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A Comprehensive Review on Cable-Driven Rehabilitation Robots Targeted for the Elbow

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Abstract

Elbow movement is necessary for day to day life activities such as reaching, eating, lifting, and personal care. Musculoskeletal, traumatic, and neurological disorders affect the movement of the elbow. Although traditional rehabilitation is useful but depends on the availability of therapist and creates burden on the medical field as well as to care facilities. Cable-driven rehabilitation robots (CDRRs) have emerged as effective solution to the emerging problem. Such robots provide a lighter and more flexible alternative to rigid exoskeletons.

This paper reviews the development in this field in terms of biomechanical requirements of the elbow joint, key design principles of cable-driven systems, major prototype developments, control strategies, sensor integration methods, and current clinical challenges with emphasis on safety, comfort, portability, and patient adaptability. Also, highlights the advantages and practical solutions for home-based use. Concluding that Overall, cable-driven systems show strong potential for future elbow rehabilitation, but further design and clinical development is needed for wider adoption.

Keywords: cable-driven rehabilitation robot; elbow rehabilitation; upper limb exoskeleton; assist-as-needed control; impedance control; stroke recovery; parallel robot; brain-computerinterface; neuroplasticity

1. Introduction

1.1 The Clinical Burden of Elbow Motor Dysfunction

Upper limb motor impairment is the most common problem following a damage to the nervous system and has the potential to severely impact the life of a person. [8, 11] Globally, strokes affect approximately 15 million people, of whom 5 million are permanently disabled [11]. Of these 30–66% experience upper-limb hemiplegia, which is a partial or complete loss of voluntary

movement of the arm. It is the most common movement-related effects of stroke. [8]. The elbow joint plays a large part in functional recovery, as it is the major joint controlling positioning of the hand for all activities including reaching, lifting, eating, grooming and hygiene activities. The elbow joint may also become fixed into a certain position following stroke. Elbow movement can also be restricted by conditions such as traumatic brain injury, cervical spinal cord injury, peripheral nerve damage, and severe elbow osteoarthritis. In addition, musculoskeletal conditions such as tennis elbow, golfer's elbow, and elbow contracture can further reduce elbow range of motion.

The modern neuroscience focuses the theory of motor recovery after injury. The principle of neuroplasticity which is the ability of the brain to reorganize cortical maps and establish new synaptic pathways in response to repetitive, task-specific motor training is responsible for shifting rehabilitation from passive mobilization toward active, high- intensity, and feedback-rich motor re- learning [11, 25]. Studies consistently show that the quality of neuromotor recovery scales with the intensity and number of repetitions of movement practice. However, the conventional manual therapy is limited to deliver the thousands of repetitions per session that optimal neuroplastic re-training demands [12].

1.2 The Emergence of Robotic Rehabilitation

The application of robotics to physical rehabilitation was first systematically seen in the early 1990s, with the MIT-Manus robot, a planar end-effector device for shoulder and elbow training representing the earliest clinical-grade device [14, 27].

Also, two of these devices have emerged over the last 30 years [5, 8]. End-effector robots directly control their interaction with the human at the hand or wrist and indirectly across the upper limb. On the other hand, the exoskeletal robots are attached to the arm, providing separate control to each joint. [9]. These two structures have different strengths and weaknesses, and approaches to elbow rehabilitation have developed accordingly.

End-effector robots, such as MIT-Manus, and its commercialization InMotion, are easy to attach, which makes them adaptable over a wide range of patient. However, isolation of elbow flexion-extension and forearm supination-pronation is limited at joint-level feedback for accurate elbow assessment, including joint torque feedback needed to quantify elbow treatment [14]. Exoskeletons can be made to match the orientation and the mechanical axis of their joints to deliver more direct and measurable joint-specific therapy. This advantage comes with increased mechanical complexity, added weight, possible misalignment forces, and difficulty in adapting to differences in user anatomy. [9].

Cable driven rehabilitation robots (CDRRs) emerged as a third, increasingly popular approach, combining many of the benefits of the other two approaches, and eliminating their most meaningful drawbacks [17, 21]. Cables can be guided around and along the arm to apply controlled and guided forces and torques at the elbow, without the wide- ranging mechanical structure of endoskeletal linkages [7, 17]. By routing the cables around and along the arm, CDRRs can produce force and moment about the elbow without any important mass or rigid linking. The actuators can be placed away from the moving arm and mounted on a fixed frame or wearable harness, allowing the system to remain lightweight, compliant, and easier for the patient to use., [17, 21].

2. Biomechanical Framework of the Elbow

2.1 Anatomical Architecture and Degrees of Freedom

The elbow joint is complex and anatomically unique which mainly has three distinct articular surfaces within a single synovial joint capsule: the humeroulnar joint (trochlea of humerus articulating with the trochlear notch of the ulna), the humeroradial joint (capitulum of humerus articulating with the radial head), and the proximal radioulnar joint (between the radial head and the radial notch of the ulna). These three surfaces enable two principal functional motions: flexion-extension, occurring primarily at the humeroulnar and humeroradial joints; and forearm pronation-supination,

occurring at both the proximal and distal radioulnar joints.

