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# Cable Driven Rehabilitation Robots: Comparison of Applications and Control Strategies

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**ABSTRACT** Significant attention has been paid to robotic rehabilitation using various types of actuator and power transmission. Amongst those, cable-driven rehabilitation robots (CDRRs) are relatively newer and their control strategies have been evolving in recent years. CDRRs offer several promising features, such as low inertia, lightweight, high payload-to-weight ratio, large work-space and configurability. In this paper, we categorize and review the cable-driven rehabilitation robots in three main groups concerning their applications for upper limb, lower limb, and waist rehabilitation. For each group, target movements are identified, and promising designs of CDRRs are analyzed in terms of types of actuators, controllers and their interactions with humans. Particular attention has been given to robots with verified clinical performance in actual rehabilitation settings. A large part of this paper is dedicated to comparing the control strategies and techniques of CDRRs under five main categories of: Impedance-based, PID-based, Admittance-based, Assist-as-needed (AAN) and Adaptive controllers. We have carefully contrasted the advantages and disadvantages of those methods with the aim of assisting the design of future CDRRs.

**INDEX TERMS** Cable driven rehabilitation robots, rehabilitation robots, control strategies, upper limb rehabilitation, lower limb rehabilitation, waist rehabilitation.

## I. INTRODUCTION

According to a report published by the World Health Organization [1], there are over a billion of individuals, almost 15% of the world's population, facing some kind of movement-related disability, mainly because of stroke, intellectual impairment, traumatic brain injury, musculoskeletal and neurological disorders [2]. Also, movement-related disabilities are often seen in older people. There are strong evidence that these movement-related disabilities can be restored by intensive repetitive rehabilitation training [3], [4].

Physiotherapy is a common approach for rehabilitation, which has limitations in terms of availability and intensity of therapists. Additionally, manual training is time consuming, expensive and also depends on therapist's experience. Robotic rehabilitation offers promising features including repetitive training with uniform performance for a long period of time and quantitative measures for performance analysis. It can also reduce labour intensity as well as cost, and improve the efficiency of rehabilitation process.

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Typically, rehabilitation robots are classified into three main categories, end-effector, exoskeleton, and planar based on their kind of attachment to the user [5]. In an end-effector type [6], [7], the end-effector of robot is generally attached to the user body while in an exoskeleton type, also known as wearable rehabilitation robots, the robot is wrapped around the human body, and each joint is controlled independently [8]–[10]. In the planar type, robot only allows movements of its attachment points to the body in a specific plan [11].

The common actuation techniques in rehabilitation robots include, pneumatic, hydraulic, series elastic and electric. Hydraulic and pneumatic actuators are bulky, noisy and has possibility of compressed air or fluid leakage, which may limit their usage. For power transmissions, different approaches are used including ball screw driven, belt driven, gear driven, and cable driven [12]. Important characteristics of rehabilitation robots, in terms of power transmissions, are compared in Table 1, where the desirable characteristics are underlined [13]–[16]. Compared to other types, CDRRs offer several promising features such as: low inertia, light weight, high payload-to-weight ratio, and large workspace [17]–[20]. They also have a few deficiencies

**TABLE 1.** Comparison of cable, belt, ball screw and gear driven rehabilitation robots.

Properties	CDRR	BDRR	BSDRR	GDRR
Distance between source and load/Workspace	Large	Large	Medium	Small
Manipulation accuracy at low speed	High	Medium	Medium	High
Payload-to-weight ratio	High	High	Low	Low
Moving inertia of robot's link	Low	Medium	High	High
Weight of rehabilitation robot	Low	Low	High	High
Maintenance	High	Medium	Low	Low
Direction of power transmission	Uni-Dir	Bi-Dir	Bi-Dir	Bi-Dir
Undesired vibration	High	High	Low	Low

Keywords: CDRR- Cable driven rehabilitation robot, BDRR- Belt driven rehabilitation robot, BSDRR- Ball screw driven rehabilitation robot, GDRR- Gear driven. Uni-Dir- UniDirectional, Bi-Dir- BiDirectional

due to uni-directional power transmission, vibration and maintenance.

Although there are a large number of review papers on rehabilitation robots [21]–[43], only one has so far focused on cable driven rehabilitation robots [44]. The paper analyzes CDRRs in terms of safety, back-drivability, weight, adaptability, versatility, and misalignment features. The paper however does not include other important aspects such as control strategies, clinical studies, physical human-robot interaction and human-machine interfaces, which we have covered in this work to complete the analysis. The control strategies are critical and different among various transmission approaches. Due to the elasticity of cables and the fact they can only apply tensile forces [45], [46], many of the control strategies deployed in robots with gears, belts, ball-screws, linkages, or others [25], [27], [31], [34], [43], [47], cannot be directly applied to CDRRs [18], [20].

In this paper, we categorize the CDRRs into three main groups concerning their application for upper limb, lower limb, and waist rehabilitation, as shown in Fig. 1. For each group, target movements are identified, and existing CDRRs are reviewed in terms of types of actuators, controllers, clinical studies, physical human-robot interactions, and human-machine interfaces (these are complimentary to the topics presented in [44]). Particular attention has been given to clinical performance and results of CDRR's in actual rehabilitation environment. A large part of this work is dedicated to compare the control strategies and techniques used for CDRRs. These are divided into five main categories including Impedance-based, PID-based, Admittance-based, Assist-as-needed, and Adaptive-based controllers. We conclude the paper by identifying major challenges facing the future development of CDRRs and their suitability for rehabilitation.

The classification schema is explained in section II. Section III reviews the design characteristics of existing CDRRs for upper, lower and waist rehabilitations. Then the control strategies of CDRRs are presented in section IV.

Lastly, in section V challenges and future works are summarized.

## II. PRELIMINARIES AND CLASSIFICATION OF CABLE-DRIVEN ROBOTS FOR REHABILITATION

Conventionally, rehabilitation robots are classified into only two groups of upper and lower limbs as there are significant differences in motor function, mobility and gait of the upper and lower extremity of human body. The application of rehabilitation robots has been extended in recent years to other parts of the human body (e.g. waist) and the related aches caused by diseases, old age, or sedentary lifestyle. The differences in motor function and mobility of upper limb, lower limb and waist also led researchers to design and implement specific CDRRs for different extremities of human body. In this work, the existing cable driven rehabilitation robots are preliminarily classified into three groups based on their applications in upper limb, lower limb, and waist rehabilitation. Around 200 references and research articles, which present a novel or enhanced cable-driven rehabilitation mechanism, or discussing key technologies, design characteristics or control strategies for CDRRs, have been reviewed in this work. Among those references, 86 are recent works published after 2015. Overall, we have identified and summarized 66, 31 and 4 state-of-the-art CDRRs for upper limb, lower limb and waist rehabilitation, respectively. To facilitate the discussion, the CDRRs belonging to each group (upper limb, lower limb and waist) are then classified and compared based on the design characteristics and control strategies, as shown in Fig. 1. The classification and review schema is as follows:

### Classification and review schema

#### I. Rehabilitation application:

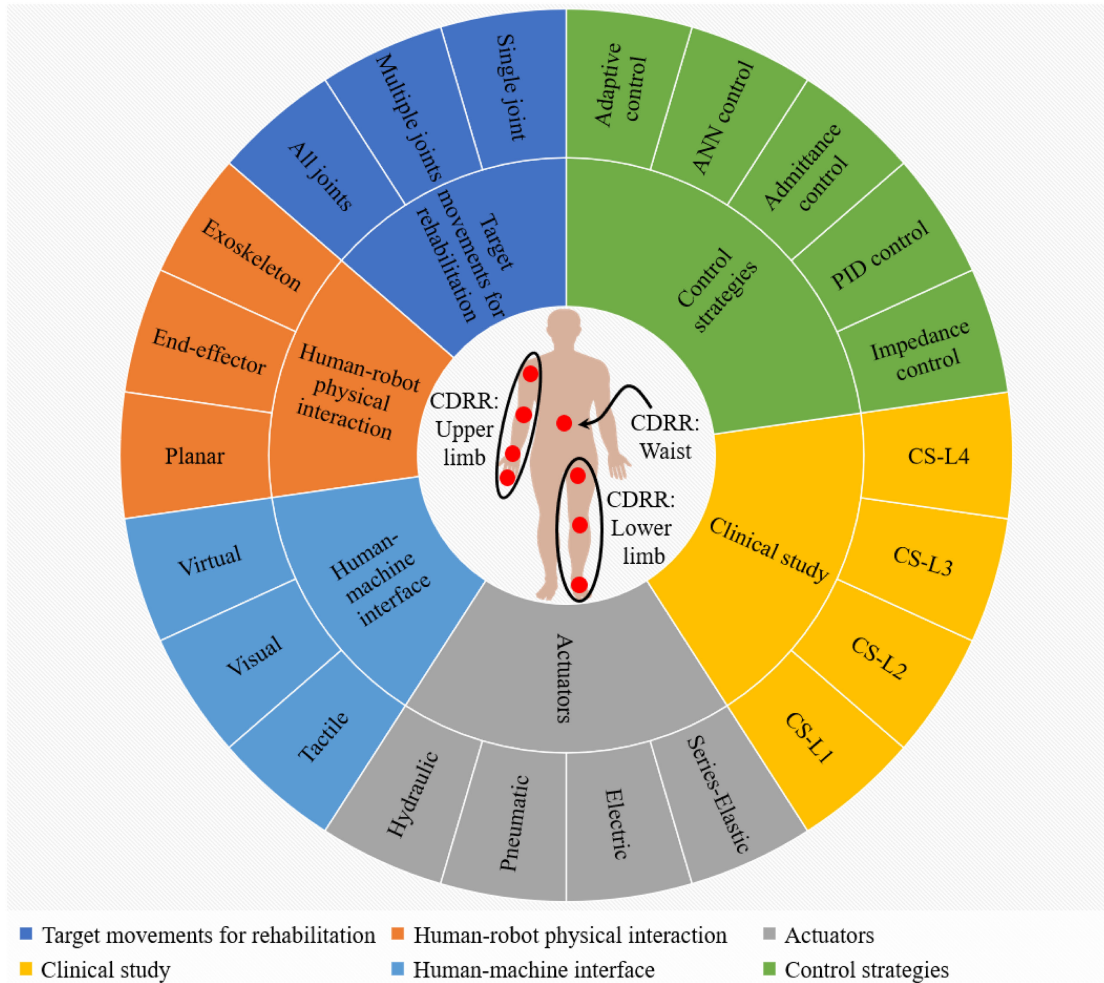
- Upper limb: elbow, shoulder, wrist, forearm, fingers.
- Lower limb: hip, knee, ankle and foot.
- Waist rehabilitation.

#### II. Design characteristics:

- Target joint movements: single, multiple or all joints.
- Types of actuators: pneumatic, hydraulic, series elastic, and electric actuators.
- Type of sensors: IMU, force, torque, EMG, load cell.
- Human-robot physical interaction: exoskeleton, end-effector, and planar type.
- Human-machine interface: virtual, visual, or tactile
- Clinical study: levels 1, 2, 3, and 4.

#### III. Control strategies (impedance, PID, admittance, AAN, and adaptive controllers):

- Control's level: high, mid, and low-level.
- Modelling approach: model-based, model-free, and hybrid control.
- Performance: measurements of error, cartesian error for task space tracking, and joints trajectory tracking error.
- Operating space: task and configuration space.
- Stability: asymptotic, non-asymptotic and not applicable.



**FIGURE 1.** The review structure and classification schema considering application, design characteristics and control strategies. Around 66, 31, and 4 different CDRRs are found for upper limb, lower limb, and waist rehabilitation, respectively.

**A. TARGET JOINT MOVEMENTS**

Target movements refer to the specific movements in human joints for which the rehabilitation robot is designed. Based on the target movements, CDRRs can be divided into three categories; CDRRs that can assist and train only single joint, multiple joints, and all joints of upper or lower limbs.

**B. TYPE OF ACTUATORS**

Different types of actuators are used in the cable driven rehabilitation robots, which are electric, hydraulic, series elastic, and pneumatic. An actuator in CDRRs is responsible for generation of mechanical energy and motion [48].

*Electric actuators* convert electric energy into mechanical energy. There are large varieties of commercially available electric actuators with different specifications used in CDRRs. *Pneumatic* and *Hydraulic actuators* convert highly compressed air and hydraulic fluid pressure into mechanical energy, respectively. *Series Elastic Actuators (SEA)* in CDRRs use an elastic element between the actuator and load.

**TABLE 2.** Glossary: human-robot physical interaction.

Term	Description
E-CDRRs: Exoskeleton Type	CDRRs resemble the skeletal structure of the human limb and connect to patients at multiple points. Robot’s joint axes have one to one correspondence with the human joints.
EE-CDRRs: End-effector Type	CDRRs are connected to patients only at the most distal part of the extremity.
PL-CDRRs: Planar Type	CDRRs allow movements of end-effector in a specific plane. Even though the robot’s movements is performed in a single plane, but limb joints may move in a three-dimensional space.

**C. HUMAN-ROBOT PHYSICAL INTERACTION (HRPI)**

The human-robot physical interaction points to how the rehabilitation robots are attached to the patients. We categorize the CDRRs into three groups; end-effector, exoskeleton, and planner type CDRRs based on human-robot physical interaction. The used terminologies are explained in the Table 2. The end-effector, exoskeleton, and planner type CDRRs can

**TABLE 3. Glossary of terms: classification of clinical study.**

Term	Description
Level 1 CS-L1	Initial study is carried out with only few healthy volunteers, to check the CDRR efficiency, safety, and controllability. It also involves evaluating the CDRR performance with external disturbance.
Level 2 CS-L2	Trials are performed with large healthy volunteers or less than 30 individuals suffering from the target disease, to evaluate the CDRR performance, effectiveness in assistance, and training the targeted disability.
Level 3 CS-L3	Trials are performed with 30 to 100 patients suffering from the target disease. It is conducted to verify the ability in assist and training the targeted disability.
Level 4 CS-L4	Final level of clinical study is performed with a large number of patients suffering from the target disease for further verification of the CDRR performance.

be further categorized into serial and parallel mechanisms. *Exoskeleton type CDRRs*, also known as wearable robots, have mechanical structure correspondence to the actuated skeleton structure. An *End-effector type CDRR*, has its end-effector in contact with only one segment of the human body or upper limb only at its most distal part. A *planar type CDRR*, provides movements in a specific plane but allows limb to move in three-dimensional space.

#### D. HUMAN-MACHINE INTERFACE (HMI)

Human-Machine Interface refers to a type of virtual, visual, or tactile interface that is usually incorporated in rehabilitation exercises to allow patient or user interaction with robot, HMI could also increase the recovery rate of rehabilitation.

#### E. CLINICAL STUDY

The clinical study refers to the verification of rehabilitation robots in practice with real patients. It is an essential step in evaluating the actual performance of CDRRs, control strategies, and various aspects of robot interaction with patients. However, conducting clinical trials is expensive, challenging, and needs a higher level of reliability and safety measures to verify the robot in actual settings with multiple humans or patients involved. While clinical trials are of great importance, there is less information on clinical studies for different CDRRs and those might depend on unique cases and cable configurations. Particular attention is given in this work to summarize the major information on existing clinical trials for CDRRs with the aim of assisting the design and assessments of future CDRRs through clinical studies.

The clinical trials with patients and/or healthy human are compared here in four levels as outlined in Table 3. *Initial clinical study or level 1* is carried out with only few healthy volunteers, to evaluate a CDRR. *Level 2* clinical study is carried out with large healthy volunteers or less than 30 individuals suffering from the target disease, to check performance in assistance and training the targeted disability. *Level 3* clinical study is performed with 30 to 100 patients suffering from target disease. *Level 4* is the final level of clinical trial with more than 100 patients suffering from a target disease for further verification of the CDRR performance.

### III. DESIGN CHARACTERISTIC OF CDRRS

Main features or design characteristics of the existing CDRRs for upper limb, lower limb and waist rehabilitation are discussed in separate subsections. Approximately 66, 31 and 4 different designs of CDRRs are found in literature for upper limb, lower limb, and waist rehabilitation, respectively. The advantages and disadvantages of different characteristics are summarised in the last subsection.

#### A. CABLE-DRIVEN ROBOTS FOR UPPER LIMB

There are large number of CDRRs designed for patients with upper limb disabilities. A few key technologies in cable-driven robots for upper limb rehabilitation are CAREX [8], [49], Dampace [50], Planar Cable-Driven Robot [51], [52], MEDARM [11], PACER [53], [54], and Active therapeutic device (ATD) [55] as shown in Fig. 2. A complete list of existing CDRRs for upper limb rehabilitation are summarized in Tables 4, 5, and 6.

