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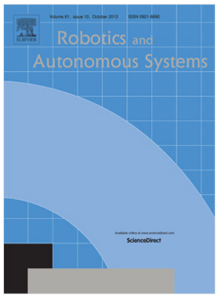

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Cable Driven Exoskeleton For Upper-Limb Rehabilitation: A Design Review

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Abstract

One of the primary reasons for long-term disabilities in the world is strokes. The causes of these cerebrovascular diseases are various, i. e., high blood pressure, heart disease, etc. For those who survive strokes, this affectation causes lose in mobility of extremities, requiring the intervention of long session with a therapeutic professional to recover the movement of the impair limb. Hence, the investment to threat this condition is usually high. Those devices permit the user a mean to conduct the therapies without the constant supervision of a professional. Furthermore, exoskeletons are capable of maintaining a detailed recording of the forces and movements developed for the patients throughout the session. However, the construction of an exoskeleton is not cheap principally for the actuation systems, especially if the exoskeleton requires the actuator to be placed at the joints of the user; thus, the actuator at a joint would have to withstand the load of the actuator of the following joint and so on.

Researchers have addressed this drawback by applying cable transmission systems that allow the exoskeleton to place their actuator at a base, reducing the weight of their design and decreasing their cost. Thus, this paper reviews the principal models of cable-driven exoskeleton for stroke rehabilitation focusing on the upper-limb. The analysis departs from the study of the anatomy of the arm in all its extension, including the shoulder, elbow, wrist, fingers, and the thumb. Besides, it also includes the mechanical consideration the researchers have to take in mind to design a proper exoskeleton. Then, the article presents a compendium of the different transmission systems found in the literature, addressing their advantages, disadvantages and their requirements for the design. Lastly, the paper reviews the cable-driven exoskeleton for stroke rehabilitation of the upper limb. Again, for this analysis, it is included the design consideration of each prototype focusing on their advantages in terms of anatomical mechanics.

Keywords: Cable-driven exoskeletons, Transmission systems, Stroke rehabilitation

1. Introduction

Robotic exoskeletons are exoskeletal structures worn on limbs that serve to enhance or sense the physical capabilities of a user. This technology has been under study since the early 1960s for military applications [1]. Nowadays, according to their functionality, exoskeleton can be classified by their purposes in: rehabilitation [2, 3, 4, 5], haptics [6, 7, 8, 9], assistive device [10], teleoperations [11, 12], and power augmentation [13, 14]. Moreover, from the listed applications, rehabilitation has been of special interest in recent days due to its high potential in the treatment of limb impairment occasioned by strokes [15].

Cerebrovascular diseases or stroke is the principal cause of long-term adult disability in Europe and many other countries. Furthermore, stroke cases are estimated to consume near 3-4% of health expenditures in developed countries [16]. In more than 85% of cases, stroke causes impairment of the upper limb and disabilities in performing activities of daily living [17], and only in near 10% of cases the subject recovers the mobility of the arm despite therapeutic intervention [18].

The process of return of mobility is slow partly due to the complexity of movement required for the upper limb function [19]. Moreover, to regain function capabilities, the patients have to be submitted to repetitive and task-oriented functional training [20], representing a time consuming and intense labor for the therapists [21]. Thus, researchers have inclined to implement exoskeletons into the process of rehabilitation demonstrating that these devices are useful for motor rehabilitation and can decrease the amount of expenditure in treatments [22]. Robotic exoskeletons can also include sensors to monitor and register the progress in the process of rehabilitation.

Robotic exoskeletons are usually assembled by rigid links using rotational joints in parallel to the joint axes of the human arm to emulate the movement of the upper limbs. Due to the linear configuration, some exoskeletons use serially coupled motors on the structure to actuate each revolute joint [23, 24], this arrangement increases both, the inertia of the robot, and the size of the motors. Moreover, this issue induces misalignment of the arm joint axes with the robot axes, which promotes compensatory movements which can restrain the recovery and decrease real-life use of the arm [25]. Furthermore, the parasitic forces generated by the misalignment causes discomfort and pain on the patient's arm even may lead to dislocation or fracture [26]. Some researchers have addressed the problem of misalignment by adding passive degrees of freedom (DOF) to the device [27, 28, 29]. However, this solution usually increases the complexity of the robot.

A method to resolve the problem of high inertia in exoskeletons is the use of cable-based actuation. This approach uses lightweight cables to transmit motion and forces allowing the actuators to be mounted away from the joints, achieving low weight and increasing the cost-effectiveness relation [30]. Besides, remote actuation enables the mechanism to add more DOF, due to the decrease in complexity, permitting to address the problem of axes misalignment. In the literature exists various examples of cable-based actuation used for rehabilitation [31, 32, 33, 34, 35].

In the context of upper limb rehabilitation, researchers have classified cable-driven robots into two categories: end-effector devices [36, 37] and exoskeletons. In the former, the patient takes a hand-holder programmed to follow trajectories that stimulate the natural movements of the arm [38, 37] without considering individual joint motions. In the literature exists examples of this category such as MARIONET [39, 38], HandCARE [37], NeReBot [40, 41, 42], and PACER [43]. Compared with exoskeletons, end-effector devices lack a detailed recording of the upper-arm joint movements, which do not allow an accurate evaluation of the rehabilitation progress.

Cable-driven exoskeletons also have other advantages such as the transmission itself which can be designed to implement speed reductions with low friction forces and zero backlash, as long the cables are tensioned [44]. This feature allows the reduction of the actuation system that ultimately decreases the weight of the mechanism. However, as cables cannot transmit compression forces most cable transmissions require the utilization of an antagonistic force to control the joint movements [45].

This article presents a review of the cable-driven exoskeletons for upper limbs. The survey includes a detailed analysis of the different configurations for transmission using cables. Besides, the article shows an overview of the upper arm-limb anatomy, presenting the design difficulties and the range of motion of each articulation. This article is intended to be a reference guide for the design of cable-driven exoskeleton for upper limb rehabilitation. Although we believe that we include most of the reference, it is possible that we omitted a few.

2. Anatomical Review of the Upper Limb

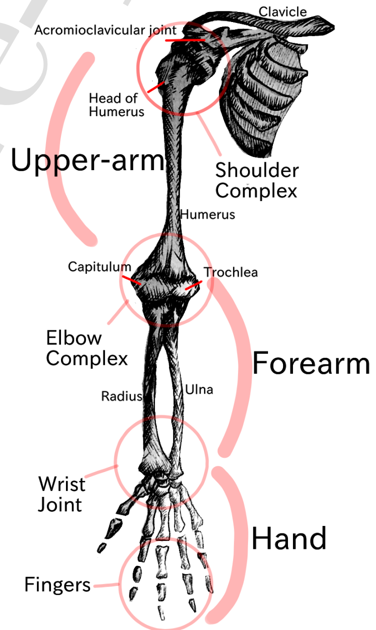


Figure 1: Anatomy of upper limb.

This section summarizes the design requirements from the biomechanical viewpoint of the upper limb exoskeletons. The arm movement is possible thanks to the interaction of four joint systems: the shoulder complex, the elbow complex, the wrist, and the phalanges (Fig. 1). Thus, table 1 compiles the information regarding each joint system, including their types of movements, the range of motion, and an explanation of the design issues.

Table 1: Anatomic description of upper-limb joints for the design of exoskeletons

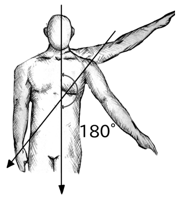
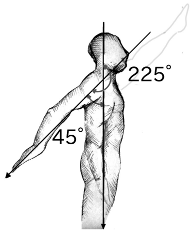
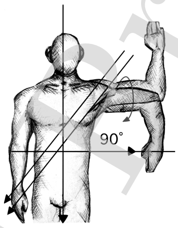
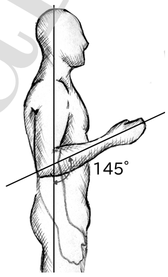
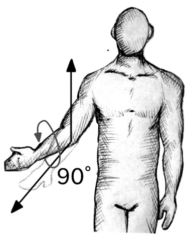
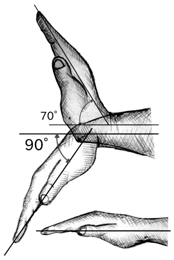
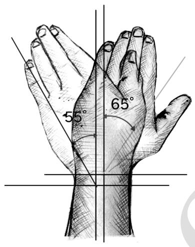
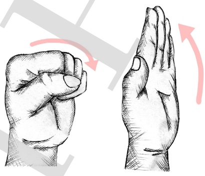
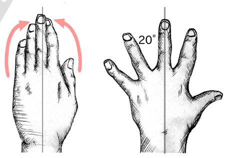
Anatomical sections	DOF	Range of Motion	Design Issues
Shoulder Complex	Abduction/Adduction		The complex glenohumeral (GH) joint of the shoulder generates an instantaneous center of rotation (ICR). If an exoskeleton is built without taking into consideration the ICR, the parasitic forces generated within the GH can generate dislocation [46]. Many authors propose to add passive DOF to combat the effects of these misalignments. Park. Hyung-Soon et al. propose to add two passive DOFs in anterior/posterior and medial/lateral displacement of the glenohumeral joint [47].
	Flexion/Extension		
	External rotation/Internal Rotation		
Elbow and Forearm	Flexion/Extension		The motion of the axis of rotation causes misalignments between the human and robot joint, generating translational forces at the physical human-robot interaction surface [48]. These translational forces are very undesired since they load the skin and the musculoskeletal system making the interaction uncomfortable or even painful [49]
	Supination/Pronation		In the case of pronation/supination, the movement occurs in one axis orthogonal to the flexion/extension axis. The movement involves a superposition in which the radius rotates around the ulna. This rotation is not necessarily parallel to the forearm, but the misalignment between the orthosis device and the forearm prosupination axis are not necessarily critical in the design [50]. That idea allows the displacement of the rotation axis for pro-suplination movement.

Table 1 (Continuation) : Anatomic description of upper-limb joints for the design of exoskeletons

Anatomical sections	DOF	Range of Motion	Design Issues
Wrist	Flexion/Extension		The wrist joint possesses two pairs of orthogonal motion. Although each pair of motion corresponds to rotations in the same directions, the axes of rotations are misaligned. Hence the wrist complex posses four different axes of rotations [46]. For each pair of axes, the difference in the axis of rotation is near 5 mm [51]. Taking into consideration the difference in the axis position is a mandatory design requirement for wrist joints, obliging to utilize a minimum of two DOF to emulate each of the wrist movements completely
	Ulnar-Radial deviation		
Hand[1]	Fingers Flexion/Extension		Each of the fingers is composed of four articulations: carpometacarpal (CMC) joint, metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint, and distal interphalangeal (DIP) joint [52]. The CMC is a biaxial joint that allows two different movements: flexion/extension and abduction/adduction [52]. From a design perspective, most researchers do not consider the abduction/adduction when designing an exoskeleton for the hand, instead, prefer to add a passive DOF [53]. However other designers add actuation to this joint as in the case of Li et al. in [54].
	Fingers Abduction/Adduction		

[1] Not all hand DOF are covered, due to the lack of exoskeleton's designs for them.

3. Cable-based Transmission Systems for Exoskeletons

To classify cable-based transmission exist two main categories: open-ended cables and close-loop cables. Inside those two categories, there are various subdivisions as presented in table 2. Additionally, Table 2 presents the comparison of the actuation systems in terms of their non-linearities (friction and backslash), bulkiness, range of motion, efficiency, and controllability. This section reviews each category of cable transmission, focusing on the advantages and disadvantages of each category. Besides, this section also mentions the requirements of design to implement each transmission.

Table 2: Comparison of Types of Actuation-transmission Mechanisms.

