to increase the backdrivability of the systems, hand force/torques and elbow load cells can be introduced at the connection points with the human, so that a closed-loop force control can be used, as in the case of MGA [18] exoskeleton.

Also, specifically designed joints can be used to obtain high-fidelity joint torque, by means of joint torque sensors integrated at the level of joints, so that impedance

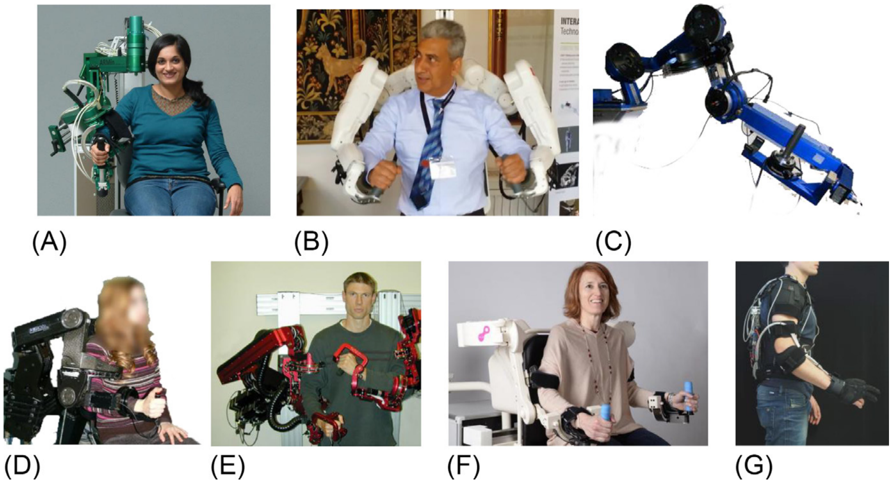

FIG. 5

Top, gear-drive designs, (A) ARMin III [16], (B) ABLE exoskeleton [17], (C) Rehab-Exos [19] at bottom tendon drive designs, (D) L-Exos [20], (E) EXO-UL77 [21], (F) ALEx [22], and (G) soft-arm compliant exoskeleton [23].

(A) Courtesy of Prof. Robert Riener, ETH. (B) Courtesy of Eng. Philippe Garrec, CEA. (E) Courtesy of Prof. Jacob Rosen, UCLA. (G) Courtesy of Prof. Lorenzo Masia, NTU.

behavior is achieved by closed-loop control. One of the issues with the design of integrated torque sensors is however the residual sensitivity to other force components and the bandwidth of the closed-loop controller that depends on actuator dynamics. The Rehab-Exos [19] makes use of a joint torque sensor to provide accurate torque control and increase backdrivability, while high torque can be delivered thanks to almost 1:100 Harmonic Drive gear reduction (Fig. 5).

Tendon transmission designs

Using tendon transmission allows to physically separate the motors from the joints where the actual torque is transferred: this has as strong effect on the reduction of moving masses, since motors can all be located at the level of a fixed frame, still achieving some force reduction according to the ratio between motor- and actuated joint-driven pulleys.

The tendon-driven designs have been proposed first with the L-Exos [20], characterized by four degrees of actuation for shoulder and elbow joints. The system is characterized by having all motors located at the back on a fixed frame, while steel metal tendons are used to transmit the torque to each joint. This design requires that the cable transmission system is characterized by a constant length, and this is achieved by a set of idle pulleys that drive the cable all over the joints. This leads to a consistent reduction of weight and inertia of the moving parts and smooth dynamic behavior.

Later, the Exo-UL7 was introduced [21], a seven-degrees-of-freedom tendon-driven exoskeleton based on the same principle of actuation, extended also to include wrist actuation. In both designs, the shoulder pronation/supination is implemented by means of an open circular guide to allow the compatibility with human arm.

Recently, Frisoli et al. proposed Alex [22], a bimanual tendon-drive exoskeleton that is based on a tendon transmission, exploits a novel kinematic solution to implement the shoulder joint, and is based on innovative patents remote of center mechanism.