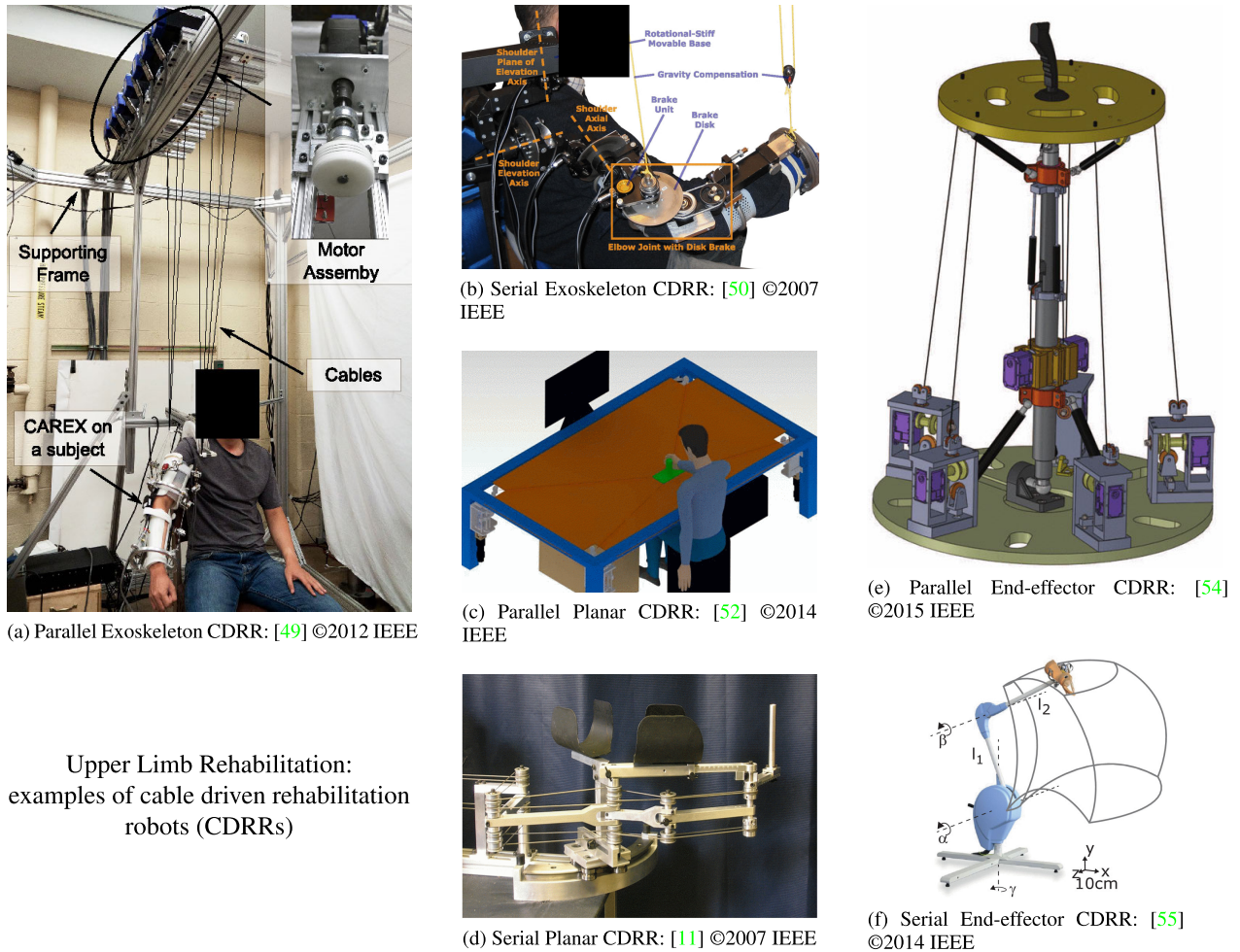
##### 1) TARGET MOVEMENTS FOR REHABILITATION

Based on the target movements, CDRRs for upper limb can be divided into three categories. The first category includes CDRRs that can assist and train only one joint movement, which can be shoulder, elbow, forearm, wrist or finger movement, as summarized in Table 4. A few examples are, a) MEDARM [56], [57], Wearable Soft Orthotic Device [58], HRM [59], and Active Soft Orthotic Device [60] to assist shoulder; b) NEUROExos [61], CADEL [62] and BJS [63] to assist elbow; c) Active Therapeutic Device (ATD) [55] to assist forearm; d) CDWRR [64] to assist wrist; and e) Exoskeleton glove [65], Tendon Driven Hand orthosis [66], CDRH [67], Home-based hand rehabilitation [68], wearable robot hand [69] and IOTA [70] to assist fingers joints. The second category of CDRRs, shown in Table 5, is designed to assist a combination of two or more joints movements of the upper limb, for example, ULERD [71], SUEFUL-7 [72], CABXLexo-7 [73] and CAREX-7 [9], [74]. The third category of CDRRs, as summarized in Table 6, can assist and train all the joints of upper limb except fingers. There doesn't seem to be any CDRR that can train the whole arm including fingers.

##### 2) TYPES OF ACTUATORS

Electric actuators are widely used in the upper limb CDRRs, such as ULERD [71], [75], SUEFUL-7 [72], CAREX [8], CDWRR [64]. Compare to electric actuators, the use of pneumatic actuators in CDRRs has gained less attention from the research community. IKO [76], [77], Exoskeleton Rehabilitation Robot [78], 9-DoFs rehabilitation robot [79], [80], RUPERT [81], [82] [83], Wearable Rehabilitation Robotic Hand [84] are a few CDRRs that have been designed using pneumatic actuators. There are currently only two upper limb CDRRs, NEUROExos [61], Dampace [50], which use Hydraulic actuators. Series Elastic Actuators are also found in four upper limb CDRRs, namely: Wearable Soft Orthotic





**FIGURE 2.** Upper limb rehabilitation: examples of cable driven robots (CDRRs). (a): Parallel Exoskeleton type CDRR - CAREX [49] ©2012 IEEE. E/Reprinted, with permission from "Transition from mechanical arm to human arm with CAREX: A cable driven ARm EXoskeleton (CAREX) for neural rehabilitation" by Ying Mao *et al.* in IEEE International Conference on Robotics and Automation 2012; (b): Serial Exoskeleton type CDRR - Dampace [50] ©2007 IEEE. E/Reprinted, with permission from "Dampace: dynamic force-coordination trainer for the upper extremities" by Arno *et al.* in IEEE 10th International Conference on Rehabilitation Robotics 2007; (c): Parallel Planar type CDRR - Planar Cable-Driven Robot [52] ©2014 IEEE. E/Reprinted, with permission from "Workspace analysis of upper limb for a planar cable-driven parallel robots toward upper limb rehabilitation" by XueJun *et al.* in IEEE International Conference on Control, Automation and Systems 2014; (d): Serial Planar type CDRR - MEDARM [11] ©2007 IEEE. E/Reprinted, with permission from "A planar 3DOF robotic exoskeleton for rehabilitation and assessment" by Stephen *et al.* in 29th Annual International Conference of the IEEE Engineering in Medicine and Biology 2007; (e): Parallel End-effector type CDRR - PACER [54] ©2015 IEEE. E/Reprinted, with permission from "Modeling and control of a novel home-based cable-driven parallel platform robot: PACER" by Aliakbar *et al.* in IEEE/RSJ International Conference on Intelligent Robots and Systems 2015; (f): Serial End-effector type CDRR-Active therapeutic device (ATD) [55] ©2014 IEEE. E/Reprinted, with permission from "A Damper Driven Robotic End-Point Manipulator for Functional Rehabilitation Exercises After Stroke" by Ard *et al.* in IEEE Transactions on Biomedical Engineering 2014.

Upper Limb Rehabilitation:  
examples of cable driven rehabilitation  
robots (CDRRs)

Device [58], Active Soft Orthotic Device [60], BJS [63], and Elbow Exoskeleton [85]. While each type of actuator has some advantages and disadvantages, one often selects the best choice for a specific rehabilitation application based on the most critical features that are nonnegotiable.

3) HUMAN-ROBOT PHYSICAL INTERACTION

Exoskeleton type CDRRs for upper limb rehabilitation have mechanical structure correspondence to the upper limb skeleton structure of a human extremity. The CAREX [8] and Dampace [50] are parallel and serial exoskeleton type CDRRs, respectively, shown in Figs. 2-(a), (b). The CAREX [8] is a 5-DOF rehabilitation robot. It has a novel design,

in which cuffs of CAREX are attached to the upper arm that are driven by the cables. The Dampace [50] is a passive exoskeleton to assist the 3 rotational DOFs of shoulder joint and one DOF of elbow joint. It was designed to combine the functional training of daily life activities with force coordination training.

A parallel and one serial planar type CDRRs are shown in Figs. 2-(c) and 2-(d), respectively. They provide movements in a specific plane but allow limb to move in three-dimensional space. Planar Cable-Driven Robot [51], [52] is a parallel 3-DOF CDRR for upper limb rehabilitation. It provides a relatively large workspace and less moving inertia. MEDARM [11] is a serial CDRR and can assist in

**TABLE 4. CDRRs for upper limb rehabilitation: targeting only a single joint.**

Name of CDRR; Reference	DOF	Actuator	Sensor	HRPI	Control Strategy	Clinical & HMI
<b>Target movements of rehabilitation; shoulder movements</b>						
MEDARM [11]	{3}	EA	Encoder	PLS-E	Joint position control	Prototype
Upper Arm Exoskeleton [116]	{3}	—	—	PE	Force control	—
Wearable Soft Orthotic Device [58]	{1}	SEA	Piezoresistive flex + IMUs	PE	Impedance control	Prototype
Active Soft Orthotic Device [60]	{1}	SEA	Electromagnetic + 6-axis force-torque	PE	Adaptive control	Prototype
<b>Target movements of rehabilitation; elbow movements</b>						
NEUROExos [61]	<4>	EMA+HA	Encoder + Load cells + Linear potentiometers	SE	Passive-compliance + Impedance torque ctrl	Prototype
BJS [63]	{1}+<3>	SEA	Rotary + Hall effect sensors	SE	Sliding mode controller	Prototype
Upper Limb Soft Exoskeleton [117]	{1}	EA	Flex + Film pressure sensor	PE	Hierarchical cascade controller	Prototype
Adaptive Rehab. Sys. [118]	{4}	PAM	KinectTM + EMG sensors	SE	Pressure control	Prototype
Elbow Exoskeleton [85]	{2}	SEA	Torque sensors	PE	PID feedback control	Prototype; Forearm
CADEL [119]	{1}	EA	Force + IMU sensors	PE	—	Prototype
Elbow Rehab. [120]	{1}	EA	—	PE	Sensor-assisted control	Prototype
<b>Target movements of rehabilitation; forearm movements</b>						
ATD [55]	{3}	EA	Six-DOFs force sensor + Angular encoders	SEE	Impedance + Position control	Prototype
<b>Target movements of rehabilitation; wrist movements</b>						
CDWRR [64]	{3}	EA	Load + IMU	PE	Assist-as-needed	Prototype
<b>Target movements of rehabilitation; fingers movements</b>						
Wearable Rehab. Robo. Hand [84]	{2}	PAM	Angle + Pressure + Force Sensor	PE	Variable integral PID control	Prototype; CS-L1
CADEX Glove [121], Finger Rehab. [122]	Multi- DOF	EA	—	PE	—	Prototype
Wearable Hand [123]	—	EA	Load cell	PE	Force control	Prototype
Tendon Driven Hand orthosis [66]	{3}	EA	Encoder + Load sensor	PE	Position PID controller	Prototype; CS-L2
SNU Exo-Glove [124]	Multi- DOF	EA	Custom-made tension + Force sensors	PE	Isotonic + Isokinetic + Impedance control	Prototype
CAFÉ [125]	{3}	EA	Force + Angle sensors	SE	PI control	Prototype
Hand Exoskeleton [126]	{7}	EA	—	SE	—	Prototype
Hand Exoskeleton [127]	{4}	EA	Force sensors	SE	Resistance compensation control	Prototype
HIT-Glove [88]	{2}	EA	Position + Force sensors	SE	Patient-cooperative control	Prototype; HMI:DS
Hand Exoskeleton [128]	Multi- DOF	EA	—	SE	High-order iterative learning Ctrl (ILC)	Prototype
IOTA [70], [129]	{2}	EA	Encoders + Bend sensors	SE	Proportional control	—
Hand Exoskeleton [130]	Multi- DOF	EA	Hall + EMG sensors + Bend sensors	SE	Active disturbance rejection control	Prototype
Hand Exoskeleton [131], Soft Glove [132]	Multi- DOF	EA	EMG sensors	SE	—	Prototype

First column: shows the CDRR name and reference of corresponding publication. Second column: indicates the active  $\{No\}$  and passive  $\langle No \rangle$  DOFs of CDRR; Third column: shows the corresponding sensors Fourth column: indicates the type of CDRR; PE- Parallel exoskeleton, PLS-E: Planar Serial Exoskeleton, SEE: Serial End-effector, and SE: Serial Exoskeleton. Fifth column; describes the type of control strategy. Sixth column; refers of type of actuator; EA - Electric actuator, SEA -series elastic actuator, EMA: Electro Magnetic Actuator, and PAM - Pneumatic artificial muscle. Last column; provides the more information about: prototype availability, clinical studies level, and Human-Machine Interface; CS-L1: Clinical Study at Level 1, CS-L2: Clinical Study at Level 2, and HMI:DS: Human-Machine Interface: Display Screen.

**TABLE 5. CDRRs for upper limb rehabilitation: targeting any combination of: shoulder, elbow, forearm, wrist and fingers.**

Name of CDRR; Reference	DOF	Actuator	Sensor	HRPI	Control Strategy	Clinical & HMI
<b>Target movements of rehabilitation; shoulder + elbow movements</b>						
Dampace [50]	{5}	EA + HA	—	Adjustable SE	Feedback control	Prototype; HMI:RG
Upper Limb Exoskeleton [133]	{5}	EA	—	SE	Intention-driven robotic control	—
MEDARM [11]	{3}	EA	Encoder	PE	Joint Position Ctrl	Prototype
Exoskeleton Rehab. Robot [78]	{5}+{5}	PAM	Optical motion capture system	SE	EMG based real-time control	—
ABLE [134]	{4}	EA	3D displacement + Position sensors	SE	PID-position control	Prototype
9-DoFs Rehab. Robot [79], [80]	{8}+{1}	PAM	Angle + Force sensors	SE	PID Position + Force control	Prototype
CARR-4 [135]	{4}	EA	Load + IMUs sensors	PE	Robust Adaptive ILC + Feed forward Ctrl	Prototype
Auxilio [136]	{3}	DC-EA	Kinect motion sensor	PE	Slack mitigation Ctrl	Prototype
Parallel Structure 4-2 [137]	Multi-DOF	DC-EA	Encoder	Sus-PEE	Speed + Position closed-loop control	Gait rehab
Upper Limb Rehab. Robot [138]	{4}	DC-EA	IMU + Encoder	SE	PID control	Prototype
L-EXOS [87]	{4}+{1}	DC-EA	Position sensor	SE	Impedance control	HMI:VE; CS-L2
CDE [139]	{4}	EA	Load sensors	PE	Stiffness oriented control	Prototype
<b>Target movements of rehabilitation; Wrist + Fingers movements</b>						
MAHI [140]	{3}	EA	Angle sensors	SE	PD control	Prototype
<b>Target movements of rehabilitation; elbow + wrist movements</b>						
ULERD [71], [75]	{3}+{4}	EA	Inertia sensor	SE	PID control	HMI:VE
<b>Target movements of rehabilitation; shoulder + elbow + wrist movements</b>						
IKO [76], [77]	{5}+{3}	EA+PAM	Pressure + Length measuring sensors	SE	Position + Rotation control	Prototype
X-Arm-2 [141]	{8}+{6}	EA	Torque sensor	PE	Joint-impedance	Prototype
CABexo [73]	{6}	EA	—	SE	—	—
CABXLexo-7 [142]	{7}	EA	—	SE	—	Prototype
RUPERT [81]–[83]	{4}	PAM	Position + Inertial + Pressure sensors	SE	Open-loop feed forward position control	Prototype; CS-L1
Planar Cable-Driven Robot [51], [52]	Multi-DOF	EA	6-DOF force sensor	PLP-EE	Position-Based Admittance Control	Prototype; HMI:VG
CADEN 7 [143]	{4}	EA	Redundant position sensors	SE	Position + Force impedance Ctrl	Prototype
Robotic Exoskeleton [144]	{4}	PAM	Peripheral sensor	SE	Adaptive fuzzy sliding mode control	Prototype
UP Exoskeleton [145]	{4}	EA	Load + IMU sensor	PE	feedforward control	Prototype
<b>Target movements of rehabilitation; shoulder + elbow + forearm movements</b>						
MULOS [89]	{5}	EA	—	SE	Vel. + Force PID	HMI:JCS
CAREX [8]	{5}	EA	Orientation + Rotary + Load sensors	PE	Assist-as-needed	Prototype; CS-L2

keywords: { } : active DOF and < > : passive DOF, PE: Parallel Exoskeleton, SE: Serial Exoskeleton, Sus-PEE: Suspended Parallel End-effector, PLP-EE: Planar Parallel End-effector, DC: Direct current, EA: Electric Actuator, HA: Hydraulic Actuator, PAM: Pneumatic Artificial Muscle, VE: Virtual Planar Environment, VG: Virtual Games, JCS Joystick Control System, CS-L1: Clinical Study at Level 1, and CS-L2: Clinical Study at Level 2.

the horizontal plane. The novelty of this design is a curved track that allows the independent control of a patient's joints.

A parallel and serial end-effector type CDRRs are shown in Figs. 2-(e) and 2-(f), respectively. PACER [53], [54] is a parallel end-effector type CDRR and consists of a cable driven antagonistically actuated prismatic joint. This novel design was presented to facilitate the home-based

rehabilitation device. Active therapeutic device [55] is a serial end-effector type CDRR with 3-DOF. It was designed to support the functional reaching movements.

#### 4) HUMAN–MACHINE INTERFACE (HMI)

The IntelliArm [86], Dampace [50], L-EXOS [87], Planar CDPR [51], [52], HIT-Glove [88], MULOS [89], and

**TABLE 6.** CDRRs for upper limb rehabilitation: targeting all joints of arm except fingers .

Name of CDRR; Reference	DOF	Actuator	Sensor	HRPI	Control Strategy	Clinical & HMI
<b>Target movements of rehabilitation; shoulder + elbow + forearm + wrist movements</b>						
SUEFUL-7 [72]	{7}	EA	Force + Torque sensors	Adjustable SE	Impedance control	Prototype
IntelliArm [86]	{7}+(2)	EA	Force + Torque sensors	Adjustable SE	Intelligent stretching + Zero resistance regulation control	Prototype; HMI: G
Soft-Actuated Exoskeleton [146]	{7}	PAM	High linearity + Torque + Pressure sensors	SE	Impedance control + PID control	Prototype
CAREX-7 [9], [74]	{7}	EA	Load + IMU sensors	PE	Assist-as-needed	Prototype
Upper-Limb Powered [147]	{7}	Brushed EA	Potentiometer + Encoder	SE	Position + Force-impedance control	Prototype
Rehab. Robot [148]	Multi-DOF	EA	Force sensors	PLEE	—	Prototype
Sophia-3 and Sophia-4 [90]	Multi-DOF	DC-EA	Optical encoders	PLP-EE	Impedance + Model-based adaptive Ctrl	Prototype; HMI:VE
Cable-driven Rehab. Robot [149] [150]	Multi-DOF	—	Encoder	Sus-EE	Sliding Mode Tracking Control	Prototype
NeReBot [91], [151], [152]	{3}	EA	—	Sus-EE	PCIO4 CONTROL	Prototype; CS-L3
MariBot [153]	{5}	EA	Incremental encoder	Sus-EE	PID position control	Prototype
MACARM [154]	{6}	EA	6-DOF load sensor	Sus-EE	Motion control	Prototype
PACER [53], [54]	{6}	Linear EA	—	Spatial+ Planar-EE	Feedback + Admittance control	—
CDULRR [155]	{3}	—	Force	PEE	Assist-as-needed	Prototype
Mirror-Image Motion Dev. [156]	—	BLDC-EA	Inertial Sensors	—	PD control	Prototype
CDRR Exoskeleton Sys [156]	—	DC-EA	IMU Sensors	SE	PID force feedback control	Prototype

Keywords: { } : active DOF, ( ) : passive DOF, SE: Serial Exoskeleton, PE: Parallel Exoskeleton, PLP-EE: Planar Parallel End-effector, Sus-EE: Suspended End-effector, DC: Direct current, EA: Electric Actuator, and PAM: Pneumatic Artificial Muscle, HMI:G: Human-Machine Interface: Cursor Positioning Game, HMI:VE: HMI:Virtual Planar Environment, and CS-L3: Clinical Study at Level 3.