General classification	Transmission mechanism	References	Direction of actuation	Friction	Bulkiness
Close cable	Pulley transmission	[55], [56], [57], [58], [47],[59], [60], [11], [61], [62], [63], [39]	Bidirectional	*Medium/Low*. It depends on the number of idle pulleys.	*High/Medium*. It depends on the number and range of motion of each joint, which increases the needs for idle pulleys.
	Pulley transmission linear configuration	[64], [65]	Bidirectional	*Low*. The actuation system posses low friction, mainly because only it uses screw-balls actuators.	*High*. The linear actuator must be mounted on the structure, which adds bulkiness to the arrangement.
Open cable	Pulley transmission	[55], [66], [67], [68], [69], [70], [71],[72], [73], [10]	Bidirectional	*Medium/Low*. It depends on the number of idle pulleys.	*High/Medium*. It depends on the number and range of motion of each joint, which increases the needs for idle pulleys.
	Bowden cable to anchor point	[74], [75], [53], [76], [77], [78], [79], [80], [45], [81], [82], [83], [84], [85], [54], [86], [87], [88], [89], [90], [91], [92], [93], [94], [29], [95]	One-way	*High*, because it requires the use of sheats to guide the cable until the anchor point, also increased for pre-tension requirements.	*Low*. It allows the actuation system to be on a different structure.
	Capstan	[44], [66], [96], [97], [23], [98], [99]	Bidirectional	*Medium/High*. Besides the requirement of idle pulleys, this configuration needs pre-tension of the wires.	*High*, because it requires the actuators to be mounted on the structure, and also requires the use of idle pulleys.
	Motorized reel to anchor point	[100], [101], [30], [102], [103], [104], [105], [106]	One-way	*Low*. Each actuator only requires a pulley to guide the cable.	*Medium/low*. It depends on the DOF and workspace of each joint, which may increase the number of anchor points required to control the joint.
	Push and pull cables	[107], [108], [109]	Bidirectional	*High*, because it requires sheats, which guide the cable to the anchor point, incrementing the friction.	*Low*. It allows the actuation system to be on a different structure.
	Pneumatic muscles	[110], [111], [112], [113], [114], [115], [116]	One-way	*Low*. The friction is mainly occasioned because of fluid displacement, that generates pressure losses.	*Low*. It allows the actuation system to be on a different structure.

Table 2 (Continuation): Comparison of Types of Actuation-transmission Mechanisms.

Backlash	Range of motion allowed (workspace)	Efficiency	Controllability
High. It is inherent of the actuation system, additionally the backlash increases as a function of the additional pulleys.	*Medium/High*. To maintain a high workspace, this system requires the use of multiple idle pulleys.	*Medium/ High*. Although the system permits an adequate conversion of energy, the system loses efficiency because it is not inherently self-blocking.	*Medium*. Although this system posses diverse problems regarding nonlinearities in the analysis of friction or increases in the longitude of cables, the equations that model those phenomenons are well established, facilitating the control.
Low. The screw-balls decreases the backslash.	*Low/Medium*. It depends on the distance between pulleys.	*High*. The system is inherently self-blocking, and the actuation systems posses low friction.	*High*. The system allows the use of simple control strategies such as PID, because it behaves as a linear model.
High. It is inherent of the actuation system, additionally the backlash increases as a function of the additional pulleys.	*Medium/High*. To maintain a high workspace, this system requires the use of multiple idle pulleys.	*Medium/High*. Although the system permits an adequate conversion of energy, the system loses efficiency because it is not inherently self-blocking.	*Medium*. Although this system posses diverse problems regarding nonlinearities in the analysis of friction or increases in the longitude of cables, the equations that model those phenomenons are well established, facilitating the control.
Low. The high friction helps the system to avoid backslash.	*Low*. To maintain the integrity of the cable, the range of motion is limited to small displacements.	*Low*. The system requires additional energy consumption because of the pretension of the wires.	*Medium/High*. Although the friction within this actuation system is high, the friction increases the stiffness of the system, allowing the system a mean to handle the disturbances due to undesirable movements of the user.
Low or non-existing. The existence of backslash would depend on the amount of friction within the joint; if the friction is enough, there will not be any backslash.	*Medium*. In mechanical terms, it does not allow the complete rotation of the joint, but in anatomical terms, the range of motion is enough to emulate the human body joints.	*Medium*. This system is self-blocking, although it has friction.	*Medium*. Friction is a problem that has not been modeled yet.
Low. The system requires to keep a high force on the cables to avoid sagging, that also helps to evade backslash.	*Low/Medium*. The range o motion depends on the number and position of the actuators controlling each joint.	*Medium*. Although the system does not have problems with friction, it requires high tension to minimize sagging within the cable, decreasing the efficiency.	*Medium/High*. Because the exoskeletons that use motorized reels are over actuated, the system allows multiple torque outputs for each actuator, generating output torque for multiple situations.
Low. The high friction helps system to avoid backslash.	*Low*. To maintain the integrity of the cable, the range of motion is limited to small displacements.	*Low*. The system requires additional energy consumption because of the high friction.	*Low*, because the equation that models the friction within this system is not well established, occasioning the need for implementation of additional sensors.
Not backslash.	*Low*. The expanding length of the bladder is limited.	*Low*. Pneumatic systems are inefficient because of losses in the air pressure.	*Low*. The response is slow because the system requires the bladder to expand.

3.1. Open-ended cable transmission

Open-ended cable (OEC) systems apply forces in only one direction; thus, this configuration needs more cables than DOF to obtain motion in both directions of a joint. Therefore, for an application of n-DOF, it is required of a least n+1 wires to control the movement [117]. Due to this characteristic, OEC distributes loads across several cables, reducing the actuator requirements [67]. However, as wires cannot withstand the forces of compressions, it is required to add tension to them to avoid slackness. Although this condition may be acceptable, the dynamic transition between a tensed and a loose cable produces transversal vibrations [118], which can impair the stiffness of the mechanism [119].

3.1.1. Motorized reels

Motorized reel or winches is the most common configuration for cable-driven robots. As can be seen in Figure 2f, winches are compact and simple. In the majority of its applications, winches utilize servo actuators to control the cable length. Due to winches are usually aside of the exoskeleton, they do not impose an upper limit on the size of the motor, besides for cost reasons.

The implementation of motorized reels has two main requirements [120]. First, to ensure continuous operation of cables without deterioration, it is required that the bend radius experienced has to be significantly higher than the diameter of the wires. Secondly, it is necessary to include an omnidirectional guidance pulley into the winches to redirect the cables as they are changing their direction continuously.

In terms of control analysis, motorized reels possess two main challenges. First, the generation of trajectories that guarantee the user the realization of daily life activities [100, 104], and secondly, because of this type of system are over-actuated, the obtention of the adequate set of forces for each motorized reel [30]. For the former, researchers have reported the implementation of a static workspace optimization around the most frequently used volume [100, 101]. Although this approach does not guarantee a feasible spatial trajectory, the static workspace optimization exhibits a moment minimization and force reduction in the joints of the device [100].

For the latter, designers have used a combination of two control strategies, a low-level cable tension controller [105, 101], and a high-level force field controller [103, 102]. The first strategy tackles the nonlinearities generated by the friction within the joints and the cables; the second creates a tunnel-like force field around the nominal path for the angular displacement of each joint [102], therefore when the patient is not generating enough force to follow the trajectory, the controller assist the patient to keep the desired position.

3.1.2. Bowden cables

In this transmission system, a cable is guided through a flexible sheath and attached to an anchor point. Then, the mechanical displacement between the wire and the sheath delivers the actuation force to the anchor point [121]. Both linear or rotational actuator can be used to provide the displacement to the cable as can be seen in Figure 2d. Bowden cables require a preloading unit to maintain the tension of the cable respect to the sheaths; this requirement can be achieved using compressed springs [122, 90, 91] or helical torsion springs [123]. Bowden cables can work under compression only if the length is short and the loads are small [109].

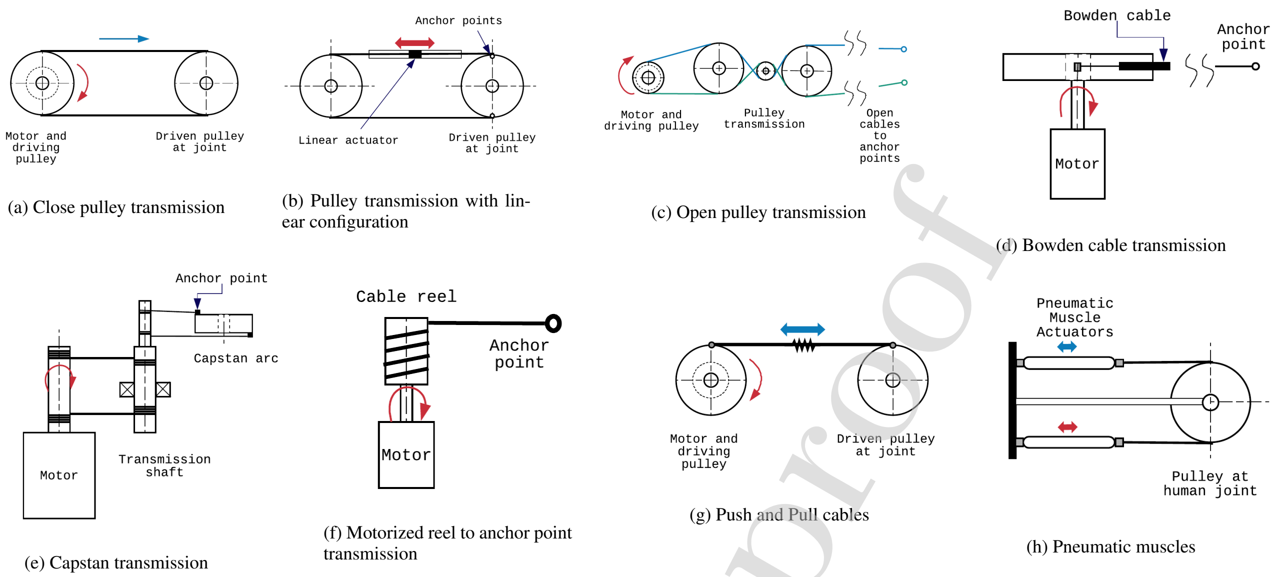
The principal consideration to take in mind when designing Bowden cables is the friction coefficients resulting from material pairs and velocity of the wire within the external sheath. The non-linear friction such as Coulomb friction, viscous friction, stiction, and stick-slip within the Bowden cables transmissions increases the inefficiencies and the difficult to sense the forces [124]. Also, according to Goiriena et al. for the same diameter, cables with more wires have better resistance to fatigue and are more flexible. Nevertheless, for the opposite, cables with fewer wires can resist greater loads but are fewer flexibles [125].

The friction on Bowden cables principally depends on curvature, pretension, and length of cable [54]. Friction is a drawback for Bowden cables because it causes low efficiencies in the power transmission system [91], increasing the resistance in the joints [88]. However, in some cases, the increase of friction is also desirable, because friction within cables reduces slackness and also absorb undesirable movements of the users [80]. Therefore, some authors increase the friction coating the cables with sheaths made of Teflon [92].

3.1.3. Pulley transmission

In open-ended pulley transmission, one end of the cables is attached to a driven pulley while the other end is connected to a linear actuator or a driving pulley that is joined to a rotary actuator [126]. This type of transmission usually comes with an antagonistic cable wounded on the opposite side of the pulley to control the joint position in both directions [69] as can be seen in Figure 2c.

To design pulley transmission to control exoskeletons exist two main requirements. First, due to the cables have to be tense around the pulleys the longitude of the



(a) Close pulley transmission
(b) Pulley transmission with linear configuration
(c) Open pulley transmission
(d) Bowden cable transmission
(e) Capstan transmission
(f) Motorized reel to anchor point transmission
(g) Push and Pull cables
(h) Pneumatic muscles

Figure 2: Types of actuation and transmission systems from the state of art

wires is fixed, then the relative position between the pulleys and the actuation system has to be constant [117]. Secondly, when controlling multiple joints, it is required to use idle pulleys to extend the range of motion of each joint, due to in rotation distal links may produce looseness in the cables [66].

This configuration suffers from loss of power generated by the nonlinear effects of different types of friction, but mainly of Coulomb. Therefore, researchers have found expression to model the friction in open cable pulley transmission systems [124]. Furthermore, another type of singularity appears when the high tensions in the cable, because of a change in the axis of actuation, increases the longitude of the cable. S. Ball et al. implemented a hinged system to guide cable, minimizing the tension in the cable and the non-linearities Ball et al. [67].

3.1.4. Capstan transmission

Capstan transmission consists of a motorized spool-shaft, from which two wire ends are winded and unwinded in opposite directions and attached to anchor points [127, 99] as shown in Fig. 2e. Some variations of this type of transmission include an intermediate capstan shaft [44] and a final arc [66] (also known as capstan wheel [97]), which rotates aligned with the limb joint.

The main advantages of capstan transmission are low friction and the absence of backlash [97]. The minimal normal forces at the final joint explain the low friction. Therefore, capstan forces at anchor points are purely tangential. Besides, the elastic behavior of the wire avoids the backlash.

On the other hand, the low capacity of transmitting torque and the pretension of the wire are the most critical limitations for capstan transmission [97]. Hence, this type is usually fixed to a previous gear stage, to accomplish the velocity reduction and the torque outputs [97]. Meanwhile, the stiffness requirement is achieved by the wire pretension, which implies the use of extra devices, such as intermediate shafts [66] and idle pulleys [23]. The last also requires a close location of motor respect the capstan arc. Thus, it can affect the ergonomics in an exoskeleton design since the limb supports the weight of the motor.