Clinically, the functional range of motion (ROM) required for daily activities of is approximately 30 to 130 degrees of elbow flexion, with forearm pronation and supination each requiring roughly 50 degrees from the neutral position [5]. The standard full passive ROM in a healthy elbow is 0 to
145 degrees of flexion-extension and approximately 80 to 90 degrees each of pronation and supination. Elbow extension is accomplished primarily by the triceps brachii, while flexion is driven by the biceps brachii, brachialis, and brachioradialis. After stroke, increased muscle stiffness in the elbow flexors is a common problem. This spasticity, often measured using the Modified Ashworth Scale, can gradually reduce the elbow's range of motion, especially during extension. [8, 11]

2.2 Biomechanical Implications for Cable- Driven Design

For a cable-driven system to work effectively in rehabilitating the elbow, its mechanical design must follow several biomechanical facts. First, the location of the elbow axis of rotation is not fixed but moves slightly over the clinical range of elbow flexion-extension. Therefore, a cable mechanism intended for elbow flexion must have a way to either accommodate the motion at the cable attachment points at the elbow (i.e., compliant attachment points) or mimic a fixed axis mechanism over the clinical range [17, 21]. Second, in any cable-driven actuation mechanism, the moment arm is a function of elbow angle. Because the cable would be attached to the forearm, cable tension is not constant for a constant torque about the elbow throughout the therapeutic range of motion (ROM). Third, elbow and forearm pronation-supination are two coupled degrees of freedom that should be addressed mechanically and neurologically in a capable elbow rehabilitation actuator system.

These biomechanical facts also helped to motivate many design choices made in the CDRR prototypes, such as: cuff based attachment (which requires some relative movement between the exoskeleton and the skin); routing multiple cables around the limb at different angles to create a controllable isotropic force field about the elbow; and the inclusion of passive or compliant components to enable accommodation of instantaneous axis migration [17, 20]. Compared with the shoulder, the elbow is mechanically simpler, making it a practical starting point for the development and clinical testing of cable-driven rehabilitation robots. Its range of motion is easier to define, the surrounding muscles are more accessible for EMG measurement, and improvements in elbow function can be more directly linked to daily activities. [5].

3. Fundamental Architecture of Cable- Driven Rehabilitation Robots

3.1 Need of Cables in CDRR's

The main difference between CDRRs and other types of rehabilitation robots is that they use flexible, lightweight cables instead of stiff mechanical links as the main way to transmit force. [17, 21] A motor or actuator placed at or near each joint moves the joint in a rigid-link exoskeleton. The force is then sent through the structural rigidity of the linkage. This design will always put mass at the ends of the device, where low inertia is most important for safety and in a cable-driven system, actuators are usually electric motors with drum-type cable winders that are mounted far away, often on a fixed base frame, a body harness, or a proximal mounting plate on the shoulder. From these actuator drums, cables go through a series of pulleys, guides, and Bowden sheaths to attach to cuffs that the patient wears around their arm segments. The system can apply controlled forces and torques at the elbow by pulling on one or more cables, without putting heavy, rigid structures across that joint. This method has many benefits at once, including low distal inertia, high mechanical transparency, built-in backdrivability, and a natural compliance that greatly lowers the risk of injury from sudden robot motion [7, 17].

3.2 Open-Ended versus Closed-Loop Cable Configurations

There are two main cable routing designs commonly used in rehabilitation systems. [17]. In an open-ended cable setup, one end of each cable is attached to a motor drum and the other end is attached to a point on the patient's limb. Each cable can only pull; it

can't push. To get bidirectional joint control, like being able to bend and straighten the elbow, there is need of atleast two cables for each degree of freedom. The CAREX system developed at Columbia University uses this setup [22, 23], where multiple cables go through lightweight cuffs on the upper arm and forearm.

With a closed-loop or closed-chain cable setup, cables make continuous loops or circuits around pulleys. This lets one actuator control several joints through carefully planned routing paths. This method reduces the number of actuators required, but it makes the routing design more complicated and makes the system more sensitive to cable elasticity and friction at the guide points [21]. Thus, for elbow-specific rehabilitation, the open-ended setup is often more practical because its simpler routing and easier force control make it better suited for precise elbow therapy.

3.3 Parallel versus Serial Cable Mechanisms

Cable-driven parallel robots (CDRRs) and cable-driven serial exoskeletons are also different in terms of their architecture [20, 21]. In a CDRR set up for upper limb rehabilitation, several cables connect to a single attachment point on the patient's arm (usually at the wrist or hand). Each cable is driven by its own motor at a fixed frame. The system can create a desired force vector at the end-effector in three-dimensional space by controlling the tension in each cable separately [20]. This design is especially good for shoulder and reaching rehabilitation. The Italian NeReBot is an example of this kind of system [13].