Sophia-3/4 [90] are few upper limb CDRRs that benefited from a type of HMI to train the patients. The IntelliArm rehabilitation robot reported a simple virtual game interface to keep patient motivated and enhance the training ability, in which the movement of the cursor in the game was commanded from the patient's joint movement. The Dampace rehabilitation robot employed a racing game interface to increase the recovery rate, where the good driving control in the game requires good coordination of elbow and shoulder torques. The L-EXOS robot incorporated the cubes game to train the patient, in which patient was commanded to move the cubes in the virtual scenario. The Planar CDRR [51] used three virtual rehabilitation therapy games: a) painting game, b) pong game, and c) ball game to train the patient in virtual environment. The HIT-Glove used tactile interface, where a display screen interface with force sensors was used to measure the patient's effort in the training exercise, while MULOS CDRR deployed a specially designed 5-DOF joystick.

##### 5) CLINICAL STUDY OF CDRRs FOR UPPER LIMB

Although, a large number of CDRRs for upper limb rehabilitation are reported in literature, only a few of them have gone under a clinical investigation. RUPERT [81]–[83] and Wearable Rehabilitation Robotic Hand [84] have reported a successful clinical study at Level 1. The RUPERT carried out the clinical study with eight able-bodied volunteers. The focus of the study was to check the robot performance in actual rehabilitation environment. The Wearable Rehabilitation Robotic Hand CDRR performed the clinical study with only one healthy subject. L-EXOS [87], Tendon Driven Hand Orthosis [66], and CAREX [8] are three CDRRs that have their clinical study reported at Level 2. The L-EXOS went through the clinical trial at the Neurorehabilitation Unit, at the University of Pisa. It was also integrated with the virtual environment to motivate the patients in the rehabilitation process. The preliminary clinical trial was carried out with a 60-year-old patient and reported satisfactory results. They also examined the robot performance by conducting an



extended clinical trial with six patients for six weeks. The CAREX demonstrated the clinical study with eight healthy volunteers and one stroke patient, and found the subject efficiently followed the desired trajectory. The CAREX does not cause hinders or incorrect posture to patient movements, except that they felt a little tired after one hour of exercise. NeReBot [91] is one of the CDRRs with results of clinical study at Level 3. This robot was used in two clinical tests. In the first scenario, the NeReBot was used in addition to the traditional method of treatment/therapy [92]. Thirty-five patients participated in this clinical trial and significant recovery was reported. In the second scenario, the NeReBot was partial substitution to the standard rehabilitation treatment by using a dose-matched approach [93]. Thirty-four patients, 11 females and 23 males, participated in this clinical trial, and patients show significant degree of acceptance to the robotic training. Up to now, none of CDRRs has reached level four of clinical trial.

### B. CABLE-DRIVEN ROBOTS FOR LOWER LIMBS

The neuro-rehabilitation of the lower limb, especially for the gait training, demands a great amount of time and effort from the physiotherapists. In most the cases, more than two physiotherapists are required to assist the rehabilitation training of patient with lower limb disabilities. CDRRs for lower limb rehabilitation can reduce the burden on the health care, cost, and can increase the recovery rate [94]. Contrary to CDRRs for the upper limb, less attention has been paid in designing CDRRs for the lower limb.

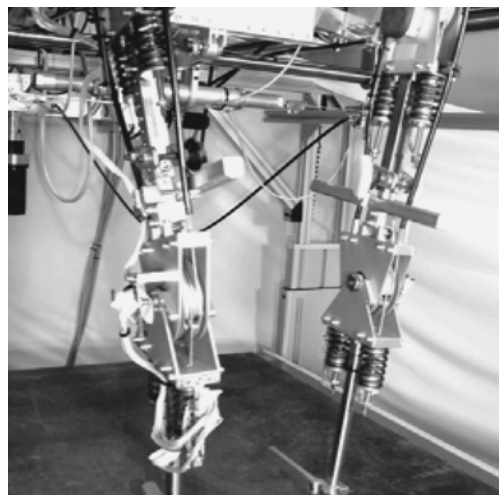
Few CDRRs for lower limb rehabilitation are LOPES [95]–[97], C-ALEX [98], COWALK-Mobile 2 [99], Lower Limb Rehabilitation Robot [100], and Bio-inspired Soft Wearable Robot [101]. A comprehensive list of existing CDRRs for lower limb are summarized in Table 8.

#### 1) TARGET MOVEMENTS FOR REHABILITATION

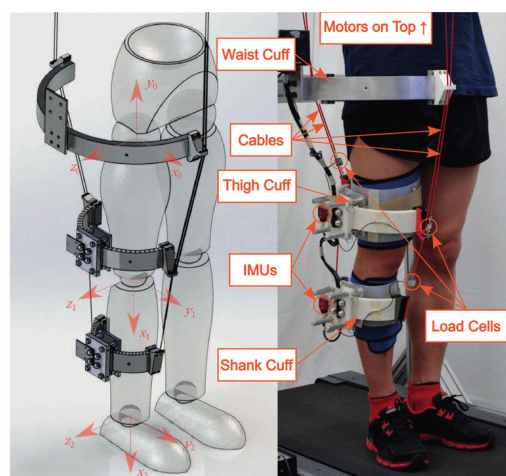
Most of the lower limb CDRRs are designed to assist all the joints of the lower limb; hip, knee and ankle joints. There are however some CDRRs to assist only one or two lower limb joints, such as, Powered Ankle Prostheses [102] and C-ALEX [98] that are proposed to assist the rehabilitation of ankle joint and hip-knee joints, respectively. The categorization of lower limb CDRRs based on number of target joints for rehabilitation is shown in Table 8.

#### 2) TYPES OF ACTUATORS

The CDRRs for the lower limb can be classified into three types: electric, pneumatic, and series elastic actuator based on how the energy is provided to the actuators. As can be seen from the Table 8, most of the CDRRs for the lower limb used the electric and pneumatic actuators. LOPES [95]–[97] is the only CDRR for the lower limb, which used series elastic actuator.



(a) Serial Exoskeleton CDRR - LOPES [96] ©2007 IEEE



(b) Parallel Exoskeleton CDRR - C-ALEX [98] ©2015 IEEE

**FIGURE 3.** Examples of cable driven rehabilitation robots for Lower limb. (a): Serial Exoskeleton type - LOPES [96] ©2007 IEEE. E/Reprinted, with permission from “Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation” by Jan et al. in IEEE Transactions on Neural Systems and Rehabilitation Engineering 2007; (b): Parallel Exoskeleton type - C-ALEX [98] ©2015 IEEE. E/Reprinted, with permission from “Design of a cable-driven active leg exoskeleton (C-ALEX) and gait training experiments with human subjects” by Xin Jin et al. in IEEE International Conference on Robotics and Automation 2015.

#### 3) HUMAN–ROBOT PHYSICAL INTERACTION

Referring to how CDRRs can be connected to the lower limb, they can be categorized into four categories, namely, serial exoskeleton, parallel exoskeleton, planar and parallel end-effector types as shown in Fig. 3. LOPES [95]–[97] is a serial exoskeleton type CDRR, which combines a pelvis segment and a leg. This design allows two therapy protocols, patient in charge and robot in charge. C-ALEX [98] is a parallel exoskeleton type CDRR designed for the gait training. It has a simple structure and add less moving inertia to the human limbs. Another CDRR presented in [103], [104] is a planar cable-driven parallel robot driven by four cables. It was proposed for gait rehabilitation and can produce a

wrench-closure trajectory. Table 8 summarizes the CDRRs for the lower limb rehabilitation and shows the type of interaction they have with patient's joints. Advantages and disadvantages of these types of physical interactions are discussed at section III-D.

#### 4) HUMAN-MACHINE INTERFACE

Contrary to CDRRs for the upper limb, limited information is reported in literature on human-machine interfaces for the lower limb training. The C-ALEX [98] was supported by a display screen to show the subject's leg movement in sagittal plan. The LOKOIRAN [105] and String Man [106] have also benefited from human-machine interface to motivate patients for exercises.

#### 5) CLINICAL STUDY

Similar to CDRRs for the upper limb rehabilitation, the clinical study of CDRRs for the lower limb rehabilitation has received very limited attention. Only a few CDRRs, LOPES [107], Soft Exosuit [108], String Man [106], Locomotor [109], and TPAD [110] were able to support their findings with clinical studies. The LOPES [107] carried out the clinical study with ten patients, and significant improvement in the rehabilitation process was reported. The Soft Exosuit [108] performed the clinical study with three patients, and showed a satisfactory performance in clinical trial. The String Man [106] has performed a clinical study with both dummies and healthy people. The Locomotor [109] used the 11 subjects with incomplete spinal cord injury to conduct the clinical trial. The TPAD [110] recruited the seven healthy subjects to perform the clinical trial. Based on the classification mentioned in the table 3, LOPES, Soft Exosuit, and Locomotor have their clinical studies at level 2, whereas the String Man and TPAD have clinical study at level 1.

### C. CABLE-DRIVEN ROBOTS FOR WAIST

The last group of CDRRs targets patients with waist injuries. Contrary to CDRRs for upper limb or lower limb rehabilitation, limited work has been done in developing CDRRs for the waist rehabilitation. The existing CDRRs are HWRR-Waist

Rehabilitation Robot [111], [112], CDPR [113], CPRWR [114], and CDP RR [115].

Table 7 shows list of CDRRs for waist rehabilitation and their features with more detail. All of the existing CDRRs for waist rehabilitation are parallel exoskeleton type. The electric and pneumatic types of actuators are used to drive the CDRRs for waist rehabilitation. None of the CDRR for waist rehabilitation went under the clinical investigation or provided the human-machine interface.

### D. DISCUSSIONS ON DESIGN CHARACTERISTICS

The cable-driven rehabilitation robots are aimed to assist patient improve their ability in performing the daily life activities. As such, the CDRRs are typically designed to support multiple target movements of upper or lower limbs. However, this is challenging for CDRRs given the uni-lateral actuation nature of the cables. The complexity in the kinematic, static, and dynamic analysis of CDRRs increases with the increases in the number of target rehabilitation movements. Additionally, actuators in CDRRs are usually placed at the base, and joints are actuated through cables, so it is challenging to design a controller that can assist large numbers of joints.

Concerning the energy source of an actuator, electric actuators have excellent motion control capabilities, accuracy and repeatability for the CDRRs. Additionally, they are quieter than hydraulic and pneumatic actuators. However, some electric actuators have backlash and tend to overheat when holding a CDRR's joint in a locked position. The pneumatic actuators are shock, explosion, and spark proof. However, their use in CDRRs is problematic particularly when those are operating at low pressure in rehabilitation applications that requires low force and slow speed. CDRRs with hydraulic actuators can deliver large forces and has ability to handle shock loads. However, the drawbacks of hydraulic actuators are fluid leakage and requirement for regular maintenance. Compare to electric and pneumatic actuators, the use of hydraulic actuators in CDRRs has received very limited attention has so far only used in two CDRR designs.

In relation to the types of human-robot physical interaction, serial type exoskeleton CDRRs have several advantages, and one can apply traditional rigid link serial robot modelling and

**TABLE 7.** CDRR for waist rehabilitation.

Name of CDRR; Reference	DOF	Actuator	Sensor	HRPI	Control Strategy	Clinical & HMI
HWRR-Waist Rehab. Robot [111]	{2}	PAM	Position + Orientation + Tension sensors	PE	Coordinate control	—
CDPR [113]	—	PAM+EA	Wire displacement + Tensile force sensors	PE	PID + fuzzy control	Prototype
CPRWR [114]	{3}	PAM	Wire displacement + Tension + Laser + Vision sensors	PE	—	—
CDP RR [115]	{3}	EA	Force sensors	PE	—	LO Rehab

All the CDRR for the waist rehabilitation are presented in this table. Keywords: PE- Parallel exoskeleton, EA - Electric Actuator, PAM - Pneumatic Artificial Muscle, and LO Rehab - Also, provide the lower limbs rehabilitation.

TABLE 8. CDRRs for Lower limb rehabilitation.

Name of CDRR; Reference	DOF	Actuator	Sensor	HRPI	Control Strategy	Clinical & HMI
<b>Target movements of rehabilitation; Hip movements</b>						
Hip-only Soft Exosuit [157]	—	EA	Load cells + IMUs	PE	Force-based position control	Prototype
Multi-Robotic Sys. [158]	{2}	EA	Tension + Position sensor	PEE	Closed-loop speed + PID control	{6} Pelvic module
<b>Target movements of rehabilitation; knee movements</b>						
Soft Wearable Robot. [159]	{1}	Flat PAM	—	PE	—	Prototype
4-4 CDPR [103], [104]	{3}	EA	—	PLP-EE	PD control	Gait rehab Shank Att.
<b>Target movements of rehabilitation; ankle movements</b>						
Soft Parallel Robot [160]	{3}	PAMs	—	PE	—	Prototype
Soft Exosuit: ankle [108]	—	EA	Load cells + IMUs	PE	hierarchical control	CS: L2
Powered Ankle Prostheses [102]	{3}	EA	IMUs	PE	Impedance control	Prototype
AFO [161]	{1}	PAM	Encoder	SE	Iterative learning control	Prototype
Bio-inspired device [101]	Multi-DOF	PAM	Strain + IMUs + Pressure sensors	PE	LTI controller	Foot Rehab
CABLEankle [162]	{3}	EA	—	PE	—	Prototype
Ankle exoskeleton [163]	Multi-DOF	BLDC-EA	Force + IMU sensors	PE	Feedforward + PD control	Prototype
Polycentric ankle exoskeleton [164]	<2>	EA	Encoder + IMU sensors	SE	Feedforward + PID Neural Network control	Prototype
<b>Target movements of rehabilitation; hip + knee movements</b>						
LOPES [95] [96] [97]	{8}	SEA	6D force + Position sensor	SE	Impedance control	CS:L2
Soft exosuit [165]	—	EA	load cells + IMUs	PE	Adaptive control	Prototype
C-ALEX [98]	{2}	Servo EA	IMU + Load sensors	PE	Assist-as-needed control	HMI:VE
<b>Target movements of rehabilitation; hip + knee + ankle movements</b>						
Powered Lower Limb Orthosis [166]	{8}+<2>	High PAM	Position + Pressure + Torque sensors	SE	3-level-PID joint torque control	Prototype
XoR [167]	{8}+<4>	PAM	Force + EMG sensors	SE	Impedance control	Prototype
Hip, Knee and Ankle Module [168]	{1}+<2> +<1>	PAM	—	SE	Proportional myoelectric control	Prototype
Soft-exosuit [169]	{6}	PAMs	—	PE	Time based control	Prototype
Lower limb RR [100]	—	DC-EA	Encoder + Load + Stretcher	PEE	Impedance control	Prototype
CDRR [170]	—	DC-EA	—	PEE	Torque Control	Shank Att.
Underactuated Lower Limb Exoskeleton [171]	{3}+<10>	DC-EA	Force + Position sensors	SE	Admittance control	Assist 1-DOF spine
ROPES [172], [173], [174]	Multi-DOF	DC-EA	Load + Orthosis + IMU sensor	SE	Joint-space PD + Task-space force control	Gait rehab
WDS [175] [176]	{4}	EA	Load cell+switch + Encoder	PEE	Open-loop control	Shank Att.
LOKOIRAN [105]	<9>	EA	Force sensors	(P+S)E	Admittance control	HMI:VRE
String Man [106]	{6}	EA	Tension + Force + Position sensors	PE	Impedance control	CS:L1 HMI:VE
TPAD [110]	—	EA	Tension sensors	PE	Assist-as-needed control	CS:L1
CD Locomotor Sys. [109]	—	EA	3D position sensors	PE	Resistance control	CS:L2
CUBE [177], [178]	{5}	EA	—	PE	Position feedback control	UP Rehab
WeARS [179]	—	EA	Load cell	SE	Resistance control	Gait rehab
Rigid-Soft Hybrid Exoskeleton [180]	multi-DOF	EA	Torque sensor	PE	Position/force closed-loop control	Gait rehab

Keywords: { } - active DOF, < > - passive DOF, PE- Parallel Exoskeleton, PEE - Parallel End-Effector, PLP-EE - Planar Parallel End-Effector, SE - Serial Exoskeleton, AC - alternating current, DC - Direct Current, EA - Electric Actuator, SEA - Series Elastic Actuator, PAM - Pneumatic Artificial Muscle, CS-L1 - clinical study at level 1, Shank attachment - CDRR is attached to the patient shank, Foot Rehab - CDRR is also providing the foot rehabilitation, Gait rehab - CDRR is providing the gait rehabilitation, Assist 1-DOF spine - CDRR is also providing the 1-DOF spine rehabilitation, and HMI:VRE - HMI; virtual reality environments.

control strategies for this type of CDRRs but they need tuning and readjustment for each patient. The misalignment between the corresponding revolute axes of a serial exoskeleton CDRR

and anatomical axes of human extremities must be avoided. Unlike serial CDRRs, parallel ones don't have rigid linkages and therefore there are no misalignment issues. However,

traditional cable-driven parallel mechanism modelling and control strategies are not directly applicable as those methods do not model the collision between cables and segments of patients. The limited workspace is another significant challenge for designing a parallel type exoskeleton CDRR. Serial end-effector type CDRRs, have drawbacks of controllability and small workspace, which limit their use in rehabilitation applications. Parallel end-effector CDRRs, don't have the adaptability and misalignment issue between the robot and patients, as they don't have the revolute joint or rigid-link. But similar to parallel exoskeletons, they also have limited workspace.