The applications of capstan actuation are mainly limited to serial exoskeletons. A drawback related to exoskeletons with this robotic typology is the presence of singularities in undesired regions of the workspace [58]. In this regard, the most common singularity occurs when a spherical joint is modeled by three orthogonal revolute joints, then, if two joints align, the system loss control of the exoskeleton. One strategy used by designers to address this problem consists on modifying the location and orientation of the fixed joints, in order to move the region of singularities to a less critical place in the workspace [97]. However, the handle of viscous or Coulomb friction and in capstan configurations is still an open problem, that is addressed directly by the control strategy [98].

3.1.5. Pneumatic muscles (PMs)

PMs are thought to exhibit similar properties as the human muscles. PMs are composed of an expandable bladder inside of a braided shell. When the bladder is pressurized, it expands in the radial direction against the braided shell, causing it to contract [128]. This contraction serves as a pull effect acting on the end effector as presented in figure QER. PMs facilitates the compliance of the actuator and the limbs to move. Nevertheless, the implementation of PMs adds additional features to consider when implementing them, such as complexity in the control and the extra cost [115].

The principal drawback in the design of PMs is that they have a slow response time in force generation. Some authors have addressed this problem in rehabilitation applications by applying iterative learning control (ILC) [113]. By the use of ILC a controller can learn from each individual updating and shaping a feed-forward control command. On the other hand, the range of motion of PMS depends on the anchor position and the length of the braided shell i. e. the more extended the PMs, the higher their capacity of contraction [111].

Moreover, authors have conducted a dynamic characterization of the response of PMs [129]. The results of this research allow designers the selection of appropriate dimensions for the PMs, permitting the implementation of more accurate control strategies.

3.1.6. Push-pull cables (PPCs)

PPCs are a type of cable transmission system that permits the power actuation with a bi-directional (push and pull) mechanical force driving [130]. A general structure of a PPC consists of an inner member, an inner tube, and an external layer, as presented in Figure 2g. The inner member is made of a wire rope covered with the inner tube. The inner tube is usually made of flexible steel. Thus, the force transmission occurs by the displacement of the inner wire rope relative to the external layer. To reduce the friction within the system between the inner tube and the outer layer a lubricant is sealed [131].

Similar to Bowden cables, PPC are flexible and permit the transmission of high power with low inertia at the end-effector. Besides, PPCs tends to be larger in diameter when compared with Bowden cables because of the requirements in stiffness. However, it is complicated to estimate the friction of the PPCs, due to this parameter depends on the spatial shape of the cable, preloading, and the relative velocity respect to the outer layer. To compensate for the issues of friction, some authors have used force cells on both sides of the PPCs to measure the amount of friction within the system[132].

3.2. Close-ended cable transmission

Close-ended cable (CEC) transmissions consist of at least two fixed pulleys coupled by a wire, which transmits motion by friction forces. The dynamics of this transmission system at the pulley can be modeled by Euler-Eytelwein's equation [174]. A rotational or linear actuator is needed to supply the DOF of the pulley joint rotation. In this sense, this transmission system is capable of exerting torques in both directions, for obtaining counter and clockwise rotation. Besides, a feature of CEC transmission is that wire initial tension is achieved by the distance between the pulleys axis and/or by using intermedial idle pulleys.

3.2.1. Pulley transmission

Pulley transmission uses a rotational actuator connected to a driving pulley and a cable, which transmits motion to a drive pulley, as shown in Fig. 2a. The torque requirement is usually accomplished by the diameter difference between both pulleys [56, 57, 10]. Another option less common consist of a previous gear velocity reduction stage with a final pulley transmission [59, 61].

The main drawback of this transmission system appears when the distance between the driven and drive pulleys does not achieve the required wire preload. Then, a set of intermediate idle pulleys is needed for routing the wire without slackness, which makes the design heavy and bulky [133]. Also, this reduces the range of motion (ROM) of the pulley joint. In this regard, in [10] was found that the ROM is increased by augmenting the pulley joint diameter.

The use of idle pulleys to keep the tension of the cable can result in undesirable singularities. J. Sulzer et al. found three types of nonlinearities for the idle pulleys: Convergent, bifurcation, and bistable states; And obtaining the respective equations that describe the torque requirements for each configuration. Therefore, facilitating the implementation of control strategies such as torque control Sulzer et al. [134].

3.2.2. Pulley trasmission with linear configuration

This transmission employs a linear actuator located in parallel to a close conventional pulley system. The actuator can transmit the motion to the pulleys in both directions by pulling the connector cable, as shown in Fig. 2b. The center distance between pulleys provides preload to the wire [64] and becomes a critical requirement in the design. Also, the linear configuration allows a compact transmission system [65] distributed longitudinally through the non-moved limb.

In this type of transmission, the linear actuator stroke limits the rotation span of the drive pulley. Additionally, the lack of accuracy and bandwidth are common problems when exoskeleton robots use hydraulic or pneumatic linear actuators [135]. Hence, this transmission system was firstly though for screw-balls actuators [136], which also allows high force capacity and low friction [64].

This configuration uses a torque control strategy. In this sense, The torque control of the motor is a combination of gravity compensation torque and a reaction torque proportional to a position error. However, the linearity between the position error and the exerted force is a function of the amount of friction in the transmission. Therefore, to decrease the non-linearities because of friction the system uses ball-screws, decreasing its value to 1/1000 of the total force [135].

4. Cable-driven upper limb rehabilitation exoskeletons review

This section is dedicated to the review of the principal cable-driven exoskeletons for upper limb rehabilitation found in the literature. Table 3 presents the exoskeletons analyzed, classifying them in terms of DOF, type of actuator, transmission system, and limb location. Besides, table 4 compares characteristics of the exoskeletons such as bulkiness, anatomical joint adjustments, non-linearities approach, and control strategy. Additionally, the review addresses the mechanical characteristics of each exoskeleton, remarking its uniqueness, advantages, and disadvantages.

Table 3: Resume table of Exoskeletons.

Name	Article references	DOF	Type of actuator	Location of the actuation unit	Type of transmission	Limb group
ABLE	[64], [65]	4, 5 or 7	Rotatory electric (DC motor) to linear ball screw	External on body (Parallel to the limb)	Close cable-pulley with linear configuration	For 7 DOF: Shoulder (3DOF), Elbow (1DOF), Forearm (1DOF), Wrist (2DOF)
ARMin	[98], [137], [138], [139]	6	Rotatory electrical (DC motor)	External on body	Capstan/Open and Close pulley transmissions	Shoulder (3DOF), Elbow (1DOF), Wrist (2DOF)
CABXLexo-7	[122]	7	Rotatory electrical (DC motor)	External	Capstan/Bowden cable	Shoulder (3DOF), Elbow (1DOF), Wrist (3DOF)
CADEN-7	[57], [10]	7	Rotatory electrical (DC motor)	External	Close cable pulley transmission	Shoulder (3DOF), Elbow (1DOF), Wrist (3DOF)
CAFE	[72]	3	Rotatory electrical (DC motor)	External frame	Open cable pulley transmission	Index: MCP (1DOF), PIP (1DOF), DIP (1DOF)
CAREX	[100], [101], [30], [102], [103], [57], [105], [106], [140]	7	Rotatory electrical (DC motor)	External frame	Motorized reel to anchor points	Shoulder (3DOF), Elbow (1DOF), Wrist (3DOF)
Exosuits	[92], [93], [95]	1	Rotatory electrical (DC motor)	External on body (user´s back)	Bowden cable	Elbow
HANDEXOS	[75], [53], [76]	3	Rotatory electric (DC motor) to linear ball screw	External on body	Bowden cable	Hand fingers: MCP (1DOF), PIP (1DOF), DIP (1DOF)
HX	[77]	4	Rotatory electrical (DC motor)	External	Bowden cable	Index: MCP (1DOF), P-DIP (1DOF); Thumb: MCP-DIP (1DOF) and Opposition (1DOF)
iHandRehab	[54]	4	Rotatory electrical (DC motor)	External on body	Bowden cable	For each finger: MCP (2DOF), PIP (1DOF), DIP (1DOF)
IntelliArm	[47], [59]	7	Rotatory electrical (DC motor)	External	Close cable pulley transmission/Capstan	Shoulder (4DOF), Elbow (2DOF), Wrist (1DOF)
MEDARM	[117], [67], [68]	6	Rotatory electrical motor	External	Open cable pulley transmission	Shoulder complex (5DOF) and elbow (1DOF)
MRAGES	[109]	4	Linear magnetorheological	External on body	Bowden cable	Hand fingers except thumb (1DOF for each one)
NEURARM	[78], [79]	2	Linear hydraulic	External	Bowden cable	Not specified
NEUROExos	[80], [45], [81], [82], [83], [84]	1	Linear hydraulic	External	Bowden cable	Elbow
RiceWrist-S	[44], [96]	3	Rotatory electrical (DC motor)	External	Capstan	Wrist
RUPERT	[111], [112], [113], [114], [115], [116], [141]	5	Linear pneumatic	External	Pneumatic muscles	Shoulder (2DOF), Elbow (2DOF), Wrist (1DOF)
ShouldRO	[85]	2	Not specified	External	Bowden cable	Shoulder complex
SUEFUL-7	[55]	7	Rotatory electrical (DC motor)	External on body	Close cable pulley transmission	Shoulder (3DOF), Elbow (1DOF), Forearm (1DOF), Wrist (2DOF)
UT Exoskeleton	[91], [90]	2	Rotatory electrical (DC motor)	External on body	Bowden cable	Index: MCP (1DOF), PIP (1DOF)
WRES	[142]	3	Rotatory electrical (DC motor)	External on body	Capstan differential transmission	Wrist
Wrist Gimbal	[66]	3	Rotatory electrical (DC motor)	External	Capstan	Wrist

Table 4: Design issues of analyzed exoskeletons.

Name	Bulkiness	Anatomical joints adjustments	Non-linearities approach	Control strategy
ABLE	Medium/Low. The use of linear screws within ABLE reduces the size of the mechanism. However, this feature also reduces its workspace.	The system does not provide means to tackle the variation of the center of rotation of the anatomical joints.	The ball screw system used to actuate the exoskeleton reduces friction and minimizes non-linearities.	The reduction of nonlinearities allows the implementation of simplified versions of torque control strategies.
ARMin	Medium. ARMin employs direct actuation external/internal rotation DOF, which increases bulkiness.	The adjustment is achieved by length adjustable links for patient's upper-arm and forearm. Besides, an extra manual passive DOF allows an initial alignment of the glenohumeral joint, by setting an offset angular position. Finally, the three fixed passive DOF are measured with two wire linear potentiometers and one rotational potentiometer, respectively.	Non-linearities related to velocity-dependent friction and spring effects from electronic cables are simplified in a torque model with experimental constants values .	The mechanism employs a close angular position loop with novel Online Adaptive Compensation (OAC). This strategy uses linear wire potentiometers for automatical gravitation compensation, based on specific patient anthropometrics for upper-limb. Also friction and spring-effects from electronical cables around the exoskeleton are considered in the loop.
CABXLexo-7	Low. The system adopts both a captan actuation system and Bowden cables to increase its compactness.	The system allows the positioning of the shoulder and wrist center of rotation. For the former, an arrangement of capstan mechanisms that allows the free motion of the patient's shoulder is used. And the latter includes a holder that allows the displacement of the hand in the case of a change in the axis of rotation. However, non of these features are included for the elbow motions.	To adjust the pre-thightening force of the Bowden cables, the mechanism implements a tension device that senses the force while pulling the cable.	The exosqueleton uses a EMG based controller that is implemented in passive move. This means that the robot does not control the position of the user's arm, but generates a force that minimize the signal from the EMG sensor.
CADEN-7	High/Medium. CADEN-7 requires a high ammount of idle pulleys to maintain the workspace, which increases the bulkiness of the device.	The system does not provide means to tackle the variation of the center of rotation of the anatomical joints.	The use of idle pulleys increases the backslack and friction within the device.	Although CADEN-7 struggles with high non-linearities, the effects of those are not considered in the control strategy. Additionally, the mentioned control strategy is simplified to only take into consideration the gravity terms.
CAFE	High. The forearm is attached to a fixed actuation system with multiple stages of pulleys. The mobil exoskeleton structure above the index requires a large vertical area. Both features increase overall bulkiness.	It assumes static axes of rotation for exoskeleton joints, which are also directly connected to their respective index joints. Hence, misalignments are not considered.	It uses a design based approach for avoiding non-linearities related to the actuation system. Namely, the combination of the use of dual cable with two motors and the gearing reduction located at the exoskeleton joint, allow high-backdrivabilty, tension requirements and minimal frictional losses.	It contemplates the use of two independent control strategies for joint position and torque. Target joint position and properly joint torque are achieved by respective PI controllers. The torque control loop works by employing a feedback signal from a strain gauge attached to a finger contact rod and by a feedforward to
CAREX	Medium/low depends on the DOF and workspace of each joint in the device, which may increase the number of anchor points required to control the joint. The actuation system is external to exoskeleton and external supports carry the device weight, which allows more wearability for the user.	The exoskeleton actuates indirectly each joint of the arm by positioning each link in a desired position. The indirect actuation allows the joints to accomodate their center of rotation.	Proper generation of feasible trajectories give the required variable force and tackle the non-linearities generated by the friction within joints and cables.	Two control strategies are combined and implemented: a low-level cable tension control and a high level force field control.
Exosuits	Low. The upper-limb is only covered with a flexible suit with Bowden cable transmission.	A virtual axis of rotation for the exoskeleton is supposed once the Bowden cable ends are attached to the user's arm and forearm. Misaligments between elbow joint axis and virtual exoskeleton joint axis are treated by the flexible condition of the suit.	The author does not present a particular approach to describe the non-linearities of the system.	None. It uses a low-level velocity control instead of current control loop, because it is better with respect of sensitivity of the former to non-linear phenomena such as friction and backlash.