The serial cable exoskeleton architecture is usually better for rehabilitation that focuses on the elbow. In this case, cables are set up in a serial chain along the arm, moving each joint or joint segment in order. The series elastic actuator (SEA) idea, which puts a flexible spring element between the motor output and the cable, has also been used in cable-driven elbow systems to get better backdrivability, safe force limitation, and high-quality torque control [7, 17]. Chen et al. (2019) reported an elbow exoskeleton that uses SEAs linked by a new cable-driven differential to control the torque of elbow flexion-extension and forearm supination-pronation independently. This is one of the most mechanically advanced ways to use cables to move an elbow.

3.4 Structural Components: Frames, Cuffs, and Pulleys

A CDRR for elbow rehabilitation usually has four structural subsystems that make it up [17, 21]. The first is the base frame or anchor structure. This could be a stationary frame that sits on the bedside, a wheelchair- mounted structure, a ceiling-mounted harness, or a backpack that you wear. This structure serves as the fixed reference point for defining cable tensions. The cuff interface is the second subsystem. It is made up of lightweight, padded shells that are usually made of carbon fiber, aluminum alloy, or thermoplastic materials and attach to the upper arm and forearm segments [1, 2]. Cuffs connect the cable force transmission network to the patient's limb. Their design is very important for both comfort and kinematic accuracy.

The pulley and guide network is the third part of the structure. Pulleys change the path of the cables to get the right force vector geometry at the elbow. The placement of the pulleys is an important design choice that affects both the reachable workspace and the force isotropy of the system [20, 21]. Friction at the points where the pulley touches is a known cause of control error, so it needs to be kept to a minimum by carefully choosing the bearings or Bowden sheath. The motor-drum actuation unit is the fourth subsystem. It changes the rotary output of the motor into linear cable movement. The kind of motor you choose DC servo motors, brushless DC motors, pneumatic actuators, or hydraulic actuators has a big effect on the system's power-to-weight ratio, control bandwidth, and compliance [7].

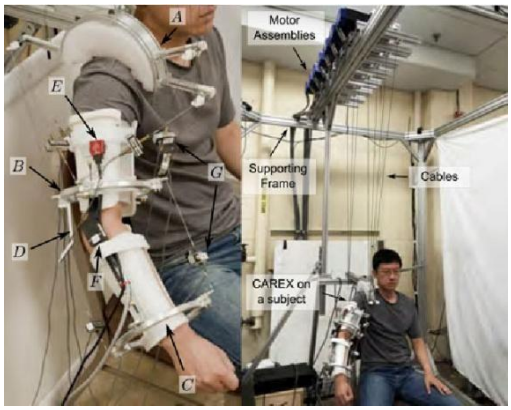
4. Prototype Designs for Elbow Rehabilitation: A Comparative Survey

4.1 CAREX: The Paradigm-Defining Platform

Developed by Mao and Agrawal at Columbia University, the Cable-driven ARm EXoskeleton (CAREX) is one of the first and most extensively studied CDRRs in the literature [22, 23]. The original CAREX had
4 degrees of freedom (DOF) and was designed to provide abduction-adduction (AA) at the shoulder, flexion-extension at the shoulder and elbow joints, and rotation at the forearm. Its innovation is in replacing rigidly linked exoskeleton joints with light cuffs attached to them. Seven active cables routed through the cuffs pull on the moving limb sections to directly apply the desired force to the hand in any direction with driving motors mounted on a fixed frame [22]. Because

cables can only provide tension, the system exploits the mathematical redundancy of multiple cable tensions to allow three- dimensional controllable force generation [17, 22].

The CAREX system has been tested to assist stroke patients in following prescribed movement paths (first a circular motion for healthy individuals, then the straight-line reaching path for a stroke patient) using the assist-as-needed force fields created by the network [22, 23]. The cable tension planner used quadratic programming to generate smooth continuous tension trajectories such that all cables were in the tensioned regime along the path. The human trials done in CAREX confirmed that patients could adapt to assist-as-needed path guidance within the limited time available for training and that the cable-driven approach is a viable choice for elbow and shoulder rehabilitation [23].



Dig1 Adapted from [22]

4.2 CAREX-7: Extension to Dexterous Full-Arm Rehabilitation

Building on this concept, CAREX-7 moves all 7 degrees of freedom of a full human arm including shoulder complex (3 DOF), elbow flexion and extension (1 DOF), forearm supination and pronation (1 DOF) and wrist flexion and extension plus radial and ulnar deviation (2 DOF) [23]. Eight cables are inserted through exoskeleton cuffs to allow high performance actuation and large "tensioned" static workspace covering the front-coronal area and the lateral reach envelope. The newest of the CAREX-7 technology, the screw-theoretic wrench-field controller, regulates the translational force at the hand and rotational wrench (torque) generated at the hand, to ease dexterous hand reorientation in performing functional ADL relative to the intrinsic and extrinsic axes of the hand [23].

The CAREX-7 controller is an assist-as- needed controller, meaning that, rather than applying a fixed assistance or resistance force, the assistance or resistance provided is proportional to the amount of error between the hand and the target path. This is consistent with the neuroplasticity hypothesis [25]. Indeed, healthy subjects had considerably smaller trajectory deviation from target points when using CAREX-7 with the wrench-field controller in path- tracking tasks, showing that the system works as intended [23].