A significant number of CDRRs use the human-machine interface to provide rehabilitation training. HMI's mainly provides the following major advantages:

- It increases the patient interest and attention in the rehabilitation exercise.
- It keeps the patient motivated during rehabilitation.
- Allows selecting the training scenarios based on the patient's interest and monitoring of the training data.
- It is not only leverage patient's interaction with CDRR but also increase the rate of recovery as well.

Although the design and development of CDRRs has received significant attention in the last two decades, less work has been undertaken to verify the performance of these robots in actual rehabilitation settings. Among these work, most of the CDRRs are at level 1 or 2 of clinical study and few in level 3. The existing trials however reported the effectiveness and patient's acceptance of CDRRs in rehabilitation training. However, there is still very limited amount of clinical study, to move CDRRs from technical laboratories to rehabilitation centers or hospitals.

#### IV. CONTROL STRATEGIES FOR CDRRs

The main control strategies developed for cable-driven rehabilitation robots are discussed in this section. The terminology is mainly based on the one proposed in [43], which is summarized in Table 9. We review the control strategies and techniques in CDRRs into five main categories including impedance-based, PID-based, admittance-based, assist-as-needed, and adaptive based controllers, and a sixth group comprising the rest of controllers. Tables 10 and 11 summarize important information for different CDRRs focusing on the controller's type, level, modelling approach, type of performance analysis, operating space, and stability. Moreover, the overall schematics of those controllers are depicted in Fig. 4. Finally, the advantages and disadvantages of control strategies are summarised at the end of this section.

The level of strategy to control individual components or the overall CDRR can be classified into low, mid, and high level, concerning joint or task spaces, inverse kinematic or dynamic, and path planning, respectively. Different control techniques can be; model-based that rely on analytical models, model-free that use machine learning techniques, empirical methods, or hybrid which is a combination of model-based and model free approaches. The performance

of the controllers is usually evaluated in literature based on the joints angle tracking error, Cartesian error for task space tracking, or position tracking error. Task space or configuration space are the main two operating space used in controlling CDRRs. Task space refers to the position and orientation of the end-effector in Cartesian space. Configuration space refers to the set of all possible configurations of CDRRs' joint. The stability of a control strategy means it's ability to produce bounded outputs with bounded inputs.

#### A. IMPEDANCE CONTROL STRATEGY

Impedance control is a kind of assistive control strategy, which makes the rehabilitation tasks easier and safer to accomplish, while supporting more repetitions. There are two main categories of impedance control strategies utilized in the CDRRs: Force-based and EMG-based impedance control. Fig. 4 (a) presents the overall block diagram of an impedance control system, in which load cells or EMG sensors are alternatively deployed in the closed loop of a force-based or EMG-based controller. Impedance parameters could be also adjusted in real time as a function of upper and lower limb posture, as discussed in [72]. There is a large number of research on the use of impedance based control strategy in CDRRs, as summarized in Table 10.

##### 1) FORCE-BASED IMPEDANCE CONTROL STRATEGY

Force-based impedance control is a dynamic control that relates the position of the patient body to the corresponding force feedback provided by the assistive robot. In this strategy, the patient is supposed to follow a particular reference trajectory. Once the patient deviates from the desired trajectory, a restoring force is applied on the patient by the assistive robot. The amount of restoring force is directly proportional to the deviation between actual and reference trajectories. Normally, deviation from a desired trajectory is allowed up to some margin before restoring force is applied. As shown in Fig. 4 (a), the error between actual and reference trajectories is first provided to a virtual impedance block before the force controller. For safety reasons, the desired interaction force is adjusted in virtual impedance, via therapist inputs, to ensure actual interaction forces between CDRR and patient remains below certain thresholds. The output of virtual impedance is then fed to the force controller block, from where the torque/force are commended to the robot.

##### a: UPPER LIMB

The effectiveness of impedance based control strategy in CDRRs is demonstrated by several works, including NEUROExos [61], Active therapeutic device (ATD) [55], X-Arm-2 [141], Sophia-3 and Sophia-4 [90], and SUEFUL-7 [72] via experimental investigation. Two different strategies are proposed in [61], one for robot-in-charge mode, which is an independent control of joint positions and one for the patient in-charge mode, that is near-zero impedance torque control. L-EXOS [87], Sophia-3, and Sophia-4 [90] deployed impedance based control strategies with the assistance of



**TABLE 9. Glossary of terms: control strategies.**

Term	Description
Impedance based controller	is based on force feedback as a function of the position measured.
Position/Orientation PID controller	is based on a control loop feedback to regulate position, velocity, force and other variables.
Admittance based control	modulates the position trajectory as a function of the force measured.
Assist-as-needed based controller	modulates the position trajectory as a function of the force measured.
Performance based adaptive controller	is based on measuring patient performance and preceding repetitions. It also adapts some aspects (e.g. force, stiffness, time, path) of assistance.

HMI. However clinical investigation of the impedance based controllers for upper limb rehabilitation is hardly available in literature. L-EXOS [87] is the only CDRR with clinical result of an impedance based controller, which is based on trials performed with a single patient.

#### *b: LOWER LIMB*

the use of impedance based control strategies in CDRRs assisting patients with the lower limb disabilities is also reported by [100], Powered Ankle Prostheses [102], String Man [106], and LOPES [95]–[97].

#### 2) EMG-BASED IMPEDANCE CONTROL STRATEGY

It is a kind of muscle status dependent control strategy. It encourages patient's effort by using the patient's EMG signals to proportionally control the assistance. EMG signals have the information regarding muscle activation, which is important for rehabilitation process and controlling CDRRs. The EMG signal are normally used in two ways in a control system: for activation of the robot, or as a feedback for adjusting the controller. [181]. Fig. 4 (a) shows the block diagram of a EMG-based impedance control strategy. It consists of four stages [182]: first, signal pre-processing, which involve data acquisition and signal enhancement, second feature extraction, third dimensional reduction by removing the non-distinguishing feature, and fourth, classification of muscle activation patterns. Then, the estimated pattern of muscle contraction is fed to the controller block.

**Upper limb:** The application of EMG-based control systems is also reported in few upper limb CDRRs such as Exoskeleton Rehabilitation Robot [78] and XoR [167].

#### **B. PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER (PID)**

PID controllers are found in several CDRRs, as they are robust to wide range of rehabilitation process conditions and consists of a very simple structure. PID control systems are well-known for regulating position, velocity, force and other process variables, via using control feedback loop. The controller response is characterized by settling time, overshoot, rise time, and steady state error.

Fig. 4 (b) depicts a block diagram of a simple PID control strategy. This control system consists of three fundamental

parameters [183]. The proportional gain determines the ratio of system response to the error between a set point and process variable. The integral gain is tuned to minimise steady state error. The derivative term tries to bring the rate of change of error to zero and reduces the overshoot. The CDRRs used PID control are summarized in Table 10.

#### *a: UPPER LIMB*

Several experimental investigation and performance analysis of PID position and velocity controllers for CDRRs are available in literature, such as ULERD [71], [75], MULOS [89], ABLE [134], 9-DoFs rehabilitation robot [79], [80], NeReBot and MariBot [91], [151], and Tendon Driven Hand orthosis [66]. PI and PD controllers are also used in CDRRs for controlling the position of patients hands, CAF [125] and MAHI Open Wrist exoskeleton [140]. Clinical verification of PID position controllers is reported for NeReBot [91], [151], and Tendon Driven Hand Orthosis [66]. Clinical trials reported significant improvement and patients have shown favourable impressions about the treatment, without any side effects. However, the sole use of position control is not enough to ensure safe dynamic interaction between human and robot [184] as it does not take into account the required force.

#### *b: LOWER LIMB AND WAIST*

The PID control strategy is applied in few lower limb rehabilitation works such as Multi-Robotic System [158] and Powered Lower Limb Orthosis [166]. It is also used in waist rehabilitation by [113], in which a fuzzy PID control is developed and examined.

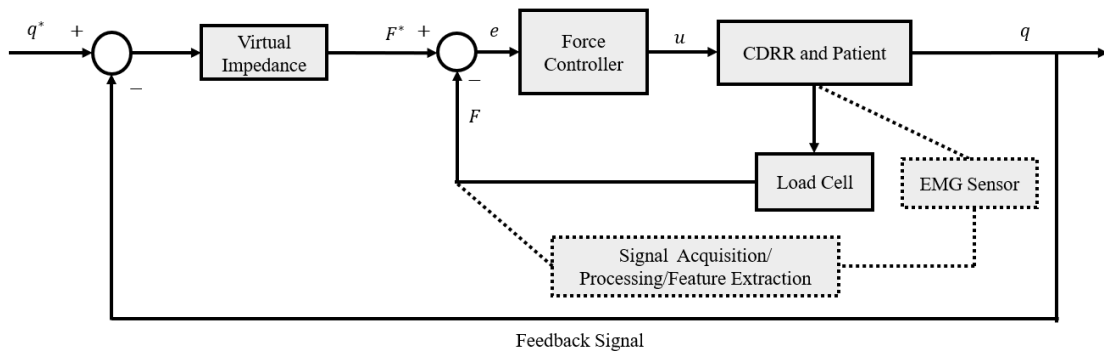
#### **C. ADMITTANCE BASED CONTROL**

It relies on the measurements of interaction force to ensure the compliance of robots during rehabilitation. Admittance control strategy is the opposite of impedance control method. While admittance-based strategy controls motion by measuring the force, the impedance-based strategy controls force by measuring the motion and deviation from a referenced trajectory [185]. Fig. 4 (c) depicts the overall block diagram of admittance based control system. It is assumed that patient is subject or subjected to interaction or external forces. The virtual admittance block updates patient's desired trajectory based on the interaction force between CDRR and patient, measured by load cell. The CDRRs used admittance based control are summarized in Table 11.

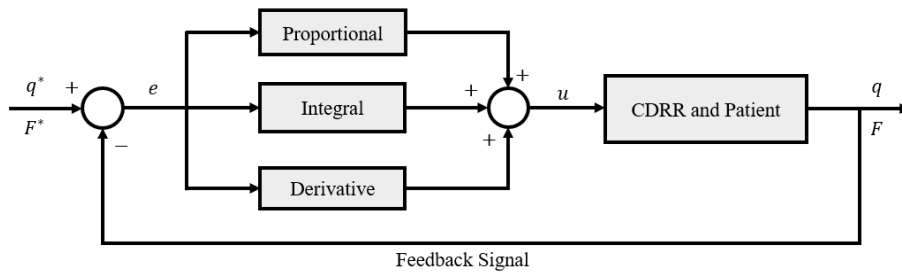
**Upper and Lower Limbs:** Admittance-based controllers are found in few CDRRs and their performance was verified through experimental investigation and simulation, both for upper limb rehabilitation, such as Planar Cable-driven Parallel Robot [51], [52] and PACER robot [53], [54] and lower limb rehabilitation, such as Underactuated Lower Limb Exoskeleton [171] and LOKOIRAN [105].

#### **D. ADAPTIVE CONTROL STRATEGY**

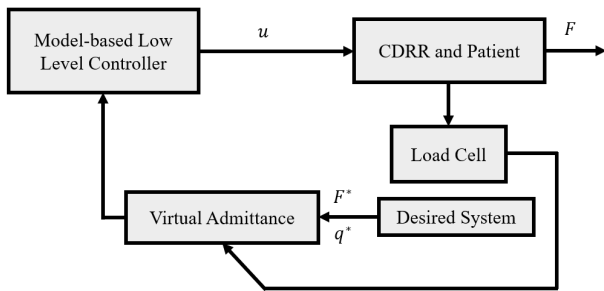
Adaptive control strategies offer better performance in the presence of exogenous disturbances, imperfect modeling,



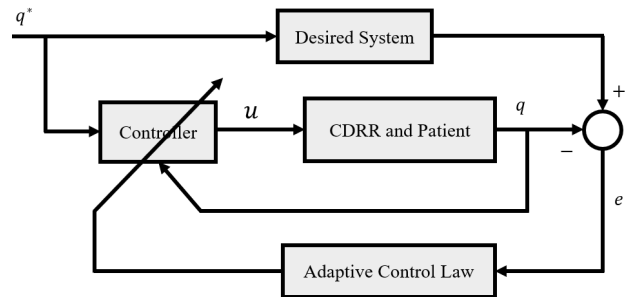
(a) Force/EMG based Impedance control strategy



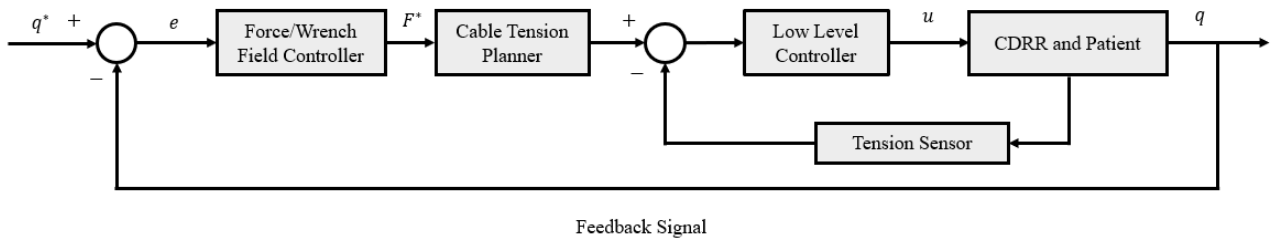
(b) Simple PID control strategy



(c) Admittance control strategy



(d) Adaptive control strategy



(e) Assist-as-needed control strategy

**FIGURE 4.** Control strategies of cable driven rehabilitation robot:  $q^*$  means the referenced trajectory,  $q$  means the actual motion trajectory,  $F^*$  means the referenced force trajectory,  $F$  means the actual force trajectory, Error  $e$  is the deviation of the actual trajectory from the reference trajectory.

adverse system conditions, structural damage, changes in system dynamics, and cable or/and actuator failure [186]. Although other control strategies with fixed gains could also deal with adverse system conditions, but accurate

modeling of the system and knowledge of uncertainty bounds are required. Adaptive control strategy has the capabilities for automatic tuning of controllers, and maintaining the system performance when the system parameters vary in

TABLE 10. Controller details.

CDRR's Name; Reference	Control's level	Modeling approach	Performance	Operating space	Stability
<b>Impedance control strategy</b>					
Wearable Soft Orthotic Device [58]	Low-level	Model-free	Angular and linear misalignments error	Configuration space	N/A
NEUROExos [61]	High-level	Model-based	Steady-state angular error, gravity compensation	Configuration space	Asymptotic
ATD [55]	High-level	Model-based	Force tracking error, gravity compensation	Task space	Asymptotic
SNU Exo-Glove [124]	Low-level	Model-based	Cartesian error for task space tracking	Configuration space	N/A
L-EXOS [87]	High-level	Model-based	Cartesian error for task space tracking, gravity compensation	Task space	N/A
X-Arm-2 [141]	Mid-level	Model-based	Friction compensation	Configuration space	Asymptotic
CADEN 7 [143]	High-level	Model-based	Joints trajectory tracking error	Configuration space	N/A
SUEFUL-7 [72]	Low-level	Hybrid	Joints trajectory tracking error	Configuration space	N/A
Soft-Actuated Exoskeleton [146]	Low-level	Model based	Joints trajectory tracking error	Task space	N/A
Upper-Limb Powered [147]	High-level	Model based	Joints trajectory tracking error	Configuration space	N/A
Sophia-3 and Sophia-4 [90]	High+Low-level	Hybrid	Cartesian error for task space tracking	Task space	N/A
Powered Ankle Prostheses [102]	High-level	Model based	Cartesian error for task space tracking	Task space	N/A
LOPES [95] [96] [97]	High-level	Model based	Joint angle trajectory tracking error, cartesian impedance error, external disturbance rejection, gravity compensation	Task space	N/A
XoR [167]	Low-level	Model based	Force tracking error, external disturbance rejection, gravity compensation	N/A	N/A
Lower limb Rehab. Robot [100]	High-level	Model based	Cartesian error for task space tracking	Task space	N/A
<b>Proportional integral derivative based control strategy</b>					
Elbow Exoskeleton [85]	Mid-level	Model-based	Joint angle tracking error	Task space	Asymptotic
Wearable Rehab. Robo. Hand [84]	High-level	Model-free	Joint angle tracking error	Task space	N/A
Tendon Driven Hand orthosis [66]	Low-level	Model-free	Joint angles tracking of the index finger	Configuration space	N/A
ABLE [134]	Low-level	Model-free	Cartesian error for task space tracking, gravity compensation	Task space	N/A
9-DoFs Rehab. Robot [79], [80]	Mid-level	Model-based	Position, force tracking error, friction, gravity compensation,	Configuration space	N/A
Upper Limb Rehab. Robot [138]	High+low-level	Model-based	Trajectory tracking error, friction, gravity compensation,	Task space	Stability-Lyapunov
ULERD [71], [75]	Low-level	Model-free	Joint angle traj. tracking error	Task space	Asymptotic
MULOS [89]	Low-level	Model-free	Quantitative measurements of error	N/A	N/A
Mirror-Image Motion Dev. [156]	Low-level	Model-free	Quantitative measurements of error	Configuration space	N/A
CDPR [113]	High+low-level	Model-based	Cartesian error for task space tracking, external disturbance rejection	Configuration and task space	Stability-Lyapunov
CDRR [158]	Low-level	Model-free	Position tracking error	N/A	N/A
Polycentric ankle exoskeleton [164]	Low-level	Model free	Joint angle tracking error	Configuration space	N/A
Powered Lower Limb Orthosis [166]	Low-level	Model-free		N/A	Asymptotic

Controller details of CDRRs

TABLE 11. Controller details.