Table 4 (Continuation): Design issues of analyzed exoskeletons.

Name	Bulkiness	Anatomical joints adjustments	Non-linearities approach	Control strategy
HANDEXOS	Low. Underactuation of the system with Bowden cables allows to remotely place the actuation unit and to simplify the actuation and control system.	There are three active DOFs. One active DOF assists the extension/flexion of the human MCP joint. A slider-crank-like mechanism is used to transmit the driving torque onto the human MCP joint, minimizing undesired forces loading such articulation. Two active DOFs allow the assistance of extension/flexion of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints.	The finger extension/flexion dynamics depends on a higher number of parameters than the control variables, increasing the number of non-linearities for the controller to handle. However, this drawback of underactuation doesn't affect the use of the exoskeleton as a rehabilitation tool.	The structure counts with a high number of sensors embedded both in the exoskeleton and in the actuation unit. A standalone motion controller, implements the position control of the linear slider in a classical PID closed-loop regulator with an anti-windup scheme.
HX	Medium. The actuation unit is located remotely. Also, the exoskeleton uses mainly shell-linkages, which reduces bulkiness. However, it results heavier than other hand exoskeletons.	In both index and thumb flexion/extension, a compensation approach is used for the correction of PIP and DIP misaligments. Otherwise, the exoskeleton employs a self-aligment PRR chain for the MCP joint and a parallelogram four-bar mechanism for the thumb opposition motion.	The design lacks a non-linearity analysis that takes into account the friction losses of Bowden cables. Hence, the device exhibits poor backdrivability.	Four independent position loops, one for each DOF.
iHandRehab	High. Although the actuation system is distant from the exoskeleton, because of the four bar arrangement used to actuate each joint, Ihandrehab is still bulky.	Both, the finger and thumb joints are actuated using a four bar mechanism. Although the changes in the center of rotation modify the kinematics of the analysis, the potentiometers compensate this drawback by measuring the joints angular displacement.	The analysis states that friction accounts for a large portion of the driving torque and requires future investigation.	iHandRehab implements both, force sensor and potentiometers. The former to measure the force exerted by the human fingertips, while the latter measures the rotational angle of the finger joints. Thus, the information was integrated to implement a torque controller, however the controller is not able to compensate the friction of the system.
IntelliArm	High. The exoskeleton is supported by a bulky and heavy structure although it is not completely carried by the user. Each DOF from the shoulder (abduction-adduction), elbow and wrist (flexion-extension) is driven by a dc motor with a built-in encoder and a harmonic drive system aligned with the corresponding human arm joint axis.	To compensate the anatomical disalignment, the mechanism has two passive DOF motion in the horizontal plane andactive vertical displacement of the shoulder, which are included to ensure the alignment of the glenohumeral joint with the shoulder joint of the mechanism considering thehuman scapular and trunk movements.	According to the author intelliarm is mounted on transverse plane frictionless linear guides and every DOF has a zero-backlash harmonic gear. Thus, the exoskeleton does not suffer from non-linearities.	There are two control systems: Intelligent Stretching Control (ISC) for tasks such as the passive ROM test during diagnosis, and the passive stretching treatment. The Zero Resistance Regulation Control (ZRRC) is used for tasks such as the active ROM test during diagnosis and voluntary movement training.
MEDARM	High. The mechanism tends to be heavy and bulky, putting high static torque requirements on the first shoulder girdle joint. In order to make the mechanism work, an external gravity compensation system is employed.	MEDARM includes 5-DOF to completely emulate the shoulder girdle movementes. Also, the exoskeleton includes 2-DOF to handle the elbow motions. Thus, MEDARM copes the issue of the anatomical misalignment in all the actuated joints.	Because of the high amount of DOF of MEDARM, the principal non-linearitiy considered by the author is the singularities within the workspace. Thus, to minimize the effects of this issue, MEDARM uses a spherical joint that allows the exoskeleton to reach singular configurations.	The author does not present details regarding the control strategy used, only mentions the utilization of an external gravity compensation system that handles the high torque requirements.
MRAGES	Low. The hand is inside a flexible glove and each finger is actuated by a Bowden cable inspired technology, which consists on a spine sheath with a internal cable attached to the finger tip. Also, the linear actuators are located externally in the carpal area and the forearm.	The anchor point of the exoskeleton finger spine is at the finger tip. Hence, the exoskeleton does not actuate directly the finger joints. Compliance between exoskeleton and fingers is achieved due to the flexible design of the former.	None kind of non-linearities analysis is covered in the design.	Force gauges and linear potentiometers sensors are used for force and position control, respectively. No details of control loops are provided. In general, control requirements are not critical for the operation, since the device only exerts reaction-resistive forces to the fingers.

Table 4 (Continuation): Design issues of analyzed exoskeletons.

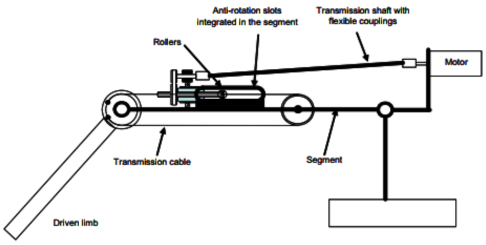
Name	Bulkiness	Anatomical joints adjustments	Non-linearities approach	Control strategy
NEURARM	Low. Neurarm is a 2-DOF structure that is actuated by bowden cables. Thus, because of the simplified model, NEURARM is a light robot.	NEURARM mechanism does not provide the means to tackle the variation of the center of rotation of the anatomical joints.	The author developed a model to describe the singularities that relate the kinematics of NEURARM, with the actuation system. The system is actuated by Bowden cables coupled with a non-linear spring, and a cam mechanism that generates the antagonistic forces required.	NEURARM uses an open-loop strategy divided in two layers to control the position of the desired joint. The HIGH level layer consider desired angle position, while the LOW level layer includes the actuation of the electro valves and Hydraulic pistons. Is in the latter layer in which MEDARM includes the non-linearities of the actuation, and implements an un-specified controller to handle the position of the pistons.
NEUROExos	Low. Althought the mechanism has four passive DOF to control the misalignments, the system is highly compact and portable. Besides, the actuation system can be placed in a different structure.	NEUROExos includes a 4-DOF passive mechanism to handle the misadlignments of the elbow.	The non-linearity of the antagonist compliant elements is desired to make easier the control strategy. This can be explained through the design of the mechanism. NEUROExos is built with a passive-compliant actuator, working as an antagonistic non-linear elastic actuation system, with the purpose of imitating the human musculoskeletal system, which powers itself through antagonistic muscle pairs and has the advantage of simplifying the control system and providing the joint with software-controllable hardware compliance.Therefore, the actuation system is based on a pair of remote and independent antagonistic units that consists on a series of a non-linear elastic elements, based on a linear tension spring coupled with a cam mechanism.	NEUROEXOS uses two alternative control strategies: passive-compliance control and the torque control. First take inspiration in musculoskeletal system which generates a convergent force field around an equilibrium position of the limb by relying on the elastic properties of antagonistic muscles. The selective activation of one of the two muscles displaces the convergent field toward a new equilibrium position and, consequently, changes the position of the limb. Second, torque control should be able to provide the patient with an assistive torque with near-zero output impedance, i.e., with minimum to null joint parasitic stiffness.
RiceWrist-S	Low/Medium. RiceWrist-S is a compact and stiff 3-DOF exoskeleton. However, the double capstan transmittion and the use of a handle to increase the stiffnes reduces the device portability.	The mechanism can actuate forearm pronation/supination (PS), wrist flexion/extension (FE), wrist radial/ulnar deviation (RU) DOF separately and the system employs a passive linear DOF on the handle coupling to maintain the wrist in an anatomical natural posture.	The mechanism is characterized by a zero backlash and low friction on the FE (flexion/extension) and RU (radial/ulnar) joints, thanks to the capstan drive transmissions and use of a frameless brushless motor in direct drive configuration in the PS (prona-tion/suprination) joint.	RiceWrist-S uses a torque control algorithm with film force sensing resistors to sense the normal forces acting on the user.
RUPERT	High. The Pneumatic Muscles Actuators (PMA) require to be attached to the upper-limb, namely to the affected part which needs terapy.	It uses a length adjustable structure. It does not include a joint misaligment correction approach.	The PMA and the functional electric stimulation (FES) stimulators present highly non-linear and time-dependent features, that difficult the control.	A Iterative Learning Control (ILC) strategy is used in a loop position. The control strategy achieves target positions by modifyng signal inputs to pneumatic valves and FES electrodes stimulators.
ShouldRO	Medium. The exoskeleton is supported by the patient, and its proximal end is fastened into a rucksack structure.	In the distal end of the structure, the exoskeleton is fixed to the patient's arm through a splint, an universal joint and a prismatic joint. The last one is aligned with the humerus through a linear slide bearing, which gives one passive translational DOF. The universal joint gives two additional passive DOF, which combined with the translational DOF, allow complete freedom of the relative positioning of the glenohumeral joint and the robot.	In this mechanism, the relationship between the rotating angle of the articulation and the stroke of the cables is not linear. The solution applied by the author is based on the reproduction at the other end of the cable transmission the same mechanism to be operated, using a mechanical inverter that consists in the replacement of the cables in the actuation mechanism by rigid bars, in order to convert the closing motion in a traction motion of the cable.	The cable actuation mechanism reduces to two the number of DOF of the exoskeleton and a mechanical inverter ensures a constant tension in the cables.

Table 4 (Continuation): Design issues of analyzed exoskeletons.

Name	Bulkiness	Anatomical joints adjustments	Non-linearities approach	Control strategy
SUEFUL-7	Medium SUEFUL-7 uses a combination of Bowden cables and DC motors to actuate the structure. Although, the exoskeleton may seen bulky, the utilization of gears over the cuff, permits an overal compact design.	SUEFUL-7 implements a slider mechanism to adjust the misadligments in the shoulder joint. However, this mechanism is exclusive of the shoulder.	SUEFUL-7 handles the singularities by implementing a fuzzy algorithm that determine the coefficients of the mathematical model.	SUEFUL-7 uses a electromyography (EMG) Based control method, using a linear relationship that determine the require torque of each joint from 16 different EMG signals.
UT Exoskeleton	High/medium. UT Exoskeleton uses a slider mechanisms on each joint of the finger, increasing the complexity of the device, and limiting its implementation on multiple fingers.	The utilization of slider mechanisms to actuate each joint of the finger alleviate the effects of joint misalignments.	The principal nonlinearity of the system is due to the slinding of the slider mechanism. Thus, by implementing a redundant position sensor this problem is minimized. Additionally, UT exoskeleton also tackles the backslash problem of the Bowden cables using the redundant sensor.	UT exoskeleton uses a modifyiend torque control strategy adjusted with the redundant sensor to compensate for the backslash and the redundancy of the device.
WRES	Medium. The use of three capstan systems to actuate the two wrist motions and the forearm motion, increase the complexity of the device. However, the structure has the capability to be attached to a bigger exoskeleton.	The exoskeleton uses a passive extra DOF for translation along the Pronation/Supination axis, this DOF allows a length variable for the support link of the axis creating a modular device for diferents hand sizes.	The device gets together the main advantages of capstan transmision, compacteness, zero-backlash, back-driveability, and stiffness with the high torque weight ratio of a differential transmission.	WRES uses a feed-forward controller to compensate the gravity torque and the gearmotor viscous friction.
Wrist Gimbal	Medium/High. Wrist Gimbal has a similar structure to WRES, however, the structure is considerably bigger eviting its attachment to another exoskeleton.	Wrist Gimbal uses a handler to allow the user to compensate for the joint misalignments. The handler is also allowed to move in the distal/proximal direction via linear bearings.	The author does not report any non linearity problem. This is mainly due to the system uses a capstan configuration to control its position.	Wrist Gimbal was actuated using two control strategies. First, a PD controller to do test the movement capabilities of the exokeleton, and second a torque control strategy to simulate a virtual viscous damping that resist the user movements.