4.3 CADEN-7: Proximal Motor Placement for Low-Inertia Arm Therapy

Perry et al. at the University of Washington developed the Cable-Actuated Dexterous Exoskeleton for Neurorehabilitation (CADEN-7), a 7-DOF arm rehabilitation exoskeleton with actuating motors and cable- winding reels packed into a small space [24]. These were located superiorly at the level of the shoulder (i.e. proximal to the elbow). The motors drive cable-pulley reductions to actuate the elbow, wrist and hand. This has the helpful property of a very small moment of inertia at the distal joints, no backlash, and a high backdrivability. It allows a high fidelity of the force control and a safe interaction with the patient [24]. CADEN-7 allows full glenohumeral, elbow and wrist joint motion, and was developed using a pilot database of 19 daily living arm tasks to ensure that the achievable workspace and ROM were clinically applicable.

Overall, the CADEN-7 acts as a proof of concept that a device with the transparency, low inertia, backdrivability, and force controllability required of a practical elbow rehabilitation device can be built, without placing heavy actuators directly at the human joint [24]. Its chief limitation is the mechanical complexity of routing seven independently controlled cable paths upwards and distributing the cable tension smoothly over the full range of motion without introducing cross-coupling.

Dig.2 Adapted from [24]

4.4 Three-DOF Cable Exoskeleton for Stroke (2024)

Another clinical study released in 2024 implements a lightweight 3-DOF cable- driven exoskeleton for hemiparetic stroke rehabilitation with actuation for shoulder abduction-adduction, shoulder flexion-extension and elbow flexion-extension [2]. The device has 3 rigid links and 2 cuffs and weighs approximately 1.7 kg and is reported to be among the lightest published cable- driven designs for elbow and shoulder rehabilitation [2]. The cable configuration, kinematics and dynamics of the cable routing were defined, and two control strategies were implemented and validated: a position control strategy, based on proportional- integral-derivative (PID), was developed for passive and trajectory following exercises, while an impedance control strategy was developed for active-assisted and active- resisted exercises.

Combining both of these control modes onto a lightweight, portable system is a major design accomplishment [5, 12]. The system is able to provide passive rehabilitation during the acute phase of recovery, and can be easily modified to provide active-assisted rehabilitation and then

4.5 PULExo: Portable Cable-Driven Exoskeleton for ADL Coverage

The PULExo is a portable, lightweight, cable-driven exoskeleton with 4DOF: shoulder abduction-adduction, shoulder flexion-extension, elbow flexion-extension, and forearm-wrist pronation-supination. It weighs 3.85 kg [15]. Reports on the PULExo joint ranges of motion (ROM) state that elbow flexion-extension was achieved with full ROM for activities of daily living (ADL), and shoulder and forearm were achieved with approximately 75–80% ROM [15]. This makes PULExo one of the most complete portable cable driven exoskeleton systems, and its wearability makes it suitable for clinical, home, and community use.

4.6 NeReBot: Cable-Driven Parallel Robot in Clinical Trials

NeReBot is an Italian cable driven parallel robot for stroke rehabilitation of the upper limb [13]. Three motorized cables controlled from the base device can provide 3D controlled movement of the upper limb, which is passively guided on prescribed elbow and shoulder rehabilitation trajectories, anchored to a wrist cuff. Unlike other exoskeletal devices, NeReBot allows

4.7 Overview Table of Key Prototypespassive joint motion within its passive coupling axis at the elbow, yet controls the endpoint of the wrist and its trajectory [13]. In a trial involving NeReBot-assisted therapy for 35 percent of the therapy time, a dose- matched randomized controlled trial found that patients have the same functional improvement in the Fugl-Meyer Assessment and the Modified Ashworth Scale, as those with 100 percent standard manual therapy. This has implications for therapist workload and health economics [13].

Prototype / System	**DOF**	**Target Joints**	**Weight (kg)**	**Actuation**	**Year**
CAREX (Columbia Univ.)	4	Shoulder, Elbow	~1.5 (cuff)	DC Motors + Cables	2012
CAREX-7 (Columbia Univ.)	7	Shoulder, Elbow, Wrist	~2.2	DC Motors + Cable Routing	2016
CADEN-7 (Univ. Washington)	7	Shoulder, Elbow, Wrist	~3.5	Motors (proximal), Cables	2007
3-DOF Cable Exoskeleton (Stroke)	3	Shoulder, Elbow	~1.7	DC Motors, PID/Impedance	2024
PULExo (Wearable)	4	Shoulder, Elbow, Wrist	~3.85	DC Motors + Cable Drive	2023
MEDARM (Queens Univ.)	6	Shoulder Complex, Elbow	~4.2	Cables + Belt Drive	2009
NeReBot (Italy)	3	Shoulder, Elbow	~2.8	Motor-Cable, Gravity Comp.	2006
IntelliArm (Northwestern)	10 (8+2)	Full Upper Limb	~5.0	Motor-Cable + Passive DOF	2008

