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.

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                        | CDDR | BDRR | BSDRR | GDDR |
|-----------------------------------|------|------|-------|------|
| 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-Di | Bi-Di   | Bi-Di   | Bi-Di   |
| Undesired vibration               | High  | High   | Low   | Low   |

Keywords: CDDR- Cable driven rehabilitation robot, BDRR- Belt driven rehabilitation robot, BSDRR- Ball screw driven rehabilitation robot, GDDR- Gear driven. Uni-Di- UniDirectional, Bi-Di- BiDirectional

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.

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

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...
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 skeleton structure. An end-effector in contact with only one segment of the human 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 the target disease. It is conducted to verify the ability in assist and training the targeted disability. 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.

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], CDHR [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

| 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. |
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 |
|-------------------------|-----|----------|--------|------|------------------|----------------|
| **Target movements of rehabilitation: shoulder movements** |
| MEDARM [11]             | (3) | EMA      | Encoder + Load cells + Linear potentiometers | SE   | Passive-compliance + Impedance torque 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 sensors | PE   | Adaptive control | Prototype |
| **Target movements of rehabilitation: elbow movements** |
| NEUROExos [61]          | (4) | EMA+HA   | Encoder + Load cells + Linear potentiometers | SE   | Passive-compliance + Impedance torque control | Prototype |
| BIS [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 |
| CADIO [119]             | (1) | EA       | Force + IMU sensors | PE   | —                | Prototype |
| Elbow Rehab. [120]      | (1) | EA       | —      | PE   | Sensor-assisted control | Prototype |
| **Target movements of rehabilitation: forearm movements** |
| ATD [55]                | (3) | EA       | Six-DOFs force sensor + Angular encoders | SEE  | Impedance + Position control | Prototype |
| **Target movements of rehabilitation: wrist movements** |
| CDWRR [64]              | (3) | EA       | Load + IMU | PE   | Assist-as-needed | Prototype |
| **Target movements of rehabilitation: fingers movements** |
| Wearable Rehab. Robotic 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 |
| CAPE [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; HML-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 (N) and passive (N) 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 to 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 |
|-------------------------|-----|----------|--------|------|------------------|----------------|
| Dampace [50]            | (5) | EA + HA  | -------| Adjustable SE | Feedback control | Prototype; HMI: RG |
| Upper Limb Exoskeleton [133] | (5) | EA      | -------| SE    | Intention-driven robotic control | ------- |
| MEDARM [111]            | (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 |
| Auxilho [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 |

Target movements of rehabilitation; Wrist + Fingers movements

| Name of CDRR; Reference | DOF | Actuator | Sensor | HRPI | Control Strategy | Clinical & HMI |
|-------------------------|-----|----------|--------|------|------------------|----------------|
| MAHI [140]              | (3) | EA      | Angle sensors| SE | PID control | Prototype |

Target movements of rehabilitation; elbow + wrist movements

| Name of CDRR; Reference | DOF | Actuator | Sensor | HRPI | Control Strategy | Clinical & HMI |
|-------------------------|-----|----------|--------|------|------------------|----------------|
| 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 |

Target movements of rehabilitation; shoulder + elbow + forearm movements

| Name of CDRR; Reference | DOF | Actuator | Sensor | HRPI | Control Strategy | Clinical & HMI |
|-------------------------|-----|----------|--------|------|------------------|----------------|
| 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 |

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 | Control Strategy | Clinical & HMI |
|-------------------------|-----|----------|--------|------------------|----------------|
| Target movements of rehabilitation: shoulder + elbow + forearm + wrist movements |
| 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 |
| Rehabilitation Robot [148] | Multi-DOF | EA | Force sensors | PLEB | ———— | Prototype |
| Sophia-3 and Sophia-4 [90] | Multi-DOF | DC-EA | Optical encoders | PLP-BE | Impedance + Model-based adaptive Ctrl | Prototype; HMI: VE |
| Cable-driven Rehabilitation Robot [149][150] | Multi-DOF | ———— | Encoder | Sus-BE | Sliding Mode Tracking Control | Prototype |
| NeReBot [91], [151], [152] | (3) | EA | ———— | Sus-BE | PTO4 CONTROL | Prototype; CS-L3 |
| MariBot [153] | (5) | EA | Incremental encoder | Sus-BE | PID position control | Prototype |
| MACARM [154] | (6) | EA | 6-DOF load sensor | Sus-BE | Motion control | Prototype |
| PACER [53], [54] | (6) | Linear EA | ———— | Spatial+ Planar-E | 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-BE: Planar Parallel End-effector, Sus-BE: Suspended End-effector, DC: Direct current, EA: Electric Actuator, and PAM: Pneumatic Artificial Muscle, HMI: G; Human-Machine Interface: Cursor Posting 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 commended 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][82] 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.
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 CDPRR [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