4.1. ABLE

(a)



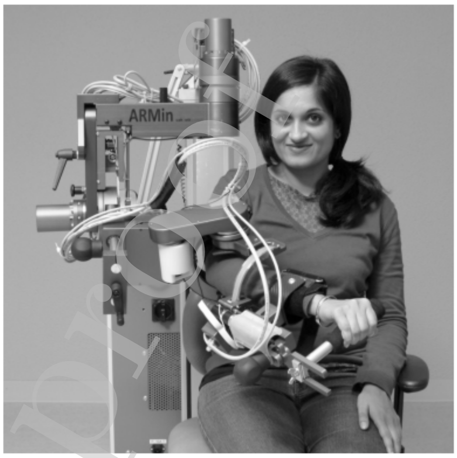
(b)

Figure 3: (a) ABLE prototype (b) ABLE exoskeleton transmission system. The figures are reproduced from [64].

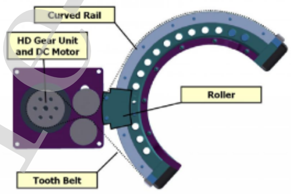
ABLE is a cable driven exoskeleton for upper limb designed by the Interactive Robotic Unit of CEA LIST™ in France and commercially distributed by Haption® (see Fig. 3a). For the actuation and transmission system, ABLE introduces the concept of Screw Cable System (SCS), developed previously for robotics arms [143]. The SCS for ABLE can be analyzed into two stages. The first stage consists of a rotational motor coupled to a belt and pulley transmission. Due to ergonomics, the motor is externally located [65]. Thus, a large shaft and two flexible couplings are required to connect the motor with the driving pulley, as shown in Fig. 3b. A second stage transforms the rotational motion into linear by using a ball-screw, guided by a fixed anti-rotation slot. At this stage, a cable is attached inside the hollow screw and routed through an idle pulley for moving the final pulley joint. This final motion is back-drivable.

In ABLE preliminary designs, the SCS actuator was proved in 4-DOF, considering shoulder abduction/adduction, external/internal rotation and flexion/extension movements, and elbow flexion/extension [64]. Nowadays, ABLE is available with 5-DOF, adding pronation/supination of the forearm; and also with 7-DOF, including 2-DOF for the wrist [144].

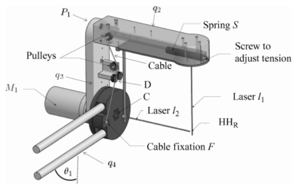
4.2. ARMin



(a)



(b)



(c)

Figure 4: (a) ARMin III in a healthy user. This figure is reproduced from [138]. (b) Actuation unit for shoulder external/internal rotation in ARMin II. This figure is reproduced from [137]. (c) Spring and cable mechanism for passive weight compensation in ARMin III. This figure is reproduced from [138].

ARMin is an upper-limb exoskeleton with 6-DOF for rehabilitation after stroke. This exoskeleton supplies 3-DOF for the shoulder abduction/adduction, flexion/extension, and internal/external rotation; 1-DOF for the forearm pronation/supination and 2-DOF for the flexion/extension of the elbow and the wrist, respectively. The development of ARMin has been gradual with successive and improved versions [23], [137], [138]. In the first ARMin I, e.g., the actuation of the shoulder internal/external rotation is done by two cables, attached to the ends of a ring road and pulled by a motorized shaft, in a capstan configuration. In the following ARMin II, the actuation unit for the shoulder external/internal rotation consists of a fixed DC motor coupled to an HD gear reduction, with an output shaft [137]. The motion transmission is through a toothed belt, tensioned by idle pulleys and connected to a curved rail, as shown in Fig. 4b.

ARMIN I and II also employ an open cable-capstan transmission for the forearm pronation/supination, whereas, for the rest joints, use DC motors with harmonic drive (HD) gear or ball-screws transmissions. Besides, in both versions, two passive DOF allows the displacement of the humerus head (HH) and compensates the misalignment defects.

On the other hand, a novel version of ARMIN, i.e., ARMIN III, focuses on the shoulder complex and the elbow motions (4-DOF). The design departs from a detailed and complete kinematic analysis of the HH translation [138], which gives as a result that an optimized circular path can be a suitable approximation to the HH motion in y and x-axes. ARMin III in this sense does not use an additional actuator, and this passive rotation DOF only appears when the exoskeleton makes an abduction or adduction movement. Also, another three passive DOF allows adjustability between different users, due to variable upper-limb lengths. Respect to the actuation system, ARMin III employs for the shoulder external/rotation and the elbow flexion/extension a close pulley transmission with belts. This transmission connects the rotation of the DC motors with a final stage of HD gears located at the end joints. Moreover, ARMin III introduces a spring and cable mechanism which works as a passive weight compensation system in case of power loss (See Fig. 4c).

The main advantage of all ARMin versions, as seen, is their capability of allowing a natural motion of the shoulder complex by adding passives DOF. However, in the case of ARMin I and II, this feature affects the mechanical support and the guidance of the upper-limb [138], which can also interfere negatively in the rehabilitation [139].

4.3. CABXLexo-7

Figure 5: Prototype of CABXLexo-7. This figure is from [122].

CABXLexo-7 is a 7-DOF exoskeleton, which is compact, lightweight, and comfortable for post-stroke patients (see fig 5). CABXLexo-7 is the newer version of CABexo [60]. The exoskeleton includes the shoulder movements of flexion/extension, abduction/adduction, and internal/external rotation; the elbow complex movements of flexion/extension and supination/pronation; and the wrist movements of flexion/extension and radial/ulnar deviation. To actuate the shoulder movements, CABXLexo-7 utilizes a driving link that rotates over a driving wheel to generate adduction/abduction and is actuated using open cables capstan transmission system. Around the driving wheel, passes other pair of wires that reach to a planet wheel, perpendicular to the driving wheel, that generates the flexion/extension. On the driving link, CABXLexo-7 uses Bowden cables to actuate the internal/external rotation of the shoulder. The use of Bowden cables permits the position of the actuator of this joint far from the upper limb decreasing is weight.

In the case of the elbow complex, the system uses a configuration of three driving wheels, two parallel and one planet wheel perpendicular to both. The planet wheel is connected to each driving wheel by pairs of cables. For the flexion/extension, the system actuates the parallel wheels using Bowden cables to made them rotates in the same direction while maintaining the plane wheel fix. This transmission system is similar to the used by WRES, with the disadvantages that it does not include a linear DOF to accommodate the elbow in case of the center of rotation displacement. In the case of the supination/pronation, the plane wheel is actuated directly using Bowden cables. Lastly, the wrist is controlled by pairs of Bowden cables that transmit motion to two linearly coupled joints that control the radial/ulnar deviation and the flexion/extension movement of the hand. CABXLexo-7 has been used to help patients with stroke obtaining favorable results [122].

4.4. CADEN-7

CADEN-7 is a cable-actuated dexterous exoskeleton for neurorehabilitation (see fig 6). The exoskeleton has seven single-axis revolute joints across the upper limb. The movements include shoulder abduction/adduction, flexion/extension and internal/external rotation; elbow complex flexion/extension and supination/pronation; wrist flexion/extension and radial-ulnar deviations. The system uses three types of configurations for the actuation of each joint movement: 1) 90° ; 2)180° ; 3) axial (see fig 7). Both, the 90° and 180° arrangements consist of closed-loop cables with pulleys wrapped around ”joint idler pulleys” concentric to the

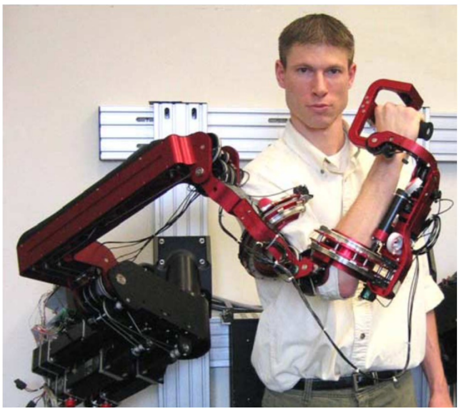
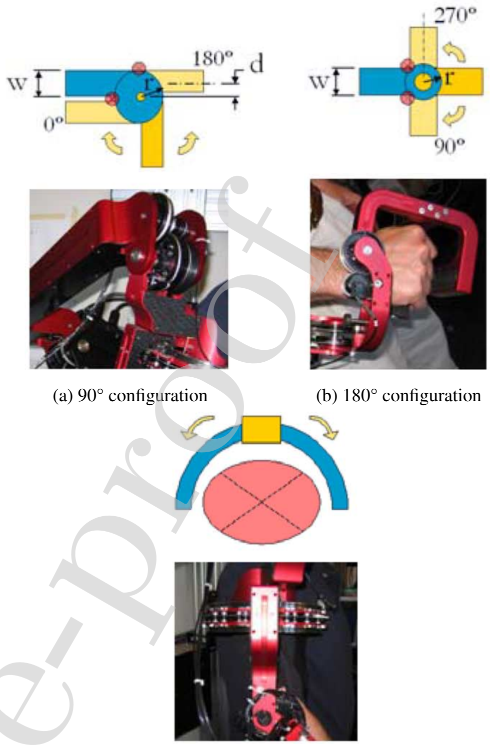


Figure 6: CADEN-7, a seven DOF exoskeleton. This figure is from [10].



(a) 90° configuration (b) 180° configuration

(c) Axial configuration

Figure 7: Different transmission configurations for the CADEN-7. This figure is from [10].

axis of revolution. To maximize the transmission ratio the actuation uses to stages of amplification for each DOF [10]. Besides, for those two configurations, their range of motion is respectively 90° and 180°.

For the axial arrangement, this configuration uses a series of nine idler pulleys positioned at a constant radius from the axis of revolution, as a single diameter joint idler pulley. This pattern allows the cable to keep the tension along the range of movement of the joint. The axis configuration is found on the shoulder internal/external and the supination/pronation movements. For the 90° arrangement they are located in the shoulder, wrist, and elbow flexion/extension movements. Lastly, the 180° configuration is found at the shoulder abduction/adduction and the radial/ulnar deviation movements. This design is innovative in the form in which uses the pulleys to transmit the actuation. However, CADEN-7 suffers for not consider the misalignment of each joint of the exoskeleton with the limb joints. Besides, the use of pulleys limits the flexibility of the to adjust its dimensions to different users.

4.5. CAFE

CAFE is a 3-DOF index exoskeleton actuated by cables and designed for hand rehabilitation after stroke. This exoskeleton provides flexion/extension motion for the MCP, PIP and DIP joints. The MCP abduction/adduction and the wrist movements are, on the other hand, avoided by fixing the rest of the upper-limb to an external frame. The structure of CAFE consists of a set of rigid links with a variety of lengths, to increase adjustability between different users. The three joints of CAFE located at MCP, PIP, and DIP joints have fixed axes of rotation and can achieve a ROM of -15-75°, 0-90°, and 0-90°, respectively [72]. To actuate a joint in one direction, CAFE employs a gearless DC servomotor with an open cable pulley transmission. Hence, to obtain back-driveability another pair of motor and open cable is needed, giving a total of six actuators for the entire exoskeleton. An additional gear stage at the driven pulley is also used to reduce the tension of the cable. Besides, the complete actuation unit is located remotely in an external plate above the forearm, as shown in Fig. 8.

Although CAFE features the typical advantages of cable transmission, such as low friction and low backlash, it also presents several drawbacks. One of these is its cumbersome structure, due to the gear sections and the excessive number of components, e.g., servomotors and pulleys. Hence, the use of two actuators per DOF results impractical in economic terms and adds bulkiness to the exoskeleton. Also, the fixed joints and the rigid interface with the finger affects the ergonomics.