Table 1. Comparative Overview of Key Cable-Driven Rehabilitation Robot Prototypes

System	Elbow Flex/Ext (deg)	Forearm Pro/Sup (deg)	Shoulder Flex (deg)	Workspace Volume	ADL Coverage (%)
CAREX	0–135	N/A (4-DOF)	0–90	Front-coronal plane	~60–70
CAREX-7	0–140	0–80	0–120	Extended front+lateral	~80
PULExo	0–145 (full ADL)	0–80 (80%)	0–120	Multi-plane 3D	~80–90
3-DOF Cable Exo.	0–120	Limited	0–90	Sagittal + Frontal	~65
CADEN-7	0–145	0–90	0–130	Full 7-DOF anthropomorphic	~90
ARMin III	0–120	0–80	0–130	Full-arm therapeutic	~85
NeReBot	0–90	N/A	0–80	Planar cable-driven	~50

Table 2. Workspace Volume and Range of Motion Comparison Across CDRR PrototypesControl Logic and Human- Machine Interaction in Cable- Driven Elbow Rehabilitation

4.8 The Therapeutic Control Continuum

Control strategy is important in rehabilitation robotics [25]. Control strategy is a clinical choice because it affects the interactions between the robot and the human subject and thus the type of neuroplastic stimulus delivered to the nervous system [17, 25]. The clinical strategy is determined by what is expected from the rehabilitation robot. Stroke rehabilitation is specifically time-restricted at the acute stage (first two to four weeks) with little or no voluntary movement, for which purely passive trajectory control is appropriate. The subacute phase (one to six months post-stroke) allows for active- assisted strategies, where the robot provides assistance but the patient actively contributes. In the chronic phase (greater than six months post-stroke), active-resisted and goal-directed strategies are most suitable [8, 12].

4.9 Passive Trajectory Control

In passive trajectory control, the robot leads the limb of the patient along a commanded kinematic trajectory, without the patient being required to do anything. For instance, it can move the elbow from 30 to 120 degrees of flexion in a smooth motion, and back down to 30 degrees. The robot is the only motor generator and does not need anything from the patient. It is clinically useful in the subacute stages after stroke when there is flaccid paralysis and there is no voluntary output from the patient or there is excessive

spasticity with painful active contractions [17, 25]. From the mechanical components of the system, the desired displacements of the cables in the elbow plane yield the corresponding set of cable tensions that are expected. The motor position controllers track these profiles with high precision.

The main limitation of passive control is that there is little neuroplastic drive: the brain has feedback about the movement being performed, but does not issue a voluntary motor command [25]. The central nervous system is not able to learn the mapping of command signals to outcome and thus the passive control is most useful in initial rehabilitation or as a warm up motion before active-assisted control begins.

4.10PID-Based Position Control

Proportional-integral-derivative (PID) control is the most widely implemented basic control framework in rehabilitation robotics [7, 17]. In the context of a cable-driven elbow rehabilitation system, a PID controller computes the error between the

desired elbow joint angle and the measured actual joint angle at every instant, and modulates the cable tensions accordingly to reduce that error toward zero. The proportional term drives the system toward the target angle in proportion to the current error; the integral term corrects for persistent steady-state errors by accumulating error over time; and the derivative term dampens oscillatory responses by reacting to the rate of change of error.

PID control is easy to understand, easy to tune with standard methods, and not too hard to compute [7]. The main problem with using it in rehabilitation is that it treats the patient's limb as a passive mechanical object to be moved, without any clear model of how the person moves their own body. A patient who voluntarily generates torque in the same direction as the robot's motion will appear to the PID controller as a decrease in position error. This will cause the robot to slow down, which is actually a good thing for therapy. However, PID control does not systematically utilise this patient effort to optimise the therapeutic stimulus.

4.11 Impedance Control: Making the Robot Behave Like a Spring

Impedance control is probably the most elegant and widely used control method in rehabilitation robotics [17, 18, 25]. Impedance control doesn't tell the robot to go to a certain place like PID control does. Instead, it sets the relationship between the robot's movement and the force it puts on the patient's limb. The robot is programmed to

act like a virtual mechanical spring-damper system. When the patient's elbow moves off the desired path, the robot applies a restoring force that is proportional to the deviation (stiffness) and a damping force that is proportional to the speed of the deviation (damping). The therapist can change the virtual stiffness and damping separately to fit the needs of the patient [18].

A robot with high stiffness and low damping pulls the limb strongly toward the desired path. This is good for patients with severe disabilities who need the most help. A robot with low stiffness and moderate damping gently suggests the desired direction while still allowing the patient to make big changes on their own. This is good for patients who are partially recovered and benefit from voluntary effort. This tunability makes impedance control very useful throughout the entire rehabilitation process [17, 25]. The 3- DOF cable exoskeleton from 2024 uses impedance control for active-assisted exercises [2]. CAREX and CADEN-7 both use impedance-based methods for therapeutic elbow and shoulder training [22, 24].