CDRR's Name; Reference	Control's level	Modeling approach	Performance	Operating space	Stability
<b>Admittance based control strategy</b>					
Planar Cable-Driven Robot [51], [52]	Low-level	Hybrid	Trajectory tracking error in task space	Task space	N/A
PACER [53], [54]	High-level	Model based	Position and orientation error for task space tracking	Task space	N/A
Underactuated Lower Limb Exoskeleton [171]	High+low-level	Model based	Power augmentation error in load-carrying	Configuration space	N/A
LOKOIRAN [105]	Low-level	Model free	Friction and Gravity Compensation	Configuration space	N/A
<b>Adaptive control strategy</b>					
CARR-4 [135]	High +low -level	Model-free control	Position tracking errors	Configuration space	N/A
Robotic exoskeleton [144]	Mid -level	Model-free control	Cartesian error for task space tracking	Configuration and task space	Stability-Lyapunov
Sophia-3 and Sophia-4 [90]	High +low -level	Model-free control	Cartesian error for task space tracking	Task space	N/A
Soft Exosuit [157]	Low -level	Model-free control	RMS error for the peak force	Task space	N/A
<b>Assist-as-needed based control strategy</b>					
CDWRR [64]	Mid-level	Model-based	Joint angle tracking results	Configuration space	N/A
CAREX [8]	High+low-level	Model-based	Cartesian error for task space tracking, friction and gravity compensation	Task space	N/A
CAREX-7 [9], [74]	High+low-level	Model-based	Cartesian error for task space tracking, friction and gravity compensation	Configuration and task space	Stability-Lyapunov
CDULRR [155]	Mid-level	Model-based	Cartesian error for task space tracking, gravity compensation, external disturbances rejection	Configuration and task space	N/A
C-ALEX [98]	High+low-level	Model-based	Cartesian error for tracking, friction & gravity compensate	Task space	N/A
TPAD [110]	High+low-level	Model-based	Cartesian error for task space tracking, friction compensation	Configuration and task space	N/A

unforeseen conditions, without excessively relying on system modeling.

Fig. 4 (d) presents the overall architecture of an adaptive controller with four main parts. It is assumed that the system model is known but it consists of uncertain parameters. The desired system block provides a reference behavior. The CDRR and patient block represents the actual dynamical system. The difference between desired and actual trajectories is then fed to the controller, in which the control law is parameterized with a number of adjustable parameters. The role of adaptive control law block is to update the controller parameters based on the performance error signal. The CDRRs used adaptive controller are summarized in Table 11.

**Upper and lower limb:** To compensate the model uncertainties and external disturbance of upper limb CDRRs, an ILC adaptive control is used in CARR-4 [135], and an adaptive fuzzy sliding mode control is employed in Robotic Exoskeleton by [144]. The use of adaptive controllers is also studied in CDRRs for lower limb such as Soft Exosuit; hip and ankle [165], Sophia-3 and Sophia-4 [90].

#### E. ASSIST-AS-NEEDED (AAN) BASED CONTROL STRATEGY

An Assist-as-needed control reacts to trajectory error of robot end-effector and provides the patient with minimal amount of assistance necessary to complete a movement, while encouraging patient to make significant effort. This type of control strategy is used in many CDRRs, [8], [9], [64], [74], [155]. Fig. 4 (e) shows the overall block diagram of an Assist-as-needed control system.

Force field and wrench field are two types of AAN control strategy used in CDRRs. In the former strategy, a force field is generated around the referenced trajectory, which is then deployed to plan the cables tension. The low-level controller takes the tension commands and maintain the cables in tension. In the latter strategy, a six-DoFs wrench field is constructed based on the deviation from the desired pose to generate dexterous manipulation, including the three rotation and three translation. Compare to the force field Assist-as-needed controller, wrench field type provides the both force and torque commands to train and assist the patient. The CDRRs used AAN are summarized in Table 11.



### c: UPPER AND LOWER LIMB

The performance of a force field Assist-as-needed control when patient pulls the end-effector of an anthropomorphic arm is studied in [8]. Similar control strategy is used to perform real-time estimation of glenohumeral joints rotation [187]. A six-DoFs wrench field AAN controller is deployed in CAREX-7 [9], [74]. The research on AAN control is reported in several other upper limb applications, such as C-ALEX [98], CDULRR [155], and CDWRR [64], and lower limb rehabilitation by TPAD [110].

### F. OTHER CONTROL METHODS

There are some other control strategies that yet have received less attention in designing and developing CDRRs.

**Sliding mode control strategy** is used as a robust control strategy for nonlinear systems, in which the tracking error approaches to zero asymptotically in the presence of nonlinear disturbances, [149], [150]. For instance, it is deployed for controlling damper like joints of BJS [63]. The effectiveness of the controller is validated through clinical trial.

**Iterative learning control strategy** can be referred as a trajectory tracking control strategy, which works in a repetitive mode. The robustness of iterative learning control against external disturbance and uncertainties in CDRRs is studied in [135]. The performance of this controller is evaluated through simulation and improvement in tracking performance was observed. Another CDRR is developed with this control strategy via using error information of the two adjacent iteration in Hand exoskeleton robot [128] and its performance was validated through the tracking results.

**Resistance compensation control strategy** was proposed to avoid undesired resistance in CDRRs [127]. This control strategy greatly solve the friction issue in CDRRs through resistance or friction compensation.

**Hierarchical cascade control strategy** consists of three levels of high, mid and low level controllers is to perform assistance level estimation, adaptive gap compensation, and adaptive position control with friction compensation, respectively. A soft exoskeleton robot for upper limb rehabilitation is reported in literature with this type of controller [117].

**Intelligent stretching control** is suitable for specific tasks, such as passive range of motion test during diagnosis and the passive stretching treatment. In an experiment, the patients were asked to relax, while Intelliarm [86] stretch the patient's joints with a specific commanded velocity.

**Patient-cooperative and Intention-driven control strategy**, are two other types of controller to support and encourage patients participate actively in the rehabilitation, which have been employed in HIT-Glove [88] and Upper Limb Exoskeleton [133], respectively.

### G. DISCUSSIONS ON CONTROL STRATEGIES

The control strategies for CDRRs should consider the system coupling (robot-human interaction) in the control loop. A sole force or position controller could not ensure safe dynamic

interaction between robot and human [188]. The pros and cons of mostly used control strategies in CDRRs are discussed here and also summarized in Table 12.

The impedance control strategy is largely used in CDRRs, as it provides stable interaction between human and robot. The impedance value or desired interaction force is selected by the therapists based on their experience and considering the level of patients' disability. The challenge is to ensure an intrinsically stiff actuation, which can be achieved by compensating the natural impedance of system, and other effects due to the friction and gravity [189]. Impedance control allows the actuation in three modes, robot in charge, patient in charge, and therapist in charge. In the robot in charge mode, the value of impedance is chosen to be high, and robot guides the patient to follow the desired trajectory. In the patient in charge mode, the value of impedance is set to be low, and the robot does not hinder the motion by the patient. In the therapist in charge mode, the value of impedance is chosen manually to provide a corrective or supportive torques for patient training [96].

The impedance control strategy allows the real-time adjustment of impedance parameters such as damping, inertia, and stiffness, without leading to any significant stability problems [190]. Impedance control can be considered as a suitable candidate for interaction control strategy as it does not rely on the precise knowledge of external parameters [191]. Unlike other control strategies, where the force and position are controlled separately, impedance controller controls the dynamic relationship between the force and velocity, also known as impedance of the CDRR's end-effector [192], [193]. The impedance control does not have significant difference with position control except it offers less interaction torque and large spatial variety [190]. Its accuracy can be further improved by using low-friction joints, inner loop torque sensors or direct drives. This control strategy also circumvents the need of using force sensors, which are generally expensive and sensitive to temperature changes.

EMG-based impedance controller is a control strategy, which uses the patient's electromyography biological signals to control the robot. It is suitable where muscle strength needs to be monitored and improved. A potential drawback of EMG based controller, is the lack of patient in charge mode or the voluntary movements of patient, as the change in muscles strength trigger the controller [189]. Another problem is the difficulty in precise generation of the force base on the varying EMG signals in real time. This problem can be addressed in future research by using a combination of multiple biological signals such as electroencephalogram, electromyogram, and electrooculogram.

Admittance based control relies on measuring the force exerted by the patient to generate the corresponding displacement of the assistive robot. This control strategy provides higher accuracy for contact-free tasks, but dynamic interactions between human and robot can lead to unstable performance [22]. While both impedance and admittance controllers could be used for interaction with soft

**TABLE 12.** Advantages and disadvantages of mostly used control strategies in CDRRs.

Control strategies	Advantages	Disadvantages
Impedance based control strategy	<ul style="list-style-type: none"> <li>● stable interaction between human and robot.</li> <li>● allows adjustment of impedance value based on the therapist's experience and patient's disability.</li> <li>● control ability in three modes, robot in charge, patient in charge, and therapist in charge.</li> <li>● real-time adjustment of impedance parameters such as damping, inertia, and stiffness.</li> <li>● does not rely on the precise knowledge of external parameters.</li> <li>● monitor and improve the muscle strength by using EMG-based impedance control.</li> </ul>	<ul style="list-style-type: none"> <li>● performance declines with the decrease in the environment's stiffness.</li> <li>● requires the force sensors, which are generally expensive and sensitive to temperature changes.</li> <li>● does not allow the voluntary movements of patient, as the change in muscles strength trigger the controller (EMG-base impedance control).</li> <li>● faces difficulty in precisely generation the force base on the varying EMG signals in real time (EMG -base impedance control).</li> <li>● faces difficulty in ensuring the intrinsically stiff actuation system.</li> </ul>
Proportional integral derivative based control strategy	<ul style="list-style-type: none"> <li>● easy to apply for CDRRs.</li> <li>● robust performance with simple structure.</li> <li>● robust to tuning mismatches.</li> <li>● asymptotic convergence of errors in task space.</li> <li>● independent control of the joints in joint space.</li> </ul>	<ul style="list-style-type: none"> <li>● a sole force or position PID controller could not ensure safe dynamic interaction between robots and human.</li> <li>● produces large overshoots which are not desirable for CDRRs.</li> </ul>
Admittance based control strategy	<ul style="list-style-type: none"> <li>● provides higher accuracy for contact-free tasks.</li> <li>● works well when accurate information of interaction force between patient and robot is available.</li> </ul>	<ul style="list-style-type: none"> <li>● dynamic interactions between human and robot can lead to unstable performance.</li> <li>● performance declines with the increase in the environment's stiffness.</li> </ul>
Adaptive control strategy	<ul style="list-style-type: none"> <li>● robust to uncertain dynamic systems.</li> <li>● ability to improve its performance under adverse and unforeseen conditions.</li> <li>● suitable if system stability problem is detected.</li> <li>● compensates the friction and hysteresis backlash.</li> </ul>	<ul style="list-style-type: none"> <li>● it is rarely optimal as it does not rely on the accurate modelling of the rehabilitation robot.</li> </ul>
Assist-as-needed control strategy	<ul style="list-style-type: none"> <li>● parameters are adjusted based on the level of assistance required by the patient or rehabilitation exercise.</li> <li>● evaluated for CDRRs using both lab experiments and clinical investigation.</li> </ul>	<ul style="list-style-type: none"> <li>● inconsistent and inaccurate estimation of patient's functional movement can be a major limitation in use of this approach</li> <li>● generating accurate level of robotic assistance in real-time based on estimation of the patients' functional ability is challenging</li> </ul>

environments, their performance are opposite. The performance of admittance control declines with the increase in the environment's stiffness. In contrast, the performance of impedance control decline with the decrease in the environment's stiffness [194]. Additionally, the performance of impedance controller depends on the precision of the position sensors, whereas the performance of admittance controller depends on the accuracy of the force/torque sensors. Admittance control may be preferred, where the accurate information of interaction force between patient and robot is required [27]. A combined use of impedance and admittance control in CDRRs could benefit from the advantages of both methods.

Adaptive control is preferred when dealing with uncertain dynamic systems in CDRRs. This type of control does not rely on the modelling accuracy, and has the ability to improve its performance under adverse and unforeseen conditions.

It can deal with uncertainty in both kinematic and dynamics of system being controlled. Adaptive control strategy is very effective to assist the patient in recovering the balance, especially when the stability problem is detected, and It can also compensate the friction and hysteresis backlash [195]. Adaptive control shows a better tracking performance compare to the simple PD controller, with same feedback gain. Instead of using high controller gains, adaptive control learns from the system dynamics, patient's effort and ability [196]. However, it is rarely optimal as it does not consider or rely on the accurate modelling of the rehabilitation robot [197].

The Assist-As-Needed is one of the most important control strategies. AAN parameters are adjusted according to the required level of assistance, which not only varies from patient to patient but also depends on different rehabilitation exercises [198]. The Assist-As-Needed control systems are evaluated for CDRRs using both lab experiments and clinical

investigation. A potential drawback of assist-as-needed based controller is the reliance on the accurate knowledge of patient's functional ability. An inconsistent or inaccurate estimation of patient's functional movement can lead to failure of this approach [199]. Therefore, a challenge is how to appropriately estimate the patient's functional ability to precisely generate required level of robotic assistance with this type of controller [200]. Less work is done in literature on precise estimation of patient's functional ability [201]. These issues can be further analysed through clinical trials and considered as a direction of future work.

Direct comparative experiments on different control strategies of CDRRs are very limited in literature. Stein *et al.* [202] is one of the very few works with comparative experimental study between the Impedance and Resistance-based control strategies and reported no significant difference in performance. In another research, Lance *et al.* [203] claimed comparing two assist-as-needed control strategies, one with interlimb coordination constraints that showed more pronounced and fast recovery. Based on our knowledge, there is no other direct comparison of control strategies in CDRRs. The control strategies are mostly evaluated in different experimental environments, with different cable driven rehabilitation robots, and for different target movements for rehabilitation. The main pros and cons of control strategies based on the available literature are summarized in Table 12.

## V. DISCUSSION AND FUTURE CHALLENGES

There is a growing interest in research and development of CDRRs for rehabilitation. Around 200 references and research articles on CDRRs are found and reviewed in this work for lower limb, upper limb and waist rehabilitation.

Concerning different training applications, rehabilitation robots should meet different requirements such as: a) repeated facilitation training, b) uniform performance in a long period of time, c) safe interaction with patients, d) back-drivability for patient-in-charge mode, e) quantitative measures for performance analysis, and f) adaptability and reconfigurability for different patients.

A cable-driven actuation can help meeting the above requirements. In CDRRs, actuators are placed at the base and joints of CDRR are actuated through cables, which make the CDRR very light weight. So, they can perform repeated training with less energy. Their light weight also provides the space for more sensors to quantitatively measure the performance of CDRRs. As the actuators are not attached to the joints, they also have less inertia, which not only increase the safety but also help in obtaining a uniform performance with CDRRs. Additionally, the cable driven actuators are back drivable and by changing cable length they provide size adaptability for different patients.

There are several key technologies reported in literature that successfully used cable driven actuation for rehabilitation applications, such as CAREX-7 [9], [74], Tendon Driven Hand orthosis [66], Soft Exosuit: ankle [108], C-ALEX

[98], CAREX [8], NeReBot [91], [151], [152], LOPES [95]–[97], and String Man [106]. These CDRRs offer low inertia, light weight, high payload-to-weight ratio, large work space, and adaptability. CAREX-7 [9], [74] is a 7-DOF CDRR that is designed for the movement training of the upper limb. The mechanical structure of CAREX-7 is light weight and have less moving inertia, as it consists of four light weight cuffs and eight cables. Tendon Driven Hand orthosis [66] is a low weight design and it also ensure safety because it does not require custom joint alignment and has low inertia. Soft Exosuit: ankle [108] is a gait rehabilitation robot and it was proposed to assist ankle plantarflexion and dorsiflexion. This allows the actuators to be placed far away from moving joints, which lead to large workspace. C-ALEX [98] is a lower limb CDRR with high payload-to-weight ratio. It consists of few cuffs and cables and designed for gait rehabilitation. These works not only prove the effectiveness through experimental investigations but also demonstrated the satisfactory performance in the clinical study.

Existing cable driven rehabilitation robots have demonstrated various capabilities to assist and train patients and have shown effectiveness in rehabilitation. Although CDRRs have a lot of promising features, there are also some limitations and deficiencies that are summarized as follows:

- The CDRRs can exert only tensile forces, as the cables of CDRRs can only be used to pull (and not to push).
- The cables of CDRRs must be in tension at all the time, making it more difficult to optimise the effective workspace of the rehabilitation robot.
- The elasticity or flexibility of cables of CDRRs causes undesirable vibrations, which may contribute to having position and orientation errors.
- The CDRRs have high maintenance requirements mainly due to the cable breakage, slackening, and friction of the system.

These limitations increase the complexity of kinematic and dynamic modelling and decrease the stiffness of CDRRs. It is also challenging to design and deploy robust controllers for CDRRs that can deal with flexibility, friction, and vibrations of the cables. A few key research and solutions focusing on these problems include; friction compensation [204], self healing concept [205], layer jamming [206], and singular perturbation approach based modeling [18]. A novel friction-tension mechanic model was proposed by Youngsu *et al.* [204] to compensate the friction between the pulleys and cables. In which two possible types of cable-pulley transmission are considered, i.e, free-free and fixed-free ended. To solve the stiffness issue with cables, a variable stiffness cable with self-healing capability was introduced by Alice *et al.* [205] that changes its stiffness relative to the variation in temperature. Another research work on cable stiffness was presented by the Yong *et al.* [206] by using layer jamming concept, in which cable's property changes from flexible to highly stiff depending on if vacuum is applied or not. To deal with the flexibility issue of cables, a dynamic modeling and control strategy based on singular

perturbation approach was introduced by [18]. However, these concepts still need to be implemented and verified with CDRRs and remains as continuing research area.