4.6. CAREX-7

The CAREX-7 utilizes the human arm as the mechanical structure, and actively drives cables to assist the arm

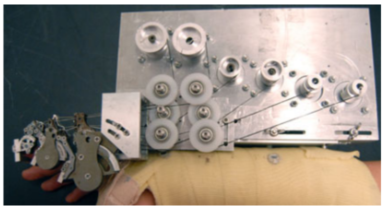


Figure 8: CAFE (Cable actuated finger exoskeleton) worn in a user's index. This figures is reproduced from [72].

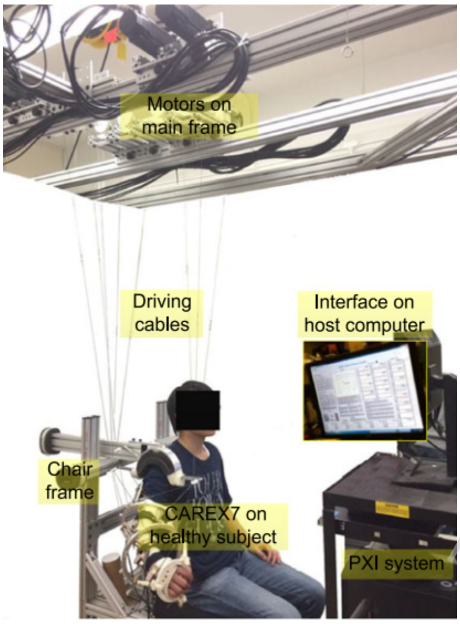
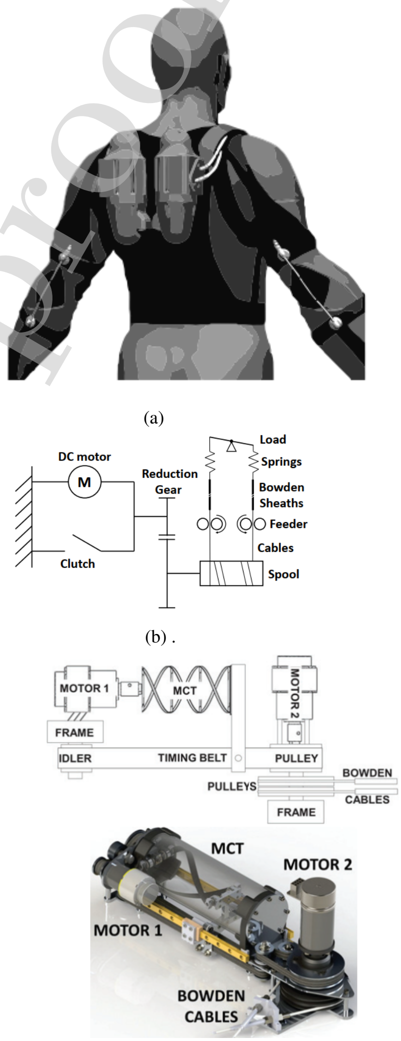


Figure 9: View of the CAREX-y system, including motors on a static frame. The figure is reproduced from [30].

motion (see fig 9) [145]. For this end, CAREX-7 considers the shoulder joint as a 3-DOF spherical joint, the elbow as a 1-DOF, and the wrist as a 3-DOF. The structure of this system consists of four cuffs, located on the shoulder, upper arm, forearm, and the hand. The position of the anchor point was determined to optimize the workspace of CAREX-7 applying an optimization problem in which the objective was the minimization of cable tensions [105]. Two cables start from the shoulder cuff and end on the upper-arm cuff. Three cables start from the shoulder cuff, go through the upper arm cuff, and end on the forearm cuff. To control the movement of the upper limb, CAREX-7 uses eight open-ended cables actuated with motorized reels mounted on an external structure. The remaining three cables start from the shoulder cuff, routed through the upper arm and forearm cuffs, and end on the handcuff. Due to CAREX-7 is designed without links and joints, the systems do not suffer for the issues of misalignment of the axis of rotation. Furthermore, another advantage of the design of CAREX-7 minimizes the effects of the shoulder girdle [104]. Due to the presented features, CAREX-7 is an essential mechanism that needs to be taken into consideration by the researchers for new designs concepts.

4.7. Exosuit



(a)

(b) .

(c)

Figure 10: (a) Exosuit exoskeleton concept. Reproduced from [92]. (b) An schematic representation of the actuation system proposed in [92]. Reproduced from [92]. (c) Actuation system proposed in [93]. Reproduced from [93].

Exosuit is a concept used for describing soft wearable exoskeletons which not present a rigid structure [92], [93], [95] (See Fig. 10a). In the case of the upper-limb motion exists a variety of alternatives for the actuation system which exploits this concept. The pneumatic muscles are one of the most common, but feature some drawbacks, such as the restringed range of motion, due to their stroke, and the sophisticated control, as a result of a high nonlinear behavior. Hence, in this section, the attention is focused on the cable actuation/transmission systems proposed in [92] and [93] for the elbow joint.

The actuation unit of the exosuit in [92] presents a DC motor input and two Bowden cable outputs (See Fig. 10b). The motor input provides torque to a winch through an intermediate gear reduction. A clutch system located between the motor and the gear stage avoids that the actuator works when the limb is static. Also, a feeder assembly guarantees the stiffness of the cables in the winch side. The use of springs at the end of the transmission allows more compliance in the motion [146]. The two cable outputs correspond to the extensor and flexor functions of an analogous human pair of muscles. In this sense, due to the different elongations of the cables and the nonlinearity of the flexor cable length, the winch has two sections for each wire. The one with the larger diameter wraps the extensor cable, and the smaller one does the same for the flexor cable. Finally, the two Bowden cables are routed and attached to the soft fabric, near to the driven joint.

Furthermore, the transmission of the exosuit in [93] is also an open Bowden cable type, like the used in [92]. However, the actuation unit employs an internal Multistable Composite Transmission (MCT) and two DC motors, instead of one. The novel MCT consists of a helicoidal deformable structure of fiber carbon similar to the shape of the ADN, as shown in Fig. 10c. The MCT twisting generates an axial displacement and moves a belt, which in turns transmits motion in a close pulley transmission stage. The second motor is aligned to the driven pulley and provides extra torque for pulling the two Bowden cables.

To conclude, the main advantages of the analyzed exosuit exoskeletons are their light-weight, negligible inertia, the soft interface between device and user, and their compact and portable actuation systems. On the contrary, their principal drawback is the presence of undesired friction for the Bowden cable transmission that affects bandwidth and performance [92].

4.8. HANDEXOS

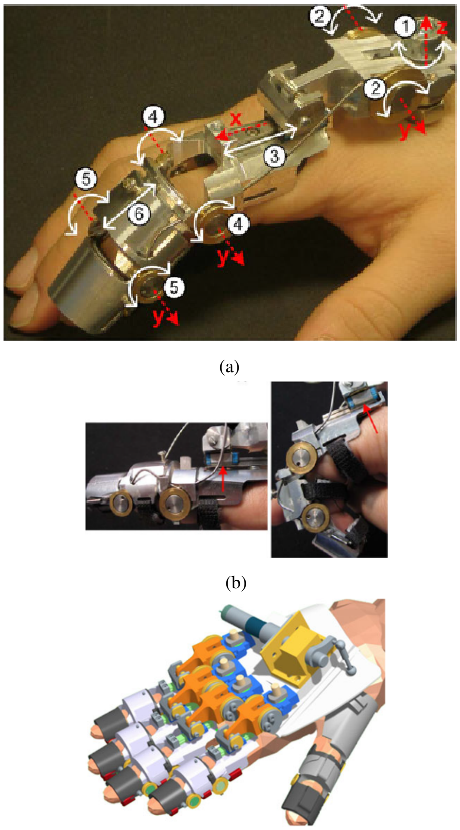
HANDEXOS is an innovative wearable modular multi phalanges device for post-stroke rehabilitation. It was designed to allow a functional and safe interaction with the user's hand, employing anthropomorphic kinematics and minimizing the human-exoskeleton rotational axes misalignments [76]. This exoskeleton proposes a modular design for each finger that approaches the fingers like a six DOF mechanism with three active DOF and three passive DOF (See Fig. 11a). The 3 actives DOF actuate over the DIP and PIP joints, and also one rotational DOF of the MP joint allowing the flexion/extension movement. HANDEXOS can actuate this active joint with a series of Bowden cables in each joint, configured in antagonist form.

The three passive DOF have three different purposes; the first is the other rotational DOF of the MP joint obtained through an elastic bushing whose permit the adduction/abduction movement in a passive way. The second DOF is a passive translational joint acting on the proximal phalanx that gives the required kinematic compatibility between human and exoskeleton's MP rotational axes[75]; as shown in Fig. 11b, such a passive mechanism is necessary, indeed, to enable the MP joint to cover its entire ROM with no constraints. The Last one passive DOF is for pure modular, and ergonomic factor allowing adjust the length of the HANDEXOS link coupled with the intermediate phalanx. One of the main features of HANDEXOS is to try to enable full mobility of the hand with a natural ROM. HANDEXOS simplify the complicated kinematics of the thumb removing the MP adduction-abduction motion, without affecting the flexion-extension of the IP and MP joints. Considering that the movements of abduction/adduction and opposition/reposition of the thumb are dependent each other, an additional slider-crank mechanism (Fig. 11c) placed on the dorsum of HANDEXOS pushes the thumb in one direction, and cover both motions in a natural movement [53].

4.9. Hand Exoskeleton (HX)

HX is a wearable exoskeleton for thumb-index rehabilitation and assistance, focused on enhancing the user experience by adopting a self-recover approach in its design [147]. This approach exploits the robotic concept of resilience [148], in order to provide the exoskeleton capability of returning a joint to an alignment state. In HX, the motion of the two sections of the exoskeleton, i.e., index and thumb, is supplied by two independent linkage mechanisms, which coincide in the use of passive DOF for dealing with the misalignment errors.

For the index section, the approaches for MCP (MetaCarpo-Phalangeal), DIP(Distal-InterPhalangeal) and PIP (Phalangeal-InterPhalangeal) misalignments differ each other respect to kinematics. Hence, the former employs a self-alignment PRR chain, with two translational passive DOF in the flexion/extension plane and one translational DOF, which allows abduction/adduction. For the DIP and PIP, on the other side,



(a)

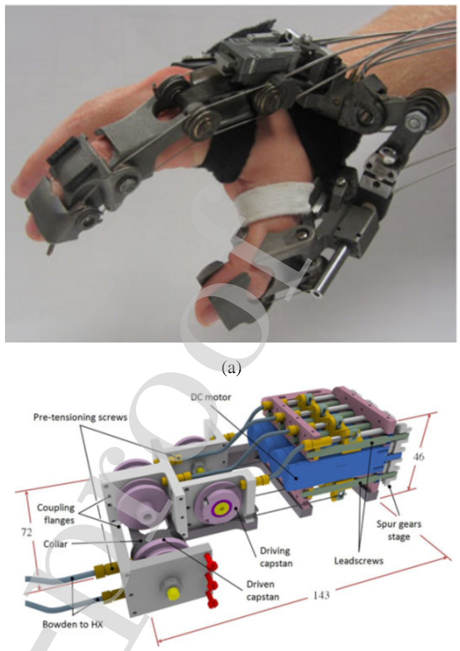
(b)

(c)

Figure 11: (a) Kinematic layout of the HANDEXOS finger module. This figure is from [75]. (b) Detail of the proximal-link mechanism for the extended (on the left) and flexed (on the right) configurations. This figure is from [75]. (c) Concept of HANDEXOS: five independent finger modules including the thumb. This figure is from [75].

a RR chain with elastic couplings between exoskeleton and finger corrects the misalignment by compensation [149]. Besides, he kinematics for thumb MCP and DIP consist of a PRRR chain, in similar arrangement respect the index's PIP and DIP. Also, the thumb carpometacarpal (CMC) is moved by an articulated parallelogram.

Respect to the actuation system in HX, a compound actuation unit transmits motion to the linkage mechanisms, through Bowden cable outputs. For each output line, the actuation unit disposes of a DC motor coupled to a spurs gear stage, which is in turns connected to a multiple capstans stage. The Bowden cables depart from the last stage and are attached to the driven pulleys located at each joint, as seen in Fig. 12b. Therefore, this kind of transmission demands an antagonistic configuration of the Bowden cables for allowing back-driveability.



(a)

(b)

Figure 12: (a) HX worn in a user's hand. Reproduced from [77]. (b) HX compound actuation unit. Reproduced from [77].