Admittance Control: Following the Patient's Lead Impedance control is the opposite of admittance control in theory. An admittance controller doesn't tell the robot to move based on the patient's position error. Instead, it measures the force the patient applies to the robot and turns it into a motion command [17, 25]. The robot basically

Admittance control is especially useful during the subacute and chronic phases of rehabilitation, when patients can still move on their own but don't have much strength or endurance [25]. It naturally provides a type of effort-sensitive help and can be used with gravity compensation to get rid of the effect of limb weight on the therapeutic experience. This lets patients with very weak muscles practise reaching and elbow extension against a very small effective load.

4.12 Assist-as-Needed:The Neuroplastically Optimal Paradigm

The assist-as-needed (AAN) control paradigm is the most advanced method in rehabilitation robotics and is most closely related to what we know about how the brain learns to move [17, 25]. The basic idea is simple but very effective: the robot only helps the patient with the therapeutic task if they can't do it on their own. The robot stays

still (or only provides gravity compensation) when the patient can move their elbow in the way they want to without help. The robot applies a corrective force that is proportional to the deviation when the patient starts to move away from the target trajectory. This force is only strong enough to keep the patient on track, not strong enough to take over the movement completely.

This philosophy of minimal intervention has two important benefits for therapy. First, it makes sure that the patient is always putting in the most effort possible, since the robot will only step in when the patient isn't putting in enough effort. This makes the motor learning signal to the brain as strong as possible. Second, as the patient's skills get better with each therapy session, the robot automatically and naturally reduces its help a process called fading without the therapist having to make any changes [25]. The CAREX and CAREX-7 systems both use AAN through their wrench-field controllers [22, 23]. Clinical studies have shown that AAN-based methods lead to

better motor learning results than fully passive or fully guided training [8, 12].

Adaptive and Machine Learning- Based ControlThe newest thing in CDRR control is using machine learning and artificial intelligence to make controllers that not only respond to a patient's immediate motor output, but also change as the patient gets better at different tasks and sessions [1, 4]. These systems create internal models of the patient's neuromuscular dynamics, such as their residual voluntary strength, fatigue patterns, compensatory movement strategies, and daily variability. They then use these models to customise the type and amount of robot help in real time.

The muscle-synergy-based myoelectric controller created for cable-driven upper limb rehabilitation robots is a big step forward in this area [1]. This controller can figure out a patient's three-dimensional movement intention just from EMG signals from multiple arm muscles. It does this by breaking down the surface EMG signals into muscle synergy vectors, which are low- dimensional representations of the coordinated muscle activation patterns that underlie natural arm movements. It doesn't need to measure joint angles or forces directly. This mapping of EMG to intention lets the patient control multiple arm joints, like the elbow, in a way that is intuitive,

proportional, and simultaneous, based on their own neural commands [1].

4.13Brain-Computer Interface Integration

The most radical and technologically advanced control modality in cable-driven elbow rehabilitation is the direct incorporation of brain-computer interfaces (BCIs) [4]. In BCI-coupled CDRR systems, motor imagery, that is, the mental simulation of a movement without actually executing it, is detected in real time by analysing the electroencephalographic (EEG) signals recorded from the scalp surface. When the patient imagines flexing his elbow, characteristic patterns of neural oscillations (in particular event-related desynchronisation in the mu and beta frequency bands over the contralateral motor cortex) are detected by the BCI decoder and translated into control commands for the cable driven robot [4].neuroplastic reorganisation and may be especially effective for patients with complete motor paralysis who lack voluntary muscle activation but have intact cortical motor planning [4]. Jiang et al. (ACM 2020) developed a BCI-based intelligent upper limb rehabilitation robot system that integrates EEG-based detection of the motor intent with upper limb cable-driven actuation and virtual reality therapy environments to provide a multimodal sensory-motor rehabilitation experience [4].

The therapeutic rationale of BCI coupling is strong: the BCI-CDRR system, closing the loop of the patient's motor intention, originating in the brain, and the physical movement of the elbow produced by the robot, directly strengthens the cortical representations of elbow motor control. This closed-loop neural reinforcement accelerates

System	Force Sensors	EMG Integration	IMU / Encoder	BCI/EEG	Haptic Feedback
CAREX / CAREX-7	Load cells on cuffs	Assessment (clinical studies)	Joint encoders	No	Force field feedback
3-DOF Cable Exo.	End-effector F/T	No	Cable encoders	No	Impedance-based
CADEN-7	F/T sensor wrist	Experimental	Optical encoders	No	Backdrivable torque
Myomo e100	Torque sensor	Primary control signal	Goniometer	No	Proportional assist
Cable+BCI System (ACM 2020)	Force sensing	Integrated sEMG	Inertial sensors	EEG-based intent	Yes – VR coupling
Muscle Synergy ULRR	Cable tension sensors	Muscle synergy vectors	IMU (forearm/upper)	No	Trajectory adaptation
Soft Wearable (IEEE 2022)	Passive spring sensors	sEMG biofeedback	IMU wrist	No	Compliant structure