The evidence from this review suggests that future work and scientific research on CDRRs could consider the following aspects and areas;

- The existing CDRRs for rehabilitation of multiple human joints consists of many passive and active cables, which make the structure of CDRRs complex, heavy and bulky. Future CDRRs should be more compact, lightweight and portable for rehabilitation of elderly people at home and assisting patients with limited access to rehabilitation centres. More research is needed to address challenges of designing CDRRs for simultaneous rehabilitation of multiple human joints.
- The cost of developing and verifying CDRRs, and need for expensive sensors such as force/torque, tension, and EEG sensors, and costly clinical trials are major hindrance in extending the application of CDRRs. Addressing these problems may dramatically impact on the use of CDRRs.
- The few shortcomings in the performance of CDRRs that need more attention in future research. For instance, compare to serial type CDRRs, the parallel type ones normally have better adaptability, but they have to deal with problems such as uncertainty, controllability and limited workspace.
- The control strategy plays a vital role in effective performance of CDRRs, where there is still room for improvement. Five main categories of control strategies in CDRRs are reviewed in this work, but only two of them have gone through clinical investigation. Moreover, the use of bio-signals in control strategies has attracted less attention. The future research could focus on clinical verification of control strategies, integration of more bio-signals such as EEG and EOG in the control systems, and human-CDRR interactive control based on reinforcement learning. Additionally, more research is needed on optimizing control strategies for rehabilitation in terms of performance and rate of recovery.
- The human-machine interface allows effective incorporation of CDRRs and motivate the patients toward rehabilitation. More work is needed for developing dexterous manipulation of CDRRs with HMI, and studying physical and clinical implications of long-term use of HMIs in rehabilitation exercise. Recently, the entertainment gaming industry have developed several new interesting VR-based interfaces to capture the motion of the user. In future, these interfaces can be integrated in CDRRs to facilitate the rehabilitation training.
- Finally, the clinical verification of the CDRRs has received very limited attention. Less than 5% of CDRRs in this review have gone through clinical investigations. These clinical studies are at initial level and there is no set of widely accepted clinical criteria for CDRRs. The updated or advanced versions of CDRRs are not

proposed to overcome the shortcoming based on the clinical study. The future research should focus on large-scale clinical investigation of CDRRs. Furthermore, clinical investigations need to provide the clear performance comparison over the manually assisted training.

## VI. CONCLUSION

Rehabilitation robots including cable-driven types, have gained a lot of attention to cope with high demands of physio therapy and reduce reliance on professional therapists. Around 200 references and research articles on CDRRs are reviewed in this work with the aim of understanding the successes and shortfalls of existing developments and future needs. To facilitate the discussion, CDRRs are categorized into three major categories for upper limb, lower limb, and waist rehabilitation. For each group of robots, target movements of rehabilitation are identified and existing CDRRs are reviewed in terms of type of actuators, sensors, controllers, physical interactions with patients, and human-machine interface.

Existing CDRRs offer significant advantages in terms of low inertia, light weight, high payload-to-weight ratio, large work space and configurability. They enable treatments with high intensity, re-peatability and real time measurement of patient performance. They can be used independently or collaboratively to support therapist in the rehabilitation process. Various control strategies are successfully developed for CDRRs, which are mainly categorized under Impedance-based, PID-based, Admittance-based, Assist-as-needed (AAN) and Adaptive controllers. The clinical studies on CDRRs performance in rehabilitation settings are also promising, though there is room for improvement.

Future works can focus on designing more compact and portable CDRRs, as well as addressing the challenges of developing CDRRs for simultaneous rehabilitation of multiple human joints. Bio-signals are invaluable source of data for the purpose of controlling CDRRs. Further enhancement in the performance and speed of control strategies is needed to deal with uncertainties of physical interaction between human and CDRRs. More attention in research is also required on clinical study and verification of CDRRs in clinical settings.

## REFERENCES

- [1] *Disability and Health*. Accessed: Sep. 9, 2019. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/disability-and-health>
- [2] *World Report on Disability*. Accessed: Sep. 9, 2019. [Online]. Available: [https://www.who.int/disabilities/world\\_report/2011/report.pdf](https://www.who.int/disabilities/world_report/2011/report.pdf)
- [3] S. Barreca, S. L. Wolf, S. Fasoli, and R. Bohannon, "Treatment interventions for the paretic upper limb of stroke survivors: A critical review," *Neurorehabil. Neural Repair*, vol. 17, no. 4, pp. 220–226, Dec. 2003.
- [4] B. H. Dobkin, "Strategies for stroke rehabilitation," *Lancet Neurol.*, vol. 3, no. 9, pp. 528–536, Sep. 2004.
- [5] S. H. Lee, G. Park, D. Y. Cho, H. Y. Kim, J.-Y. Lee, S. Kim, S.-B. Park, and J.-H. Shin, "Comparisons between end-effector and exoskeleton rehabilitation robots regarding upper extremity function among chronic stroke patients with moderate-to-severe upper limb impairment," *Sci. Rep.*, vol. 10, no. 1, pp. 1–8, Dec. 2020.



- [6] L. Dovat, O. Lamercy, R. Gassert, T. Maeder, T. Milner, T. C. Leong, and E. Burdet, "HandCARE: A cable-actuated rehabilitation system to train hand function after stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 6, pp. 582–591, Dec. 2008.
- [7] M. Shoaib, C. Y. Lai, and A. Bab-Hadiashar, "A novel design of cable-driven neck rehabilitation robot (CarNeck)," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2019, pp. 819–825.
- [8] Y. Mao and S. K. Agrawal, "Design of a cable-driven arm exoskeleton (CAREX) for NEURAL rehabilitation," *IEEE Trans. Robot.*, vol. 28, no. 4, pp. 922–931, Aug. 2012.
- [9] X. Cui, W. Chen, X. Jin, and S. K. Agrawal, "Design of a 7-DOF cable-driven arm exoskeleton (CAREX-7) and a controller for dexterous motion training or assistance," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 161–172, Feb. 2017.
- [10] A. M. Dollar and H. Herr, "Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art," *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 144–158, Feb. 2008.
- [11] S. J. Ball, I. E. Brown, and S. H. Scott, "A planar 3DOF robotic exoskeleton for rehabilitation and assessment," in *Proc. 29th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2007, pp. 4024–4027.
- [12] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, "Developments in hardware systems of active upper-limb exoskeleton robots: A review," *Robot. Auton. Syst.*, vol. 75, pp. 203–220, Jan. 2016.
- [13] H. Krebs and B. Volpe, "Rehabilitation robotics," *Handbook Clin. Neurol.*, vol. 110, pp. 283–294, Jan. 2013.
- [14] R. Colombo and V. Sanguineti, *Rehabilitation Robotics: Technology and Application*. London, U.K.: Academic, Mar. 2018, p. 382.
- [15] Z. Z. Bien and D. Stefanov, *Advances in Rehabilitation Robotics: Human-friendly Technologies on Movement Assistance and Restoration for People With Disabilities*, vol. 306. Berlin, Germany: Springer-Verlag, 2004.
- [16] E. Rocon and J. L. Pons, *Exoskeletons in Rehabilitation Robotics: Tremor Suppression*, vol. 69. Berlin, Germany: Springer-Verlag, 2011.
- [17] T. Bruckmann and A. Pott, *Cable-Driven Parallel Robots*, vol. 12. Berlin, Germany: Springer-Verlag, 2012.
- [18] M. A. Khosravi and H. D. Taghirad, "Dynamic modeling and control of parallel robots with elastic cables: Singular perturbation approach," *IEEE Trans. Robot.*, vol. 30, no. 3, pp. 694–704, Jun. 2014.
- [19] S. Kawamura, H. Kino, and C. Won, "High-speed manipulation by using parallel wire-driven robots," *Robotica*, vol. 18, no. 1, pp. 13–21, 2000.
- [20] M. Shoaib, J. Cheong, D. Park, and C. Park, "Composite controller for antagonistic tendon driven joints with elastic tendons and its experimental verification," *IEEE Access*, vol. 6, pp. 5215–5226, 2018.
- [21] M. Babaiasl, S. H. Mahdioun, P. Jaryani, and M. Yazdani, "A review of technological and clinical aspects of robot-aided rehabilitation of upper-extremity after stroke," *Disab. Rehabil., Assistive Technol.*, vol. 11, no. 4, pp. 263–280, 2016.
- [22] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *J. NeuroEng. Rehabil.*, vol. 11, no. 1, p. 3, 2014.
- [23] A. S. Niyetkaliyev, S. Hussain, M. H. Ghayesh, and G. Alici, "Review on design and control aspects of robotic shoulder rehabilitation orthoses," *IEEE Trans. Human-Mach. Syst.*, vol. 47, no. 6, pp. 1134–1145, Dec. 2017.
- [24] H. S. Lo and S. Q. Xie, "Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects," *Med. Eng. Phys.*, vol. 34, no. 3, pp. 261–268, Apr. 2012.
- [25] A. Basteris, S. M. Nijenhuis, A. H. Stienen, J. H. Buurke, G. B. Prange, and F. Amirabdollahian, "Training modalities in robot-mediated upper limb rehabilitation in stroke: A framework for classification based on a systematic review," *J. Neuroeng. Rehabil.*, vol. 11, p. 111, Jul. 2014.
- [26] R. C. V. Loureiro, W. S. Harwin, K. Nagai, and M. Johnson, "Advances in upper limb stroke rehabilitation: A technology push," *Med. Biol. Eng. Comput.*, vol. 49, no. 10, p. 1103, Oct. 2011.
- [27] T. Proietti, V. Crocher, A. Roby-Brami, and N. Jarrassé, "Upper-limb robotic exoskeletons for neurorehabilitation: A review on control strategies," *IEEE Rev. Biomed. Eng.*, vol. 9, pp. 4–14, 2016.
- [28] S. Masiero, M. Armani, and G. Rosati, "Upper-limb robot-assisted therapy in rehabilitation of acute stroke patients: Focused review and results of new randomized controlled trial," *J. Rehabil. Res. Dev.*, vol. 48, no. 4, pp. 355–366, 2011.
- [29] N. Norouzi-Gheidari, P. S. Archambault, and J. Fung, "Effects of robot-assisted therapy on stroke rehabilitation in upper limbs: Systematic review and meta-analysis of the literature," *J. Rehabil. Res. Develop.*, vol. 49, no. 4, p. 479, 2012.
- [30] R. Morales, F. J. Badesa, N. García-Aracil, J. M. Sabater, and C. Pérez-Vidal, "Pneumatic robotic systems for upper limb rehabilitation," *Med. Biol. Eng. Comput.*, vol. 49, no. 10, p. 1145, 2011.
- [31] N. Jarrassé, T. Proietti, V. Crocher, J. Robertson, A. Sahbani, G. Morel, and A. Roby-Brami, "Robotic exoskeletons: A perspective for the rehabilitation of arm coordination in stroke patients," *Frontiers Hum. Neurosci.*, vol. 8, p. 947, Dec. 2014.
- [32] P. K. Jamwal, S. Hussain, and S. Q. Xie, "Review on design and control aspects of ankle rehabilitation robots," *Disab. Rehabil., Assistive Technol.*, vol. 10, no. 2, pp. 93–101, Mar. 2015.
- [33] G. Chen, C. K. Chan, Z. Guo, and H. Yu, "A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy," *Crit. Rev. Biomed. Eng.*, vol. 41, nos. 4–5, pp. 343–363, 2013.
- [34] T. Yan, M. Cempini, C. M. Oddo, and N. Vitiello, "Review of assistive strategies in powered lower-limb orthoses and exoskeletons," *Robot. Auto. Syst.*, vol. 64, pp. 120–136, Feb. 2015.
- [35] A. Pennycott, D. Wyss, H. Vallery, V. Klamroth-Marganska, and R. Riener, "Towards more effective robotic gait training for stroke rehabilitation: A review," *J. Neuroeng. Rehabil.*, vol. 9, no. 1, pp. 1–13, 2012.
- [36] J.-M. Belda-Lois, S. Mena-del Horno, I. Bermejo-Bosch, J. C. Moreno, J. L. Pons, D. Farina, M. Iosa, M. Molinari, F. Tamburella, A. Ramos, and A. Caria, "Rehabilitation of gait after stroke: A review towards a top-down approach," *J. Neuroeng. Rehabil.*, vol. 8, p. 66, Dec. 2011.
- [37] I. Díaz, J. J. Gil, and E. Sánchez, "Lower-limb robotic rehabilitation: Literature review and challenges," *J. Robot.*, vol. 2011, pp. 1–11, Nov. 2011.
- [38] S. Hussain, "State-of-the-art robotic gait rehabilitation orthoses: Design and control aspects," *NeuroRehabilitation*, vol. 35, no. 4, pp. 701–709, Dec. 2014.
- [39] W. Huo, S. Mohammed, J. C. Moreno, and Y. Amirat, "Lower limb wearable robots for assistance and rehabilitation: A state of the art," *IEEE Syst. J.*, vol. 10, no. 3, pp. 1068–1081, Sep. 2016.
- [40] P. Heo, G. M. Gu, S. Lee, K. Rhee, and J. Kim, "Current hand exoskeleton technologies for rehabilitation and assistive engineering," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 5, pp. 807–824, May 2012.
- [41] P. S. Lum, S. B. Godfrey, E. B. Brokaw, R. J. Holley, and D. Nichols, "Robotic approaches for rehabilitation of hand function after stroke," *Amer. J. Phys. Med. Rehabil.*, vol. 91, no. 11, pp. S242–S254, 2012.
- [42] S. Balasubramanian, J. Klein, and E. Burdet, "Robot-assisted rehabilitation of hand function," *Current Opinion Neurol.*, vol. 23, no. 6, pp. 661–670, Dec. 2010.
- [43] L. Marchal-Crespo and D. J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *J. Neuroeng. Rehabil.*, vol. 6, no. 20, pp. 1–15, 2009.
- [44] H. Xiong and X. Diao, "A review of cable-driven rehabilitation devices," *Disab. Rehabil., Assistive Technol.*, vol. 15, no. 8, pp. 885–897, Nov. 2020.
- [45] Y. Cho, S. Muhammad, and J. Cheong, "Kinematic analysis of tendon driven robot mechanism for heavy weight handling," in *Proc. 12th Int. Conf. Ubiquitous Robots Ambient Intell. (URAI)*, Oct. 2015, pp. 91–94.
- [46] M. Shoaib, M. S. Khan, M. Asim, and J. Cheong, "Dynamic modeling and control of small scale wire driven robotic joints with wire elasticity," *J. Nanoelectron. Optoelectron.*, vol. 13, no. 9, pp. 1389–1396, Sep. 2018.
- [47] J. Cao, S. Q. Xie, R. Das, and G. L. Zhu, "Control strategies for effective robot assisted gait rehabilitation: The state of art and future prospects," *Med. Eng. Phys.*, vol. 36, no. 12, pp. 1555–1566, Dec. 2014.
- [48] *Actuator as a Keystone of Motion*. Accessed: Jan. 3, 2021. [Online]. Available: <https://www.progressiveautomations.com/pages/actuators>
- [49] Y. Mao and S. K. Agrawal, "Transition from mechanical arm to human arm with CAREX: A cable driven ARM EXoskeleton (CAREX) for neural rehabilitation," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2012, pp. 2457–2462.
- [50] A. H. A. Stienen, E. E. G. Hekman, F. C. T. Van der Helm, G. B. Prange, M. J. A. Jannink, A. M. M. Aalsma, and H. Van der Kooij, "Dampace: Dynamic force-coordination trainer for the upper extremities," in *Proc. IEEE 10th Int. Conf. Rehabil. Robot.*, Jun. 2007, pp. 820–826.
- [51] X. Jin, D. I. Jun, X. Jin, J. Seon, A. Pott, S. Park, J.-O. Park, and S. Y. Ko, "Upper limb rehabilitation using a planar cable-driven parallel robot with various rehabilitation strategies," in *Cable-Driven Parallel Robots*. Cham, Switzerland: Springer, 2015, pp. 307–321.
- [52] X. Jin, D. I. Jun, X. Jin, S. Park, J.-O. Park, and S. Y. Ko, "Workspace analysis of upper limb for a planar cable-driven parallel robots toward upper limb rehabilitation," in *Proc. 14th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2014, pp. 352–356.