4.10. iHandRehab

iHandRehab is a hand rehabilitation exoskeleton that seeks to satisfy requirements for both passive and active rehabilitation motions (see Fig. 13). The exoskeleton has 4-DOF for each finger and thumb. For the fingers, the joints actuate over the metacarpophalangeal adduction/abduction and flexion/extension, and the distal and proximal interphalangeal flexion/extension. To actuate each articulation iHandRehab uses a parallelogram mechanism actuated with two Bowden cables for each direction. The reason for this arrangement is that permits the installation of a sensor away from the articulation and, since the rotation of the driving link is the same as the joint, the sensor would sense the angular displacement of the joint. To accommodate each actuator the mechanism uses a fastening screw that permits its movement along the fingers [54]. However, although the design is relatively simple, the angle sensor cannot handle the error due to the misalignment of each joint, although the parallelogram mechanism permits the free motion of each finger.

4.11. IntelliArm

The IntelliArm is an exoskeleton with 9-DOF, seven active and two passive (see Fig. 14) [47]. For

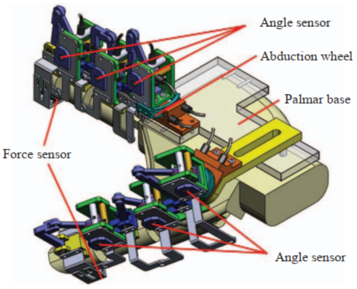


Figure 13: Virtual prototype of the iHandRehab exoskeleton. This image is from [54].

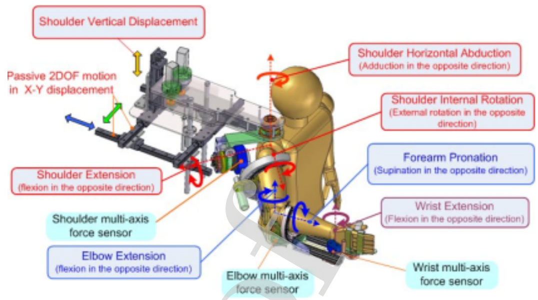


Figure 14: The seven active two passive DOF Intelliarm.The figure is reproduced from [47].

the shoulder glenohumeral movements, the exoskeleton uses four actuated DOF for the horizontal abduction/adduction, flexion/extension, internal/external rotation, and the vertical displacement of the glenohumeral joint. Besides, IntelliArm uses the two passive DOF to compensate for the movements of the shoulder girdle. In the case of the remaining DOF, InteligiArm includes two DOF for elbow complex one for flexion/extension and another for supination/pronation. Also, includes a DOF of the wrist flexion/extension.

The movements of abduction/adduction and the shoulder flexion/extension are controlled by two motors remotely placed that acts upon them using closed-loop cable transmission. Furthermore, for the vertical shoulder displacement, the mechanism includes a dc motor attached to a linear guide. In the case of the shoulder internal/external rotations and the elbow complex supination/pronation mechanism, the exoskeleton uses capstan transmission systems, with motor held on the structure. Lastly, for the elbow and the wrist flexion/extension movements, IntelliArm uses two DC motors connected to harmonic gears [59]. Although the exoskeleton possesses four motors on the exoskeleton, the three distal motors compensate the additional weight on the user's arm, allowing the compensatory control of the gravity.

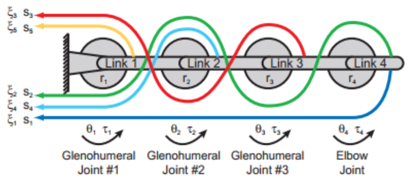
4.12. MEDARM

MEDARM is an exoskeleton with 5-DOF at the shoulder to completely emulate the shoulder girdle movements (see Fig. 15). The system also has an additional DOF to control the flexion/extension of the elbow complex for a total of 6-DOF. The first 2-DOF of MEDARM serves to allow the movements of elevation/depression and protraction/retraction of the sternoclavicular joint. This mechanism consists of a revolute joint pointing forward in the horizontal plane, allowing the elevation/depression. The position of the revolute

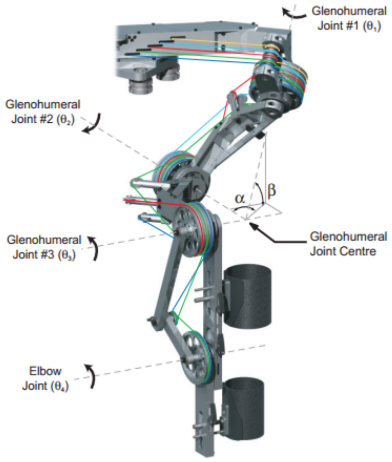
Figure 15: MEDARM a six DOF exoskeleton that controls the shoulder girdle. This image is from [67]

joint is adjustable depending on the user's requirements. In the case of the protraction/retraction, due to the complexity of this movement, the system uses a curved track system in which a carriage travels. The carriage supports the remaining 4-DOF system.

The three remaining movements of the shoulder and the movement of the elbow are controlled using an open-ended cable system with pulleys. MEDARM uses the arrangement presented in fig 16a. Due to this configuration possesses 4-DOF, it is required to use five cables to control it. The center of rotation of each pulley coincides with the center of rotation of each joint. Hence the pulleys act on different planes and use an idle pulley to maintain the tension along the range o movement, as presented in fig 16b. Besides, MEDARM posses linear joints to adjust the length between pulleys. Another feature of MEDARM is that it does not use a handler, leaving the hand free for action.



(a)



(b)

Figure 16: (a)A simplified planar schematic of the cable actuation system (b) A CAD drawing that presents the orientations of the joints. Reproduced from [67].

4.13. MRAGES

MRAGES is an exoskeleton glove developed as a feedback force haptic device for fingers rehabilitation. For this purpose, the transmission system used at each finger consists of a Magneto-Rheological Fluid (MRF) actuator and a cable attached to the fingertip. The MRF ability to variate its viscosity due to the presence of a magnetic field is used to emulate the dynamics of biological tissues [150], [151], which in turns aids to a more natural compliant motion between human and exoskeleton in rehabilitation.

The MRAGES actuator system is a passive linear force generator, which only exerts resistive forces in opposition to the finger motion [109]. A closed-loop controls the magnitude of these forces, by modifying the magnetic field. The use of a force sensor for each finger completes the feedback. Additionally, a finger spin exoskeleton routes the cable through the finger, working as a Bowden sheath (See Fig. 17). Thus, the MRAGES transmission can be considered as a variation of Bowden cable. Furthermore, due to the back-driveability of this transmission, the wire in MRAGES also works under compression. This characteristic is only possible for

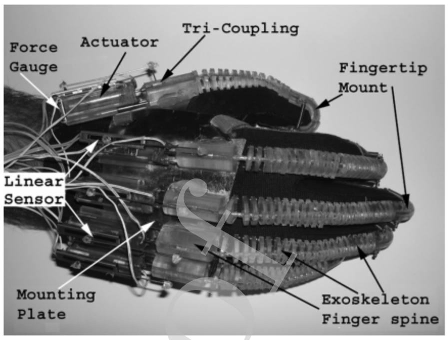


Figure 17: The MagnetoRheological Actuated Glove Electronic System (MRAGES).This figure is reproduced from [109].

short Bowden cables [125].

Finally, the main advantages of this exoskeleton glove are its compactness, light-weight and back-drivable actuation system, and its flexible and compliant transmission. The principal drawback of MRAGES is the high static forces values presented in the off state, which can generate muscular fatigue in users [109].

4.14. NEURARM

NEURARM system is a two-link 2-DOF planar robotic arm that simulates the main functional parameters of the human upper limb (See Fig. 18) taking into account kinematics, dynamic and functional features of the human arm [78]. It is specifically designed and developed for investigating models of human motor control principles and learning strategies, human-machine interfaces, and human-robot sensory-motor interaction. NEURARM posses a system of actuation composes by a Bowden cable actuation system with a no linear elastic element, these mechanism has a nonlinear tension spring coupled with a cam mechanism. The mechanism allows obtaining the wanted non-linear muscle force-elongation curve using two properties. The first property regards the kinematics function, in order to establish a nonlinear relationship between the displacement of the wire (Dl) and the elongation of the spring (Dz). The second characteristic is the force transformation function; the force used by the spring is transmitted to the wire in a non-linear manner, by a cam mechanism [79].

This planar system is a crude simplification of the complexity of the human arm, but the real thing is that the system is sophisticated enough to address fundamental questions about human arm behavior. A pair of muscles powering the human joint in antagonistic configuration gives the singular characteristics of the equilibrium point hypothesis (EPH) for human motor con-

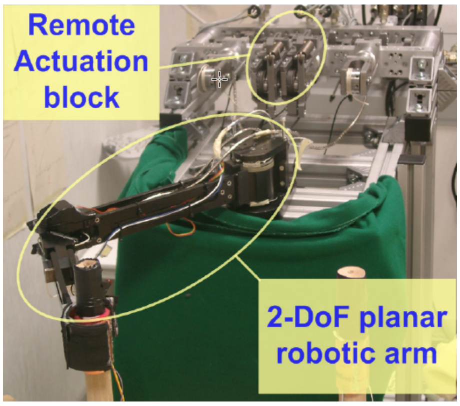


Figure 18: The NEURARM Platform. This figure is from [78].

trol [76]. The bio-inspired actuation system permits to implement motion control algorithms. Furthermore, the integrated non-linear spring element permits a preliminary experimental characterization of joint stiffness and position open loop controller, based on EPH. This mechanism can simulate a natural variable stiffness and viscosity of the arm muscle because of its actuation system.

4.15. NEUROExos

NEUROExos is a robotic elbow exoskeleton used for poststroke physical rehabilitation. It is a neuro-robot, product of the fusion of neuroscience and robotics [76], thinking to attempt a perfect coupling between the robot and the user. Neurexos provide complete kinematic compatibility with the user during motion attending all the possible misalignments in the axis of rotation in the elbow joint with a 4-DOF passive self-aligning mechanism [80]. Furthermore, NEUROExos links are designed to fit the form of the user's limb segments and distribute the interaction force between the user and the robot. NEURExos have double-shelled connections composed of two concentric shells (inner and outer)(see Fig. 19a). Outer shell provides structural stiffness and strength to the robot, also makes use of an optimized material distribution around the limb segment to reduces the possibility that the assistive load applies an uncomfortable torque. On the other hand, the Inner shell has two half-shells, one made of ethylene vinyl acetate (EVA) for moisture draining and skin transpiration, and the other made of polypropylene, both to attempt ergonomic factors [45].

NEUROExos has an adaptive, passive compliant actuator, employing an antagonistic non-linear elastic action system. This arrangement takes influence from the human musculoskeletal system, which powers the members through antagonistic muscle pairs[45]. The system of actuation is a Bowden cable actuation system with a no linear elastic element, that is based on a linear tension spring coupled with a cam mechanism (see Fig. 19b).

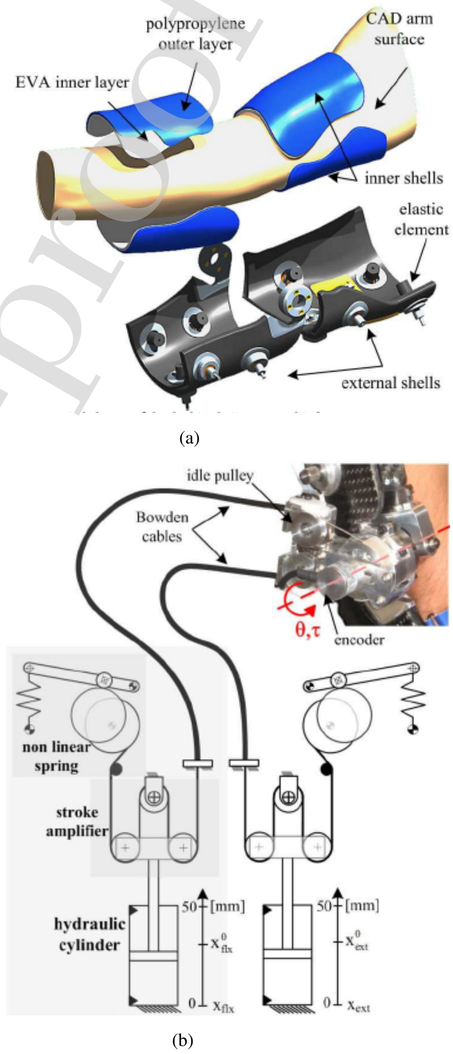


Figure 19: (a)NEUROExos Exploded view of the double-shell structured links. This figure is from [45]. (b) NEUROExos System actuation. This figure is from [45].