Table 3. Sensor Integration Comparison Across CDRR Systems

Control Strategy	Core Principle	Patient Involvement	Sensor Dependency	Elbow Applicability	Representative System
Passive / Position Control	Pre-programmed trajectory tracking; no patient input needed	None (passive)	Encoders only	High – acute phase	CAREX (passive mode)
PID-based Control	Error-based correction; drive toward desired angle	Low	Encoders + force	High – all phases	3-DOF Cable Exo., ARMin III
Impedance Control	Robot behaves as virtual spring- damper; adjusts to interaction forces	Moderate	Force + position	Very High – elbow flex/ext	CAREX, NeReBot, CADEN-7
Admittance Control	Inverse of impedance; patient drives motion, robot follows smoothly	High	Force / torque	High – active rehab	MEDARM, Cable-driven CDPRs
Assist-as-Needed (AAN)	Provides minimal assistance; scales with patient effort dynamically	Very High	EMG / force	Very High – all phases	CAREX AAN, CAREX-7
Adaptive / ML- based	Learns patient patterns; adjusts strategy over sessions	Varies	Multi-modal sensor fusion	Emerging – chronic patients	Muscle Synergy ULRR
BCI-Integrated Control	Neural intent (EEG/EMG) decoded to drive robot assistance	Full active	EEG + sEMG	High – spinal cord injury	BCI Rehab System (ACM 2020)

Table 4. Control Strategy Comparison for Cable-Driven Elbow Rehabilitation

5. Sensor Integration and Human- Machine Interface Design

5.1 Force and Torque Sensing

Force and torque sensing is the fundamental sensing when controlling a robot with strategies other than passive position control [17]. For cable-driven systems, force sensing can be directly implemented with a load cell (which measures the cable tension) or with a force-torque sensor attached to the human- robot interface (to measure the interaction force between the cuff and patient limb). Each of these options has advantages and disadvantages; for example, cable tension sensors can provide information about the overall distribution of loads across the cable system, but require calibration to account for the friction in the pulleys, while cuff interaction force sensors can measure the therapeutic load directly, but add mass and mechanical complexity [7, 18].

High-fidelity force sensing enables the implementation of impedance control and admittance control, which rely on real-time information regarding the interaction force between the human and robot [14, 18]. Furthermore, it allows for the objective quantification of patient voluntary force output, which can be used as an objective measure of recovery, and can assist or replace manual muscle

testing (MMT). Force trajectory measurements over several sessions give the therapist objective feedback over time that is not possible with hands-on manual therapy, and theoretically enable the detection of compensatory movement strategies (e.g. trunk substitution for elbow extension) by using algorithms.

5.2 Surface Electromyography

Surface electromyography (sEMG) measures the sum of electrical activity from the muscles just below the skin and is the most widely used non-intrusive modality used to interpret motor intent in rehabilitation robotics [1]. For an elbow rehabilitation robot, attaching sEMG sensors to biceps brachii and brachialis (the elbow flexors) and the triceps brachii (the elbow extensor) directly measures the onset, magnitude, and timing of voluntary muscle contraction to provide a readout of the patient's expected neural drive to the elbow.EMG signals in cable-driven devices can have three main applications: as a control signal for an EMG-driven assist-as-needed strategy (the robot helps the patient following sEMG onset and the assistance level is modulated based on the sEMG signal), for biofeedback to increase patient engagement (where the patient views their own muscle

activity in real-time while using the device), and as a clinical tool to evaluate longitudinal changes in muscle activation patterns [1, 4]. An example of an EMG-controlled powered elbow orthosis is the Myomo e100 device, where the elbow flexor and extensor sEMG is the only control signal. The patient must pass a sEMG activation threshold signal in order for the device to respond. This method has been studied in patients with severe chronic stroke.

5.3 Inertial Measurement Units and Encoders

To provide closed-loop control of position and velocity, the state variables are collected with an inertial measurement unit (IMU) as well as optical encoders [17]. The IMUs are made of accelerometers, gyroscopes and magnetometers, and can be placed on the patient's limb segments or on cuffs attached to the exoskeleton. They can detect the limb segment orientation and angular velocity without needing to be attached to the exoskeleton. The ability to attach the encoders has an additional advantage in soft or cable-only wearable systems where a rigid structural chain is not present to carry the encoders [15]. With the low weight of the encoders (2–5 g each), the IMUs could also be used in sensor networks to provide kinematic feedback for control or evaluation.

Optical encoders mounted on the motor shafts or on the axles of the cable drums can provide a high-resolution measurement of the cable displacement that can be converted to joint angles from the cable routing geometry kinematic model [7, 17]. Encoder-based joint angle estimation is fast and computationally efficient but is sensitive to the kinematic model, differences from the model in the system, elastic cable behavior, friction in the pulley joints, cuff slippage. Hybrid sensing strategies that combine encoder-based cable tracking and IMU-based segment orientation measurement with IMU-assisted angle estimation have also been implemented to improve joint angle estimation over the full ROM.