- [53] A. Alamdari and V. Krovi, "Parallel articulated-cable exercise robot (PACER): Novel home-based cable-driven parallel platform robot for upper limb neuro-rehabilitation," in *Proc. 39th Mech. Robot. Conf.*, vol. 5A, Aug. 2015, Art. no. V05AT08A031.
- [54] A. Alamdari and V. Krovi, "Modeling and control of a novel home-based cable-driven parallel platform robot: PACER," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2015, pp. 6330–6335.
- [55] A. J. Westerveld, B. J. Aalderink, W. Hagedoorn, M. Buijze, A. C. Schouten, and H. V. D. Kooij, "A damper driven robotic end-point manipulator for functional rehabilitation exercises after stroke," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 10, pp. 2646–2654, Oct. 2014.
- [56] S. J. Ball, I. Brown, and S. H. Scott, "Designing a robotic exoskeleton for shoulder complex rehabilitation," in *Proc. CMBES*, vol. 30, Dec. 2007, pp. 1–4.
- [57] S. J. Ball, I. E. Brown, and S. H. Scott, "MEDARM: A rehabilitation robot with 5DOF at the shoulder complex," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, Sep. 2007, pp. 1–6.
- [58] I. Galiana, F. L. Hammond, R. D. Howe, and M. B. Popovic, "Wearable soft robotic device for post-stroke shoulder rehabilitation: Identifying misalignments," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 317–322.
- [59] A. S. Niyetkaliyev, E. Sariyildiz, and G. Alici, "Kinematic modeling and analysis of a novel bio-inspired and cable-driven hybrid shoulder mechanism," *J. Mech. Robot.*, vol. 13, no. 1, Feb. 2021, Art. no. 011008.
- [60] S. B. Kesner, L. Jentoft, F. L. Hammond, R. D. Howe, and M. Popovic, "Design considerations for an active soft orthotic system for shoulder rehabilitation," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2011, pp. 8130–8134.
- [61] N. Vitiello, T. Lenzi, S. Roccella, S. M. M. De Rossi, E. Cattin, F. Giovacchini, F. Vecchi, and M. C. Carrozza, "NEUROExos: A powered elbow exoskeleton for physical rehabilitation," *IEEE Trans. Robot.*, vol. 29, no. 1, pp. 220–235, Feb. 2013.
- [62] M. A. Laribi and M. Ceccarelli, "Design and experimental characterization of a cable-driven elbow assisting device," *J. Med. Devices*, vol. 15, no. 1, Mar. 2021, Art. no. 014503.
- [63] C. Jarrett and A. J. McDaid, "Robust control of a cable-driven soft exoskeleton joint for intrinsic human-robot interaction," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 7, pp. 976–986, Jul. 2017.
- [64] W. Chen, X. Cui, J. Zhang, and J. Wang, "A cable-driven wrist robotic rehabilitator using a novel torque-field controller for human motion training," *Rev. Sci. Instrum.*, vol. 86, no. 6, Jun. 2015, Art. no. 065109.
- [65] L. Yang, F. Zhang, J. Zhu, and Y. Fu, "A portable device for hand rehabilitation with force cognition: Design, interaction and experiment," *IEEE Trans. Cognit. Develop. Syst.*, early access, Jan. 29, 2021, doi: 10.1109/TCDS.2021.3055626.
- [66] S. Park, L. Weber, L. Bishop, J. Stein, and M. Ciocarlie, "Design and development of effective transmission mechanisms on a tendon driven hand orthosis for stroke patients," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 2281–2287.
- [67] S. Min and S. Yi, "Development of cable-driven anthropomorphic robot hand," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 1176–1183, Apr. 2021.
- [68] K. Serbest, M. Kutlu, O. Eldogan, and I. Tekeoglu, "Development and control of a home-based training device for hand rehabilitation with a spring and cable driven mechanism," *Biomed. Eng./Biomedizinische Technik*, vol. 66, no. 4, pp. 395–403, Feb. 2021.
- [69] J.-G. Yoon and M. C. Lee, "Design of tendon mechanism for soft wearable robotic hand and its fuzzy control using electromyogram sensor," *Intell. Service Robot.*, vol. 14, no. 2, pp. 119–128, 2021.
- [70] P. M. Aubin, H. Sallum, C. Walsh, L. Stirling, and A. Correia, "A pediatric robotic thumb exoskeleton for at-home rehabilitation: The isolated orthosis for thumb actuation (IOTA)," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2013, pp. 1–6.
- [71] Z. Song and S. Guo, "Design process of exoskeleton rehabilitation device and implementation of bilateral upper limb motor movement," *J. Med. Biol. Eng.*, vol. 32, no. 5, pp. 323–330, 2012.
- [72] R. A. R. C. Gopura, K. Kiguchi, and Y. Li, "SUEFUL-7: A 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2009, pp. 1126–1131.
- [73] F. Xiao, Y. Gao, Y. Wang, Y. Zhu, and J. Zhao, "Design of a wearable cable-driven upper limb exoskeleton based on epicyclic gear trains structure," *Technol. Health Care*, vol. 25, pp. 3–11, Jul. 2017.
- [74] X. Cui, W. Chen, J. Zhang, and J. Wang, "Note: Model-based identification method of a cable-driven wearable device for arm rehabilitation," *Rev. Sci. Instrum.*, vol. 86, no. 9, Sep. 2015, Art. no. 096107.
- [75] Z. Song, S. Guo, M. Pang, and S. Zhang, "ULERD-based active training for upper limb rehabilitation," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2012, pp. 569–574.
- [76] F. Martinez, I. Retolaza, A. Pujana-Arrese, A. Cenitagoya, J. Basurko, and J. Landaluze, "Design of a five actuated DoF upper limb exoskeleton oriented to workplace help," in *Proc. 2nd IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechanics*, Oct. 2008, pp. 169–174.
- [77] F. Martinez, A. Pujana-Arrese, I. Retolaza, I. Sacristan, J. Basurko, and J. Landaluze, "IKO: A five actuated DoF upper limb exoskeleton oriented to workplace assistance," *Appl. Bionics Biomech.*, vol. 6, no. 2, pp. 143–155, Jul. 2009.
- [78] K. Liu and C. Xiong, "A novel 10-DOF exoskeleton rehabilitation robot based on the postural synergies of upper extremity movements," in *Proc. Int. Conf. Intell. Robot. Appl.* Berlin, Germany: Springer-Verlag, 2013, pp. 363–372.
- [79] X. Jiang, C. Xiong, R. Sun, and Y. Xiong, "Characteristics of the robotic arm of a 9-DOF upper limb rehabilitation robot powered by pneumatic muscles," in *Proc. Int. Conf. Intell. Robot. Appl.* Berlin, Germany: Springer-Verlag, 2010, pp. 463–474.
- [80] X.-Z. Jiang, C.-H. Xiong, R.-L. Sun, and Y.-L. Xiong, "Characteristics of the robotic joint of a 9-DOF upper limb rehabilitation robot driven by pneumatic muscles," *Int. J. Humanoid Robot.*, vol. 8, no. 4, pp. 743–760, Dec. 2011.
- [81] T. G. Sugar, J. He, E. J. Koeneman, J. B. Koeneman, R. Herman, H. Huang, R. S. Schultz, D. E. Herring, J. Wanberg, S. Balasubramanian, and P. Swenson, "Design and control of RUPERT: A device for robotic upper extremity repetitive therapy," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 336–346, Sep. 2007.
- [82] J. He, E. J. Koeneman, R. S. Schultz, D. E. Herring, J. Wanberg, H. Huang, T. Sugar, R. Herman, and J. B. Koeneman, "RUPERT: A device for robotic upper extremity repetitive therapy," in *Proc. IEEE Eng. Med. Biol. 27th Annu. Conf.*, Jan. 2005, pp. 6844–6847.
- [83] J. He, E. J. Koeneman, R. S. Schultz, H. Huang, J. Wanberg, D. E. Herring, T. Sugar, R. Herman, and J. B. Koeneman, "Design of a robotic upper extremity repetitive therapy device," in *Proc. 9th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2005, pp. 95–98.
- [84] J. Wu, J. Huang, Y. Wang, and K. Xing, "A wearable rehabilitation robotic hand driven by PM-TS actuators," in *Proc. Int. Conf. Intell. Robot. Appl.* Berlin, Germany: Springer-Verlag, 2010, pp. 440–450.
- [85] T. Chen, R. Casas, and P. S. Lum, "An elbow exoskeleton for upper limb rehabilitation with series elastic actuator and cable-driven differential," *IEEE Trans. Robot.*, vol. 35, no. 6, pp. 1464–1474, Dec. 2019.
- [86] H.-S. Park, Y. Ren, and L.-Q. Zhang, "IntelliArm: An exoskeleton for diagnosis and treatment of patients with neurological impairments," in *Proc. 2nd IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechanics*, Oct. 2008, pp. 109–114.
- [87] A. Frisoli, L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, F. Salsedo, M. Bergamasco, M. C. Carboncini, M. Tolaini, and B. Rossi, "Arm rehabilitation with a robotic exoskeleton in virtual reality," in *Proc. IEEE 10th Int. Conf. Rehabil. Robot.*, Jun. 2007, pp. 631–642.
- [88] Y. Fu, Q. Zhang, F. Zhang, and Z. Gan, "Design and development of a hand rehabilitation robot for patient-cooperative therapy following stroke," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2011, pp. 112–117.
- [89] G. R. Johnson, D. A. Carus, G. Parrini, S. Marchese, and R. Vleggi, "The design of a five-degree-of-freedom powered orthosis for the upper limb," *Proc. Inst. Mech. Eng., H, J. Eng. Med.*, vol. 215, no. 3, pp. 275–284, Mar. 2001.
- [90] G. Rosati, D. Zanotto, R. Secoli, and A. Rossi, "Design and control of two planar cable-driven robots for upper-limb neurorehabilitation," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2009, pp. 560–565.
- [91] G. Rosati, M. Andreoli, A. Biondi, and P. Gallina, "Performance of cable suspended robots for upper limb rehabilitation," in *Proc. IEEE 10th Int. Conf. Rehabil. Robot.*, Jun. 2007, pp. 385–392.
- [92] S. Masiero, A. Celia, G. Rosati, and M. Armani, "Robotic-assisted rehabilitation of the upper limb after acute stroke," *Arch. Phys. Med. Rehabil.*, vol. 88, no. 2, pp. 142–149, 2007.
- [93] S. Masiero, M. Armani, G. Ferlini, G. Rosati, and A. Rossi, "Randomized trial of a robotic assistive device for the upper extremity during early inpatient stroke rehabilitation," *Neurorehabil. Neural Repair*, vol. 28, no. 4, pp. 377–386, May 2014.

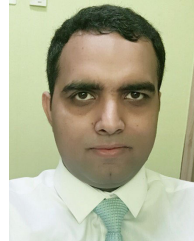
- [94] T. N. Bryce, M. P. Dijkers, and A. J. Kozlowski, "Framework for assessment of the usability of lower-extremity robotic exoskeletal orthoses," *Amer. J. Phys. Med. Rehabil.*, vol. 94, no. 11, pp. 1000–1014, 2015.
- [95] J. Veneman, R. Ekkelenkamp, R. Kruidhof, F. Van der Helm, and H. Van der Kooij, "A series elastic-and bowden-cable-based actuation system for use as torque actuator in exoskeleton-type robots," *Int. J. Robot. Res.*, vol. 25, no. 3, pp. 261–281, 2006.
- [96] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, E. H. F. van Asseldonk, and H. van der Kooij, "Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 379–386, Sep. 2004.
- [97] R. Ekkelenkamp, J. Veneman, and H. van der Kooij, "LOPES: A lower extremity powered exoskeleton," in *Proc. IEEE Int. Conf. Robot. Autom.*, Apr. 2007, pp. 3132–3133.
- [98] X. Jin, X. Cui, and S. K. Agrawal, "Design of a cable-driven active leg exoskeleton (C-ALEX) and gait training experiments with human subjects," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 5578–5583.
- [99] J. Park, S. Park, C. Kim, J. H. Park, and J. Choi, "Design and control of a powered lower limb orthosis using a cable-differential mechanism, COWALK-mobile 2," *IEEE Access*, vol. 9, pp. 43775–43784, 2021.
- [100] A. M. Barbosa, J. C. M. Carvalho, and R. S. Gonçalves, "Cable-driven lower limb rehabilitation robot," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 40, no. 5, p. 245, May 2018.
- [101] Y.-L. Park, B.-R. Chen, N. O. Pérez-Arancibia, D. Young, L. Stirling, R. J. Wood, E. C. Goldfield, and R. Nagpal, "Design and control of a bio-inspired soft wearable robotic device for ankle-foot rehabilitation," *Bioinspiration Biomimetics*, vol. 9, no. 1, Jan. 2014, Art. no. 016007.
- [102] N. Dhir, H. Dallali, E. M. Ficanha, G. A. Ribeiro, and M. Rastgaar, "Locomotion envelopes for adaptive control of powered ankle prostheses," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 1488–1495.
- [103] G. Abbasnejad, J. Yoon, and H. Lee, "Optimum kinematic design of a planar cable-driven parallel robot with wrench-closure gait trajectory," *Mechanism Mach. Theory*, vol. 99, pp. 1–18, May 2016.
- [104] S. Gharatappeh, G. Abbasnejad, J. Yoon, and H. Lee, "Control of cable-driven parallel robot for gait rehabilitation," in *Proc. 12th Int. Conf. Ubiquitous Robots Ambient Intell. (URAI)*, Oct. 2015, pp. 377–381.
- [105] A. Taherifar, M. R. Hadian, M. Mousavi, A. Rassaf, and F. Ghiasi, "LOKOIRAN—A novel robot for rehabilitation of spinal cord injury and stroke patients," in *Proc. 1st RSI/ISM Int. Conf. Robot. Mechatronics (ICRoM)*, Feb. 2013, pp. 218–223.
- [106] D. Surdilovic and R. Bernhardt, "STRING-MAN: A new wire robot for gait rehabilitation," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Apr. 2004, pp. 2031–2036.
- [107] B. M. Fleerkotte, J. H. Buurke, B. Koopman, L. Schaake, H. van der Kooij, E. H. van Asseldonk, and J. S. Rietman, "Effectiveness of the Lower extremity powered exoskeleton (LOPES) robotic gait trainer on ability and quality of walking in sci patients," in *Converging Clinical and Engineering Research on Neurorehabilitation*. Berlin, Germany: Springer-Verlag, 2013, pp. 161–165.
- [108] J. Bae, C. Sivi, M. Rouleau, N. Menard, K. Odonnell, I. Geliana, M. Athanassiou, D. Ryan, C. Bibeau, L. Sloot, P. Kudzia, T. Ellis, L. Awad, and C. J. Walsh, "A lightweight and efficient portable soft exosuit for paretic ankle assistance in walking after stroke," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 2820–2827.
- [109] M. Wu, T. G. Hornby, J. M. Landry, H. Roth, and B. D. Schmit, "A cable-driven locomotor training system for restoration of gait in human SCI," *Gait Posture*, vol. 33, no. 2, pp. 256–260, Feb. 2011.
- [110] J. Kang, V. Vashista, and S. K. Agrawal, "On the adaptation of pelvic motion by applying 3-dimensional guidance forces using TPAD," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 9, pp. 1558–1567, Sep. 2017.
- [111] B. Zi, G. Yin, and D. Zhang, "Design and optimization of a hybrid-driven waist rehabilitation robot," *Sensors*, vol. 16, no. 12, p. 2121, 2016.
- [112] B. Zi, G. Yin, Y. Li, and D. Zhang, "Kinematic performance analysis of a hybrid-driven waist rehabilitation robot," in *Mechatronics and Robotics Engineering for Advanced and Intelligent Manufacturing*. Cham, Switzerland: Springer, 2017, pp. 73–86.
- [113] Q. Chen, B. Zi, Z. Sun, Y. Li, and Q. Xu, "Design and development of a new cable-driven parallel robot for waist rehabilitation," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 4, pp. 1497–1507, Aug. 2019.
- [114] T. Zhao, S. Qian, Q. Chen, and Z. Sun, "Design and analysis of a cable-driven parallel robot for waist rehabilitation," in *Proc. IEEE Int. Conf. Mechatronics, Robot. Autom. (ICMRA)*, May 2018, pp. 173–178.
- [115] Z. Yang, B. Zi, and B. Chen, "Mechanism design and kinematic analysis of a waist and lower limbs cable-driven parallel rehabilitation robot," in *Proc. IEEE 3rd Adv. Inf. Manage., Communicates, Electron. Autom. Control Conf. (IMCEC)*, Oct. 2019, pp. 723–727.
- [116] Z.-F. Shao, X. Tang, and W. Yi, "Optimal design of a 3-DOF cable-driven upper arm exoskeleton," *Adv. Mech. Eng.*, vol. 6, Jan. 2014, Art. no. 157096.
- [117] W. Wei, Z. Qu, W. Wang, P. Zhang, and F. Hao, "Design on the bowden cable-driven upper limb soft exoskeleton," *Appl. Bionics Biomech.*, vol. 2018, pp. 1–9, Jul. 2018.
- [118] A. V. Dowling, O. Barzilay, Y. Lombrozo, and A. Wolf, "An adaptive home-use robotic rehabilitation system for the upper body," *IEEE J. Transl. Eng. Health Med.*, vol. 2, pp. 1–10, 2014.
- [119] G. Zuccon, M. Bottin, M. Ceccarelli, and G. Rosati, "Design and performance of an elbow assisting mechanism," *Machines*, vol. 8, no. 4, p. 68, Oct. 2020.
- [120] M. Ceccarelli, L. Ferrara, and V. Petuya, "Design of a cable-driven device for elbow rehabilitation and exercise," in *Interdisciplinary Applications of Kinematics*. Cham, Switzerland: Springer, 2019, pp. 61–68.
- [121] D. H. Kim and H.-S. Park, "Cable actuated dexterous (CADEX) glove for effective rehabilitation of the hand for patients with neurological diseases," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 2305–2310.
- [122] S. Mohamaddan and T. Komeda, "Wire-driven mechanism for finger rehabilitation device," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2010, pp. 1015–1018.
- [123] H. In, K.-J. Cho, K. Kim, and B. Lee, "Jointless structure and under-actuation mechanism for compact hand exoskeleton," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2011, pp. 1–6.
- [124] U. Jeong, H.-K. In, and K.-J. Cho, "Implementation of various control algorithms for hand rehabilitation exercise using wearable robotic hand," *Intell. Service Robot.*, vol. 6, no. 4, pp. 181–189, Oct. 2013.
- [125] C. L. Jones, F. Wang, R. Morrison, N. Sarkar, and D. G. Kamper, "Design and development of the cable actuated finger exoskeleton for hand rehabilitation following stroke," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 1, pp. 131–140, Feb. 2014.
- [126] M. Cempini, S. M. M. De Rossi, T. Lenzi, M. Cortese, F. Giovacchini, N. Vitiello, and M. C. Carrozza, "Kinematics and design of a portable and wearable exoskeleton for hand rehabilitation," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2013, pp. 1–6.
- [127] S. Wang, J. Li, and R. Zheng, "A resistance compensation control algorithm for a cable-driven hand exoskeleton for motor function rehabilitation," in *Proc. Int. Conf. Intell. Robot. Appl.* Berlin, Germany: Springer, 2010, pp. 398–404.
- [128] S. Liu, D. Meng, L. Cheng, and M. Chen, "An iterative learning controller for a cable-driven hand rehabilitation robot," in *Proc. IECON 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2017, pp. 5701–5706.
- [129] P. Aubin, K. Petersen, H. Sallum, C. Walsh, A. Correia, and L. Stirling, "A pediatric robotic thumb exoskeleton for at-home rehabilitation," *Int. J. Intell. Comput. Cybern.*, vol. 7, no. 3, pp. 233–252, Aug. 2014.
- [130] J. Ma, R. Mo, M. Chen, L. Cheng, and H. Qi, "Mirror-training of a Cable-driven hand rehabilitation robot based on surface electromyography (sEMG)," in *Proc. 10th Int. Conf. Intell. Control Inf. Process. (ICICIP)*, Dec. 2019, pp. 309–315.
- [131] S. Yu, H. Perez, J. Barkas, M. Mohamed, M. Eldaly, T.-H. Huang, X. Yang, H. Su, M. del Mar Cortes, and D. J. Edwards, "A soft high force hand exoskeleton for rehabilitation and assistance of spinal cord injury and stroke individuals," in *Proc. Design Med. Devices Conf.*, Apr. 2019, Art. no. V001T09A011.
- [132] M. M. Ullah, U. Hafeez, M. N. Shehzad, M. N. Awais, and H. Elahi, "A soft robotic glove for assistance and rehabilitation of stroke affected patients," in *Proc. Int. Conf. Frontiers Inf. Technol. (FIT)*, Dec. 2019, pp. 110–115.
- [133] M. S. John, N. Thomas, and V. Sivakumar, "Design and development of cable driven upper limb exoskeleton for arm rehabilitation," *Int. J. Sci. Eng. Res.*, vol. 7, no. 3, pp. 1432–1440, 2016.
- [134] N. Jarrassé, J. Robertson, P. Garrec, J. Paik, V. Pasqui, Y. Perrot, A. Roby-Brami, D. Wang, and G. Morel, "Design and acceptability assessment of a new reversible orthosis," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2008, pp. 1933–1939.
- [135] Z. Li, W. Chen, J. Zhang, and S. Bai, "Design and control of a 4-DOF cable-driven arm rehabilitation robot (CARR-4)," in *Proc. IEEE Int. Conf. Cybern. Intell. Syst. (CIS) IEEE Conf. Robot., Autom. Mechatronics (RAM)*, Nov. 2017, pp. 581–586.