Tendon transmission represents an ideal mean to achieve high backdrivability of the system and so typically adopts an open-loop impedance control scheme, meaning that there is no closed-loop control on joint torque.

Recently, the soft-exoskeleton concept has been introduced as well. Masia et al. [23], for instance, introduced sheathed tendons to control a shoulder exoskeleton, where the system is worn by the user as a garment and tendons can provide assistive torques directly at the level of the joint. To take into account the variability of friction due to change of configuration of the geometry of sheaths, calibrated dynamic friction models, e.g., LuGre model are used to compensate in feedforward.

In alternative, another example of a massless cable-driven design is the CAREX exoskeleton, where in this case it is exploited the principle that a minimum of $n+1$ cables are required to control n degrees of freedom [24].

Series elastic and variable impedance

One of the research lines to advance wearable robots is to develop and incorporate an adjustable compliance (i.e., stiffness) actuation that assists the human body to the desired dynamic motions.

The general traditional actuators, due to the absence of elastic or damping elements, can be lighter and more compact than variable-impedance actuators, and they better adapt to predefined trajectory control, but their time response and dynamic bandwidth are limited by control and electric properties of actuators, such as maximum reachable velocity by an electric motor.

In the context of research, some exoskeleton designs have been proposed based on VIA (variable-impedance actuators) actuators: they can be further divided in two categories, depending on whether the electric motor is coupled to a spring with fixed (series elastic actuator, SEA) or variable stiffness (variable-stiffness actuators, VSA) [25]. All the variable-impedance actuators have the advantage of absorbing impacts, and in addition, adding a series elastic element reduces the peak power demand on the motor, with consequent reduction of the motor size.

However, a strong limitation to adopt VIA actuators in exoskeleton design is due to their complexity, size, and/or weight.

The LOPES [26] at the University of Twente has been the first exoskeleton, for lower limb assistance, using series elastic actuation, and is capable to provide over mill gait assistance with the capability of adapting to user's motion, for example, walking and running. Recently, VIA has been successfully adopted for elbow exoskeleton in the NEURARM by Vitiello et al. [27]. Table 1 provides a summary of the main pros and cons of different electric actuator solutions.

Summary of actuation solutions

We present in Table 2 a short summary of the examined exoskeletons with indication of their actuation and adopted control solution.

Table 1 Pros and cons of SEA, VSA, and direct-drive solutions

	SEA	VSA	Direct drive
Pros	Capacity to store and restore the energy in the mechanical compliance	Variable stiffness	More compact design, high efficiency in torque transmission
Cons	Low bandwidth in position control, closed-loop bandwidth depending on two sensor readings	They generally use two motors that increases the size, weight, and complexity of the actuator in comparison with an SEA	Dynamic bandwidth limited by amount of speed reduction and speed limits of electric actuators

Table 2 Classifications of upper-limb exoskeletons according to actuation and kinematic

Exoskeleton	Actuation solution	Control	Anatomical districts	Number of DOFs
L-Exos [28]	Tendon drive	Impedance control	Shoulder and elbow	4
Exo-UL7 [21]	Cable-driven, tendon, and pulley	Impedance control	Shoulder, elbow, and wrist	7
Masia et al. [23]	Soft exoskeleton with sheathed tendons	Friction compensation	Elbow and shoulder	1
MGAXOS [18]	Gear drive	Force closed-loop control	Shoulder-elbow	4
ABLE [17]	Ball screws and cable	Impedance control	Shoulder-elbow-wrist	7
Rehab-Exos [19]	Gear drive	Closed-loop interaction joint control	Shoulder-elbow	4
Armin III [16]	Gear drive	Impedance control	Shoulder-elbow-wrist	7
T-WREX [15]	Passive exoskeleton	Spring passive behavior	Shoulder-elbow-wrist	5
Pneu-WREX [29]	Pneumatic	Nonlinear force control	Shoulder-elbow	4
BONES [13]	Pneumatic	Nonlinear force control	Shoulder-elbow	4
Salford exoskeletons [30]	Artificial pneumatic muscle	Force closed-loop control	Shoulder-elbow	7
Sarcos [31]	Hydraulic	Admittance control	Shoulder-elbow	7
NEUROExos [27]	Variable-impedance actuation	Torque control	Elbow	1

CLINICAL EVIDENCES OF UPPER LIMB REHABILITATION WITH EXOSKELETONS

There are evidences that exoskeleton can lead to significant improvement in the rehabilitation due to their capability of performing selective joint control and three-dimensional spatial training [32].