4.16. RiceWrist-S

Another 3-DOF exoskeleton for the wrist is the RiceWrist-S (see fig 20). This mechanism has three purely rotations joints that permit the movement of the forearm pronation/supination, wrist flexion/extension,

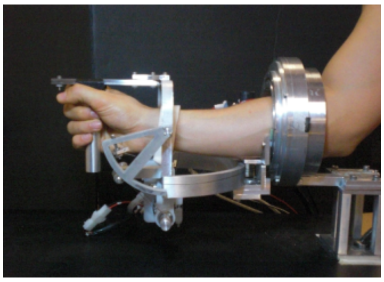


Figure 20: RiceWrist-S a Forearm and wrist exoskeleton for stroke rehabilitation. The figure is reproduced from [96].

and wrist radial/ulnar deviation. To ensure zero backlash and low friction the mechanism uses capstan transmission for the radial/ulnar deviation and the pronation/supination [96]. Furthermore, for the radial/ulnar deviation, the capstan transmission is duplicated to increase the transmission ratio. For the flexion/extension joint RiceWrist-S use idle pulleys to maintain the tension in the cables permitting to place the actuator further back; thus, allowing to install support for the device handle obtaining a more rigid device more rigid [44]. For the supination/pronation, the mechanism uses direct actuation, although it is not specified which kind.

4.17. RUPERT

Figure 21: Subject wearing RUPERT. The figure is reproduced from [141]

RUPERT is a portable upper limb exoskeleton robot developed by Arizona State University. RUPERT has 5-DOF that consist of the shoulder flexion/extension and the humeral internal/external rotation, elbow flexion/extension and supination/pronation, and wrist flexion/extension [115]. RUPERT is actuated using low-cost pneumatic muscles (see Fig 21). Due to the use of this type of actuation, RUPERT is portable for the user permitting its utilization sitting or standing. According to the experimental results on stroke patients, RUPERT is an effective rehabilitation robot for applications of active reach-to-grasp training [116]. Each segment of the device is adjustable to accommodate the variable arm lengths [110].

4.18. ShouldeRO

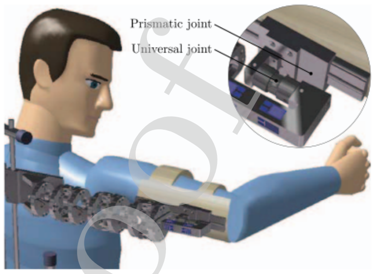
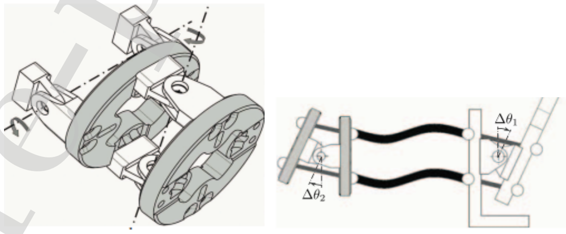


Figure 22: ShouldeRO a two DOF exoskeleton for the shoulder. This figure is from [85]



(a) (b)

Figure 23: (a) Modules of polyarticulated structure. (b) Mirror mechanism principle. Reproduced from [85].

ShouldeRO is a shoulder exoskeleton that uses a two DOF compliant mechanism (see Fig. 22). The structure of the device is composed of a base module that is fixed to the back of the patient, and a succession of N elementary modules, each consisting of two rings and four hinges (fig 23a). This arrangement permits the system the DOF around two perpendiculars axis to each module, which position is controlled for pairs of Bowden cables. One requirement of this design is that the tension remains the same in each pair of wires, to achieve this issue designers implemented a mirror mechanism at the opposite end of the pair of cables, that moves on the contrary direction of the modules (see Fig. 23b).

Moreover, the system allows the adjustment of its position by three passive DOF added at the base of the mechanism. Also, the device posses two passive joints at the coupling point with the arm to allow the movements of the shoulder girdle; the joints are one universal and a prismatic. The principal advantage of this arrangement is that permit a small design with low invasivity to the user. Besides, the device permits a sufficiently large workspace avoiding singularities [85].

However, this mechanism is just for the shoulder, and it is not clear how the additional DOF would be integrated to add actuation on the elbow or the wrist.

4.19. SUEFUL-7

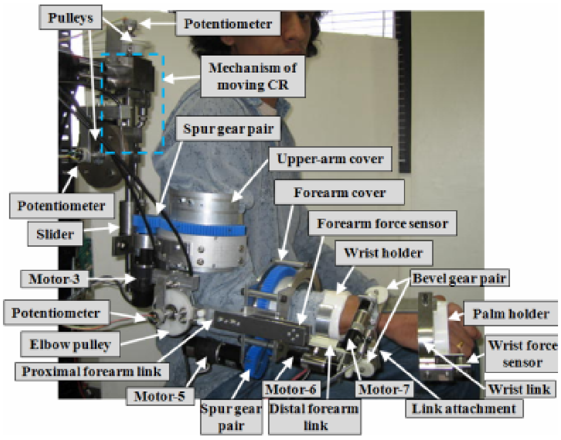


Figure 24: SUEFUL a 7-DOF upper limb exoskeleton. Image from [55]

The SUEFUL-7 is a 7-DOF upper limb exoskeleton robot (See Fig. 24), which allows the movements of flexion/extension, internal/external rotation, and horizontal abduction/adduction for the shoulder complex; Flexion/extension and supination/pronation for the elbow complex; flexion/extension and radial/ulnar deviation for the wrist [55]. The movements of the shoulder complex are transferred by pulleys from motors connected to a steady base except for the internal/rotation, which occurs due to a spur gear connected directly to a motor. To cancel out the ill effects caused by the variation in the position of the center of rotation of the shoulder the mechanism implements a slider mechanism that automatically adjusts the distance between the user and the base [152].

In the case of the elbow complex, the flexion/extension is obtained by the actuation of a configuration of pulleys that, in the same manner as the shoulder complex, is actuated from a motor fixed to the steady base. Also, a motor generates the movement of supination/pronation through the actuation of a spur gear [55]. Attached to the link that rotates with the supination/pronation of the elbow complex is the wrist mechanisms. On this link are two bewel gears that transmit the motion to the flexion/extension and radial/ulnar deviation movements of the wrist. The link also holds a handler to guide the hand of the user. This device permits the accommodation of the center of rotation of the wrist. One of the advantages of sueful-7 is that, due to its compactness, can be placed on a wheelchair. However, the use of spur gears or bewel gears represents a difficult in the design, in which the alignment of the of the transmission system may difficult its construction.

4.20. UT hand

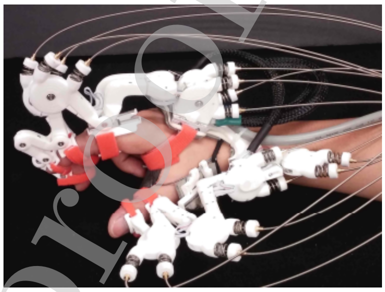
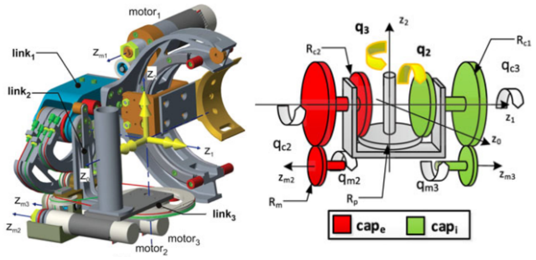


Figure 25: UT hand exoskeleton.The figure is reproduced from [91]

UT hand is an index finger exoskeleton that produces low reaction forces at the finger joints while providing maximum range of motion at the finger articulations. To ensure this, UT introduces sliding joints as the interface between the finger phalanx and the exoskeleton links producing only normal reaction forces on the finger phalanges [90] (see Fig. 25). UT acts on the metacarpophalangeal and the proximal interphalangeal joints, leaving the distal interphalangeal joint since this articulation is coupled to the other two bones; then the system has 2-DOF. The metacarpophalangeal and the proximal interphalangeal joints are connected using two links that are assembled using a revolute joint. Additionally, UT posses a passive joint in the metacarpophalangeal joint that permits the abduction/adduction of the finger. This arrangement avoids reductions in the range of motion of the fingers [90]. UT uses Bowden cables to actuate the joints; then it requires two actuators for each joint for a total of four actuators. To measure the friction within the Bowden cables UT measures the displacement of the actuator and the exoskeleton joint to estimate the deflection using the relative movement of the two. Furthermore, the mechanism implements springs connected to the cable sheath to counteract the force applied by the cable and maintain zero resultant force on the device, obtaining a pure torque source.

4.21. WRES

WRES is a 3-DOF exoskeleton for neuro-rehabilitation and teleoperation, focused on wrist motion [142]. The 3-DOF of this exoskeleton include forearm pronation/supination (PS), radio/ulnar



(a) (b)

Figure 26: (a) CAD of WRES. (b) Differential transmission kinematics representation of RU and FE joints. Reproduced from [142].

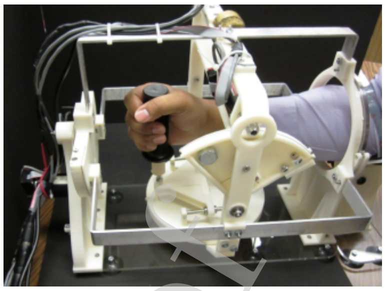


Figure 27: Wrist Gimbal: a three DOF wrist exoskeleton for rehabilitation. The figure is reproduced from [66].

deviation (RU), and wrist flexion/extension (FE). For the PS motion, this exoskeleton employs a single cable-capstan stage actuated by a gearmotor (m_1). The rotation of link 1, coupled to PS joint, is achieved by a 180° semicircular guide with a rail-rolling slider. For the RU and FE joints, WRES uses a capstan differential transmission, with two motor inputs (geared motors 2 and 3 in Fig.26a in a parallel arrangement. Both motors, fixed to link 1, actuate simultaneously for moving two pair of capstan wheels (named external and internal capstans), respectively (See Fig. 26b). Therefore, in this differential transmission, the two torque inputs are combined and transmitted to one of these RU and FE joints. In the case of single RU motion about axis z_1, both external and internal pair of capstan systems rotate in the same direction. By contrast, the contrary torque inputs for motor 2 and 3 generate a single torque output in the drive pulley aligned to the FE joint. The transmission system of WRES combines the main advantages of capstan transmission (such as compactness, back-driveability, zero-backlash, and stiffness) with the high torque-weight ratio of a differential transmission. Also, to enhance adjustability, WRES uses a passive extra DOF for translation along the PS axis. Thus, this DOF allows a length variable Link 3 for different hand sizes. Conversely, the main drawback of WRES is the non-consideration of wrist axes displacements, as a consequence of the spherical joint assumption made in conceptual design [142]. Hence, this simplification finally affects the natural motion of the wrist.

4.22. *Wrist Gimbal*

Wrist Gimbal is a wrist rehabilitation exoskeleton with 3-DOF serial configuration for the pronation/supination, flexion/extension, and radion/ulnar deviation movements of the wrist (see Fig. 27). The device utilizes a serial kinematic configuration of revolute joints actuated with capstan systems connected to dc motors. To increase the stiffness of the structure, Wrist Gimbal uses ball bearing supports at the end of its movements [66]. The bearings also allow the accommodation of the user's hand. The exoskeleton handles the misalignments of the user's joints by making use of a handle whose height can be passively adjusted and fixed via a threaded rod and two nuts. This handle also permits slight movements of the arm relative to the robot contributing to avoid misalignments.

5. Conclusions

The main apport of this paper is that it reviews the majority of the cable-driven upper limb exoskeleton available in the literature for stroke rehabilitation. The analysis was conducted to take in consideration different types of requirements that goes from the anatomical to the transmission system. The section of the anatomical review of the upper limb is included to generalize the necessities in the emulation of each joint. Thus, each movement of the arm is under examinations, remarking the DOFs and range of motion require for each joint to replicate the human movement without stressing the articulation.

In the same fashion, the section of cable-based transmission systems for exoskeletons classifies the different approaches to transmit motion in exoskeletons. Hence, the chapter presents the basic concepts of their functionality, their particular characteristics and their disadvantages and advantages for their application in exoskeletons. Thus, the review of exoskeletons made use of this information to present the analysis of each prototype remarking the approaches used in each mechanism to tackle the complication of each joint and transmission system. In this sense, the article becomes a valuable tool for the early stages of the design of exoskeletons.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Javier Sanjuan: acquired BS and MS degrees in Mechanical Engineering from Universidad del Norte, Barranquilla, Colombia in 2012 and 2016, respectively. At present, he is about to start his PhD in the University of Wisconsin-Milwaukee in the field of neuro-rehabilitation with exoskeletons. His main research interests are parallel robots dynamics, design and control.