- [136] I. Gaponov, D. Popov, S. J. Lee, and J.-H. Ryu, "Auxilio: A portable cable-driven exosuit for upper extremity assistance," *Int. J. Control. Autom. Syst.*, vol. 15, no. 1, pp. 73–84, Feb. 2017.
- [137] W. M. Nunes, L. A. O. Rodrigues, L. P. Oliveira, J. F. Ribeiro, J. C. M. Carvalho, and R. S. Goncalves, "Cable-based parallel manipulator for rehabilitation of shoulder and elbow movements," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2011, pp. 1–6.
- [138] K. Shi, A. Song, Y. Li, D. Chen, and H. Li, "Cable-driven 4-DOF upper limb rehabilitation robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Nov. 2019, pp. 6465–6472.
- [139] Z. Li, W. Li, W.-H. Chen, J. Zhang, J. Wang, Z. Fang, and G. Yang, "Mechatronics design and testing of a cable-driven upper limb rehabilitation exoskeleton with variable stiffness," *Rev. Sci. Instrum.*, vol. 92, no. 2, Feb. 2021, Art. no. 024101.
- [140] E. Pezent, C. G. Rose, A. D. Deshpande, and M. K. O'Malley, "Design and characterization of the OpenWrist: A robotic wrist exoskeleton for coordinated hand-wrist rehabilitation," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 720–725.
- [141] A. Schiele and G. Hirzinger, "A new generation of ergonomic exoskeletons—The high-performance X-Arm-2 for space robotics telepresence," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2011, pp. 2158–2165.
- [142] F. Xiao, Y. Gao, Y. Wang, Y. Zhu, and J. Zhao, "Design and evaluation of a 7-DOF cable-driven upper limb exoskeleton," *J. Mech. Sci. Technol.*, vol. 32, no. 2, pp. 855–864, 2018.
- [143] J. C. Perry, J. Rosen, and S. Burns, "Upper-limb powered exoskeleton design," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 4, pp. 408–417, Aug. 2007.
- [144] C.-T. Chen, W.-Y. Lien, C.-T. Chen, M.-J. Twu, and Y.-C. Wu, "Dynamic modeling and motion control of a cable-driven robotic exoskeleton with pneumatic artificial muscle actuators," *IEEE Access*, vol. 8, pp. 149796–149807, 2020.
- [145] J. Wang, W. Li, W. Chen, and J. Zhang, "Motion control of a 4-DOF cable-driven upper limb exoskeleton," in *Proc. 14th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2019, pp. 2129–2134.
- [146] N. G. Tsagarakis and D. G. Caldwell, "Development and control of a 'soft-actuated' exoskeleton for use in physiotherapy and training," *Auto. Robots*, vol. 15, no. 1, pp. 21–33, 2003.
- [147] J. C. Perry and J. Rosen, "Design of a 7 degree-of-freedom upper-limb powered exoskeleton," in *Proc. 1st IEEE/RAS-EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, 2006, pp. 805–810.
- [148] M. Morris and O. Masory, "Planar cable-driven rehabilitation robot," in *Proc. Florida Conf. Recent Adv. Robot.*, May 2008, pp. 8–9.
- [149] J. Niu, Q. Yang, R. Song, and X. Wang, "Sliding mode tracking control of a wire-driven upper-limb rehabilitation robot with nonlinear disturbance observer," *Frontiers Neurol.*, vol. 8, p. 646, Dec. 2017.
- [150] J. Niu, Q. Yang, G. Chen, and R. Song, "Nonlinear disturbance observer based sliding mode control of a cable-driven rehabilitation robot," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 664–669.
- [151] C. Fanin, P. Gallina, A. Rossi, U. Zanatta, and S. Masiero, "NeReBot: A wire-based robot for neurorehabilitation," in *Proc. ICORR HWRS-ERC*, 2003, pp. 23–27.
- [152] M. Stefano, P. Patrizia, A. Mario, G. Ferlini, R. Rizzello, and G. Rosati, "Robotic upper limb rehabilitation after acute stroke by NeReBot: Evaluation of treatment costs," *BioMed Res. Int.*, vol. 2014, pp. 1–5, Jan. 2014.
- [153] G. Rosati, P. Gallina, A. Rossi, and S. Masiero, "Wire-based robots for upper-limb rehabilitation," *Int. J. Assistive Robot. Mechatronics*, vol. 7, pp. 3–10, Jun. 2006.
- [154] D. Mayhew, B. Bachrach, W. Z. Rymer, and R. F. Beer, "Development of the MACARM—A novel cable robot for upper limb neurorehabilitation," in *Proc. 9th Int. Conf. Rehabil. Robot. (ICORR)*, 2005, pp. 299–302.
- [155] X. Li, Q. Yang, and R. Song, "Performance-based hybrid control of a cable-driven upper-limb rehabilitation robot," *IEEE Trans. Biomed. Eng.*, vol. 68, no. 4, pp. 1351–1359, Apr. 2021.
- [156] S. Kyeong, Y. Na, and J. Kim, "A mechatronic mirror-image motion device for symmetric upper-limb rehabilitation," *Int. J. Precis. Eng. Manuf.*, vol. 21, pp. 947–956, Jan. 2020.
- [157] J. Kim, R. Heimgartner, G. Lee, N. Karavas, D. Perry, D. L. Ryan, A. Eckert-Erdheim, P. Murphy, D. K. Choe, I. Galiana, and C. J. Walsh, "Autonomous and portable soft exosuit for hip extension assistance with online walking and running detection algorithm," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 1–8.
- [158] E. J. Park, J. Kang, H. Su, P. Stegall, D. L. Miranda, W.-H. Hsu, M. Karabas, N. Phipps, S. K. Agrawal, E. C. Goldfield, and C. J. Walsh, "Design and preliminary evaluation of a multi-robotic system with pelvic and hip assistance for pediatric gait rehabilitation," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 332–339.
- [159] Y.-L. Park, J. Santos, K. G. Galloway, E. C. Goldfield, and R. J. Wood, "A soft wearable robotic device for active knee motions using flat pneumatic artificial muscles," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 4805–4810.
- [160] P. K. Jamwal, S. Xie, and K. C. Aw, "Kinematic design optimization of a parallel ankle rehabilitation robot using modified genetic algorithm," *Robot. Auto. Syst.*, vol. 57, no. 10, pp. 1018–1027, 2009.
- [161] T. Noda, A. Takai, T. Teramae, E. Hirokai, K. Hase, and J. Morimoto, "Robotizing double-bar ankle-foot orthosis," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 2782–2787.
- [162] M. Russo and M. Ceccarelli, "Analysis of a wearable robotic system for ankle rehabilitation," *Machines*, vol. 8, no. 3, p. 48, Aug. 2020.
- [163] T.-M. Wang, X. Pei, T.-G. Hou, Y.-B. Fan, X. Yang, H. M. Herr, and X.-B. Yang, "An untethered cable-driven ankle exoskeleton with plantarflexion-dorsiflexion bidirectional movement assistance," *Frontiers Inf. Technol. Electron. Eng.*, vol. 21, no. 5, pp. 723–739, May 2020.
- [164] T. Lee, I. Kim, and Y. S. Baek, "Design of a 2DOF ankle exoskeleton with a polycentric structure and a bi-directional tendon-driven actuator controlled using a PID neural network," *Actuators*, vol. 10, no. 1, p. 9, 2021.
- [165] S. Lee, N. Karavas, B. T. Quinlivan, D. LouiseRyan, D. Perry, A. Eckert-Erdheim, P. Murphy, T. G. Goldy, N. Menard, M. Athanassiou, J. Kim, G. Lee, I. Galiana, and C. J. Walsh, "Autonomous multi-joint soft exosuit for assistance with walking overground," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 2812–2819.
- [166] N. Costa, M. Bezdicek, M. Brown, J. O. Gray, D. G. Caldwell, and S. Hutchins, "Joint motion control of a powered lower limb orthosis for rehabilitation," *Int. J. Autom. Comput.*, vol. 3, no. 3, pp. 271–281, Jul. 2006.
- [167] S.-H. Hyon, J. Morimoto, T. Matsubara, T. Noda, and M. Kawato, "XoR: Hybrid drive exoskeleton robot that can balance," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2011, pp. 3975–3981.
- [168] D. P. Ferris and C. L. Lewis, "Robotic lower limb exoskeletons using proportional myoelectric control," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2009, pp. 2119–2124.
- [169] M. Wehner, B. Quinlivan, P. M. Aubin, E. Martinez-Villalpando, M. Baumann, L. Stirling, K. Holt, R. Wood, and C. Walsh, "A lightweight soft exosuit for gait assistance," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 3362–3369.
- [170] H. Faqih, M. Saad, K. Benjelloun, M. Benbrahim, and M. N. Kabbaj, "Tracking trajectory of a cable-driven robot for lower limb rehabilitation," *Int. J. Electr. Comput. Energetic Electron. Commun. Eng.*, vol. 10, no. 8, pp. 1036–1041, 2016.
- [171] Y. Liu, Y. Gao, F. Xiao, and J. Zhao, "Research on the cable-pulley under-actuated lower limb exoskeleton," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2017, pp. 577–583.
- [172] A. Alamdari and V. Krovi, "Design and analysis of a cable-driven articulated rehabilitation system for gait training," *J. Mech. Robot.*, vol. 8, no. 5, Oct. 2016, Art. no. 051018.
- [173] A. Alamdari, R. Haghghi, and V. Krovi, "Gravity-balancing of elastic articulated-cable leg-orthosis emulator," *Mechanism Mach. Theory*, vol. 131, pp. 351–370, Jan. 2019.
- [174] A. Alamdari, "Cable-driven articulated rehabilitation system for gait training," Ph.D. dissertation, Dept. Mech. Aerosp. Eng., State Univ. New York Buffalo, New York, NY, USA, 2016.
- [175] K. Homma, O. Fukuda, and Y. Nagata, "Study of a wire-driven leg rehabilitation system," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2002, pp. 1451–1456.
- [176] K. Homma, O. Fukuda, J. Sugawara, Y. Nagata, and M. Usuba, "A wire-driven leg rehabilitation system: Development of a 4-DOF experimental system," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2003, pp. 908–913.
- [177] D. Cafolla, M. Russo, and G. Carbone, "CUBE, a cable-driven device for limb rehabilitation," *J. Bionic Eng.*, vol. 16, no. 3, pp. 492–502, May 2019.
- [178] D. Cafolla, M. Russo, and G. Carbone, "Design of cube, a cable-driven device for upper and lower limb exercising," in *New Trends in Medical and Service Robotics*. Cham, Switzerland: Springer, 2019, pp. 255–263.



- [179] S. S. Iyer, J. V. Joseph, N. S. S. Sanjeevi, Y. Singh, and V. Vashista, "Development and applicability of a cable-driven wearable adaptive rehabilitation suit (WeARS)," in *Proc. 28th IEEE Int. Conf. Robot Hum. Interact. Commun. (RO-MAN)*, Oct. 2019, pp. 1–6.
- [180] Z. Zhou, Z. Wang, and Q. Wang, "On the design of rigid-soft hybrid exoskeleton based on remote cable actuator for gait rehabilitation," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2020, pp. 1902–1907.
- [181] Y.-J. Kim, C.-K. Park, and K. G. Kim, "An EMG-based variable impedance control for elbow exercise: Preliminary study," *Adv. Robot.*, vol. 31, no. 15, pp. 809–820, 2017.
- [182] N. Nazmi, M. A. A. Rahman, S. A. Mazlan, H. Zamzuri, and M. Mizukawa, "Electromyography (EMG) based signal analysis for physiological device application in lower limb rehabilitation," in *Proc. 2nd Int. Conf. Biomed. Eng. (ICoBE)*, Mar. 2015, pp. 1–6.
- [183] D. Czarkowski, "Intelligent controller design based on gain and phase margin specifications," in *Proc. Irish Signals Syst. Conf.*, 2004, pp. 1–6.
- [184] N. Hogan, "Impedance control: An approach to manipulation: Part I—Theory," *ASME J. Dyn. Syst., Meas., Control*, vol. 107, no. 1, pp. 1–7, Mar. 1985. [Online]. Available: <https://doi-org.ezproxy.lib.rmit.edu.au/10.1115/1.3140702>
- [185] P. Lammertse. (2004). *Admittance Control and Impedance Control—A Dual*. [Online]. Available: [https://www.haptist.com/resources/Lammertse\\_2004\\_admittanceimpedancecontrol.pdf](https://www.haptist.com/resources/Lammertse_2004_admittanceimpedancecontrol.pdf)
- [186] E. Arabi, B. C. Gruenwald, T. Yucelen, and J. E. Steck, "Guaranteed model reference adaptive control performance in the presence of actuator failures," in *Proc. AIAA Inf. Syst.-AIAA Infotech @ Aerosp.*, Jan. 2017, p. 0669.
- [187] Y. Mao, X. Jin, and S. K. Agrawal, "Real-time estimation of glenohumeral joint rotation center with cable-driven arm exoskeleton (CAREX)—A cable-based arm exoskeleton," *J. Mech. Robot.*, vol. 6, no. 1, Feb. 2014, Art. no. 014502.
- [188] N. Hogan, "Impedance control: An approach to manipulation," in *Proc. Amer. Control Conf.*, Jul. 1984, pp. 304–313.
- [189] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz, "Patient-cooperative strategies for robot-aided treadmill training: First experimental results," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 380–394, Sep. 2005.
- [190] J. C. P. Ibarra and A. A. G. Siqueira, "Impedance control of rehabilitation robots for lower limbs, review," in *Proc. Joint Conf. Robot., SBR-LARS Robot. Symp. Robocontrol*, Oct. 2014, pp. 235–240.
- [191] Y. H. Tsoi and S. Q. Xie, "Impedance control of ankle rehabilitation robot," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Feb. 2009, pp. 840–845.
- [192] S. Chiaverini, B. Siciliano, and L. Villani, "A survey of robot interaction control schemes with experimental comparison," *IEEE/ASME Trans. Mechatronics*, vol. 4, no. 3, pp. 273–285, Sep. 1999.
- [193] D. E. Whitney, "Historical perspective and state of the art in robot force control," *Int. J. Robot. Res.*, vol. 6, no. 1, pp. 3–14, 1987.
- [194] C. Ott, R. Mukherjee, and Y. Nakamura, "Unified impedance and admittance control," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 554–561.
- [195] B. K. Dinh, M. Xiloyannis, L. Cappello, C. W. Antuvan, S.-C. Yen, and L. Masia, "Adaptive backlash compensation in upper limb soft wearable exoskeletons," *Robot. Auton. Syst.*, vol. 92, pp. 173–186, Jun. 2017.
- [196] A. U. Pehlivan, F. Sergi, and M. K. O'Malley, "Adaptive control of a serial-in-parallel robotic rehabilitation device," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2013, pp. 1–6.
- [197] P. E. Crago, N. Lan, P. H. Veltink, J. J. Abbas, and C. Kantor, "New control strategies for neuroprosthetic systems," *J. Rehabil. Res. Develop.*, vol. 33, no. 2, pp. 158–172, 1996.
- [198] Q.-T. Dao and S.-I. Yamamoto, "Assist-as-needed control of a robotic orthosis actuated by pneumatic artificial muscle for gait rehabilitation," *Appl. Sci.*, vol. 8, no. 4, p. 499, Mar. 2018.
- [199] S. Younis and N. Z. Azlan, "Assist-as-needed control strategies for upper limb rehabilitation therapy: A review," *Jurnal Mekanikal*, vol. 42, no. 1, pp. 57–74, 2019.
- [200] S. Y. A. Mounis, N. Z. Azlan, and F. Sado, "Assist-as-needed control strategy for upper-limb rehabilitation based on subject's functional ability," *Meas. Control*, vol. 52, nos. 9–10, pp. 1354–1361, Nov. 2019.
- [201] B. Chen, H. Ma, L.-Y. Qin, F. Gao, K.-M. Chan, S.-W. Law, L. Qin, and W.-H. Liao, "Recent developments and challenges of lower extremity exoskeletons," *J. Orthopaedic Transl.*, vol. 5, pp. 26–37, Apr. 2016.
- [202] J. Stein, H. I. Krebs, W. R. Frontera, S. E. Fasoli, R. Hughes, and N. Hogan, "Comparison of two techniques of robot-aided upper limb exercise training after stroke," *Amer. J. Phys. Med. Rehabil.*, vol. 83, no. 9, pp. 720–728, Sep. 2004.
- [203] L. L. Cai, A. J. Fong, C. K. Otoshi, Y. Liang, J. W. Burdick, R. R. Roy, and V. R. Edgerton, "Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning," *J. Neurosci.*, vol. 26, no. 41, pp. 10564–10568, Oct. 2006.
- [204] Y. Cho, B. Kang, C. Park, and J. Cheong, "Kinematics of elastic tendons for tendon-driven manipulators with transmission friction," *IEEE/ASME Trans. Mechatronics*, early access, Feb. 19, 2021, doi: 10.1109/TMECH.2021.3060424.
- [205] A. Tonazzini, S. Mintchev, B. Schubert, B. Mazzolai, J. Shintake, and D. Floreano, "Variable stiffness fiber with self-healing capability," *Adv. Mater.*, vol. 28, no. 46, pp. 10142–10148, 2016.
- [206] Y.-J. Kim, S. Cheng, S. Kim, and K. Iagnemma, "Design of a tubular snake-like manipulator with stiffening capability by layer jamming," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 4251–4256.



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