| 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 | —— | —— |
| CDPRR [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 |
|-------------------------|-----|----------|--------|------|------------------|---------------|
| **Target movements of rehabilitation; Hip movements** |
| Hip-only Soft Exosuit [157] | 1 | 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 |
| **Target movements of rehabilitation; Knee movements** |
| Soft Wearable Robot [159] | (1) | Flat PAM | — | PE | — | Prototype |
| 4-4 CDPR [103], [104] | (3) | EA | — | — | PLP-EE PD control | Gait rehab Shank Att. |
| **Target movements of rehabilitation; Ankle movements** |
| 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 |
| CABLE Ankle [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 |
| **Target movements of rehabilitation; Hip + Knee movements** |
| 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 |
| **Target movements of rehabilitation; Hip + Knee + Ankle movements** |
| Powered Lower Limb Orthosis [166] | (8)+(2) | High | 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 | — | PE | 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 [103] | (9) | EA | Force sensors | (PYS)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 |
| WeAKS [179] | — | EA | Load cell | — | 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. HMIs 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 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 Tender 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 Tender 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 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 |
|------------------------|-----------------|-------------------|-------------|-----------------|-----------|
| Impedance control strategy | | | | | |
| 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 |
| | | | | | |
| Proportional integral derivative based control strategy | | | | | |
| 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-Dof’s 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 |
|------------------------|-----------------|-------------------|-------------|-----------------|----------|
| Admittance based control strategy |
| 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 |
| Adaptive control strategy |
| 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 |
| Assist-as-needed based control strategy |
| 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 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 IntelliaArm [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 relay 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
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 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 investigations.

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

| Control strategies | Advantages                                                                 | Disadvantages                                                                                   |
|--------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Impedance based    | • stable interaction between human and robot.                             | • performance declines with the decrease in the environment’s stiffness.                        |
| control strategy   | • allows adjustment of impedance value based on the therapist’s experience  | • requires the force sensors, which are generally expensive and sensitive to temperature changes.|
|                    | and patient’s disability.                                                 | • does not allow the voluntary movements of patient, as the change in muscles strength trigger  |
|                    | • control ability in three modes, robot in charge, patient in charge, and  | the controller (EMG-base impedance control).                                                    |
|                    |   therapist in charge.                                                     | • faces difficulty in precisely generation the force base on the varying EMG signals in real     |
|                    | • real-time adjustment of impedance parameters such as damping, inertia,   | time (EMG-base impedance control).                                                              |
|                    |   and stiffness.                                                          | • faces difficulty in ensuring the intrinsically stiff actuation system.                       |
|                    | • does not rely on the precise knowledge of external parameters.           |                                                                                                |
|                    | • monitor and improve the muscle strength by using EMG-based impedance     |                                                                                                |
|                    |   control.                                                                |                                                                                                |
| Proportional       | • easy to apply for CDRRs.                                                | • a sole force or position PID controller could not ensure safe dynamic interaction between      |
| integral derivative | • robust performance with simple structure.                               |   robots and human.                                                                            |
| based control      | • robust to tuning mismatches.                                            | • produces large overshoots which are not desirable for CDRRs.                                 |
| strategy           | • asymptotic convergence of errors in task space.                         |                                                                                                |
|                    | • independent control of the joints in joint space.                       |                                                                                                |
| Admittance based   | • provides higher accuracy for contact-free tasks.                        | • dynamic interactions between human and robot can lead to unstable performance.                |
| control strategy   | • works well when accurate information of interaction force between patient| • performance declines with the increase in the environment’s stiffness.                        |
|                    |   and robot is available.                                                 |                                                                                                |
| Adaptive control   | • robust to uncertain dynamic systems.                                    | • it is rarely optimal as it does not rely on the accurate modelling of the rehabilitation robot |
| strategy           | • ability to improve its performance under adverse and unforeseen         |                                                                                                |
|                    |   conditions.                                                             |                                                                                                |
|                    | • suitable if system stability problem is detected.                       |                                                                                                |
|                    | • compensates the friction and hysteresis backlash.                       |                                                                                                |
| Assist-as-needed   | • parameters are adjusted based on the level of assistance required by the | • inconsistent and inaccurate estimation of patient’s functional movement can be a major          |
| control strategy   |   patient or rehabilitation exercise.                                     |   limitation in use of this approach                                                            |
|                    | • evaluated for CDRRs using both lab experiments and clinical investigation.| • generating accurate level of robotic assistance in real-time based on estimation of the        |
|                    |                                                                            |   patients’ functional ability is challenging                                                  |
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 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 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 Younsu 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 categorizes 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.

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