The first studies in chronic stroke with active exoskeletons were conducted with L-Exos [28,33] and ARMin II [34] exoskeletons showing significant increase in upper-extremity Fugl-Meyer score.

The rehabilitation training with L-Exos exoskeleton [6] in the recovery of spatial reaching movements, with a focus on point-to-point reaching movements performed in different directions, produced positive effects in movement execution, in terms of decreased execution time, improved movement smoothness, and increased active joint ranges of motion. In particular, the observed functional changes were found to be associated to an improvement in the cocontraction index of proximal joints, in particular for shoulder extension and flexion.

One of the earliest randomized controlled trials with exoskeletons [15] was conducted with T-WREX (31 chronic stroke patients divided in two groups), a passive instrumented arm orthosis, finding a statistically significant difference in Fugl-Meyer assessment of the upper-extremity (FMA-UE) scale between T-WREX and the conventional therapy.

A subsequent controlled study made use of a pneumatic actuated exoskeleton version, the Pneu-WREX [29], used to assist patients also in movement completion, and confirmed how in patients with chronic and moderate-severe deficits (26 chronic stroke patients divided in two groups) exoskeleton training in three-dimensional virtual tasks was more effective than conventional tabletop training.

More recently, a larger controlled study conducted with the ARMin [35] exoskeleton (77 patients with moderate to severe paresis divided in two groups) confirmed that robotic training performed with task-specific training in three dimensions reduces motor impairment more effectively than conventional therapy, since patients assigned to robotic therapy had significantly greater improvements in motor function as measured by FMA-UE.

Also, the UL-EXO7 [36] with seven DOF was applied in a clinical trial for the rehabilitation of chronic stroke patients (>6 months since acute event). The study reports the results of the comparison of unilateral robotic training (five patients), bilateral robotic training (five patients), or usual care (five patients) and showed that bilateral-movement training scheme obtained better outcome in wrist-joint movement and other quantitative parameters compared with the unilateral training group.

But what is the effect of wearing an exoskeleton on human movement performance?

Pointing movements toward target were evaluated [31] under the exposure to space artificial force field generated with Sarcos hydraulic exoskeleton. They were found to be altered in healthy subjects until sufficient adaption is reached to return to null-field trajectories. But interestingly, it was found that subjects do not return to the same null-field trajectories in the joint space, making speculation that our motor control does planning of reaching movements in extrinsic (task space) coordinates. This task was further analyzed in another study [32] by making use of the ABLE exoskeleton, where natural interjoint coordination in pointing movement was measured by means of principal component analysis (PCA), confirming the absence of joint-space adaptation but evidencing also the lack of end-point movement adaptation and the capability of using exoskeletons to teach new upper-limb synergies in pointing and tracking tasks. These are considered relevant features for the application of exoskeletons for rehabilitation of poststroke patients.

Another study, conducted with the Alex, showed that motor synergies, assessed by EMG recordings, are not altered by the usage of the exoskeleton [22].

It is moreover reported in literature that the usage of exoskeletons allows to monitor the levels of spasticity by isokinetic movements at various angular velocities within the capable range of motion for both joints [37] or perform specific training against spasticity. The results suggested that intense early rehabilitation could contribute to prevent elbow spasticity from occurring at a later stage (3–4 months after stroke) of recovery [38].

CONCLUSIONS

This chapter has presented an overview of the main issues for the design of upper-extremity exoskeleton for rehabilitation, analyzing the main aspects of choice of kinematics, actuation, and relevant results of clinical evaluation.

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