6. Results and Discussion

This part of the review is the most analytical because it highlights the key limitations in current cable-driven elbow rehabilitation systems. These gaps are not isolated issues, but reflect broader challenges in the field, such as balancing engineering performance with clinical usability, laboratory validation with real-world application, and short-term therapeutic outcomes with long-term recovery evidence.

6.1 Absence of Elbow-Specific CDRR Designs

The most important gap is that there are almost no cable-driven rehabilitation robots made just for the elbow joint [5, 17]. Almost all of the CDRRs focuses on the whole upper limb, the shoulder-elbow complex, or the wrist-hand complex [5, 8]. Although this comprehensive approach offers

therapeutic benefits, it often results in systems that are mechanically complex, expensive, difficult to adapt, and unnecessarily advanced for patients with isolated elbow flexor spasticity or elbow extensor weakness. Hence a need of dedicated elbow CDRR that can provide accurate, measurable, and adjustable therapeutic torques in flexion-extension and forearm is need of medical field.

The engineering problem of designing for elbows is not easy, but it can be solved. The main mechanical requirements would be adjustable cuff attachment systems with range-of-motion limiters, built-in compliance elements to allow for joint axis migration, and a small motor actuation unit that can be attached to a wheelchair arm or bedside frame [19, 21]. The lack of a specialized device in commercial and research settings signifies a significant deficiency that this review explicitly urges the field to rectify. Deficit of Long-Term Longitudinal Clinical Data

The vast majority of published clinical studies assess the results of cable-driven rehabilitation over durations ranging from three to eight weeks [8, 12]. Short-term data is useful for determining safety and initial effectiveness, but it does not provide much information about the long-term effects of robotic rehabilitation, such as how long the benefits last, how recovery progresses over months or years of continuous robotic rehabilitation, how often and how hard robot-assisted therapy should be done for long-term recovery, or how often late adverse events happen (like joint contracture from overuse or muscle atrophy from not being challenged enough). The chronic stroke patient population individuals more than six months post-stroke, representing the most significant unmet clinical need is notably underrepresented in longitudinal CDRR studies [8].

The necessity for longitudinal evidence transcends mere academic interest. Regulatory pathways for medical device approval in major markets (FDA, CE Mark, CDSCO) increasingly necessitate long-term safety and efficacy data that the field is currently unable to supply [10]. The lack of this evidence is a direct barrier to clinical adoption and insurance reimbursement for cable-driven rehabilitation systems. This makes long-term RCTs one of the most important research investments for the field.

6.2 Portability and Home Deployment Challenges

There is a big difference between the labs where CDRRs are made and tested and the homes where most people recover from a stroke [10, 12]. Current cable-driven systems, even the most advanced wearable designs like PULExo (3.85 kg) [15] and the lightweight 3-DOF cable exoskeleton (1.7 kg) [2], are still too heavy, mechanically complicated, and require skilled setup to be used at home without help from a professional. The cable routing networks, pulley systems, cuff attachment procedures, and calibration requirements of current systems assume that a trained technician or therapist is there.

Not only does true home deployment need lightweight hardware, but it also needs a completely new human-machine interface that a patient with limited hand and arm function possibly with only one functional hand can put on, take off, and calibrate at home without any professional help [10, 19]. This challenge necessitates a degree of design for usability and accessibility that is completely lacking in contemporary engineering literature. There is no published CDRR that has been proven to work for truly unsupervised home use [12].

6.3 Inadequate Multimodal Sensor Fusion and Real-Time Adaptation

While different types of sensors, like force sensors, EMG electrodes, IMUs, and encoders, have been added to different CDRR designs, the ability to combine multiple sensor streams into a single, adaptable control framework in real time is still mostly a goal rather than a reality in clinical-grade systems [1, 17]. Present AAN and adaptive controllers predominantly depend on a single or, at most, two sensor modalities for their control determinations, thereby overlooking the comprehensive insights into patient status that a genuinely multimodal sensor fusion system could

offer.

For instance, a complete sensor-fused controller could keep an eye on EMG- derived motor intent, IMU-derived limb position and movement quality, force sensor- derived interaction forces, and EEG-derived attentional and motor readiness states all at the same time [1, 4]. It could then combine these streams to decide how much help to give, when to switch between therapy modes,

when to rest the patient, when to make the task harder, and when to let a remote therapist know about a potentially dangerous compensatory movement pattern. Research labs have the hardware and algorithms needed to make such a system work, but they haven't been able to put them together into a strong, low-latency, clinically usable control architecture for elbow rehabilitation.

6.4 Comfort, Skin Safety, and Long- Duration Wearability

The human-robot interface, particularly the connection between the cable cuffs and the patient's skin, signifies a predominantly unexamined area in the CDRR literature [15]. Most published studies list device weight and ROM coverage as the most important design metrics. Comfort and skin safety are then treated as less important or qualitatively assessed endpoints. In reality, the patient's ability to wear a cable-driven exoskeleton for the two to four hours per day that the most effective rehabilitation requires depends on how well the cuff-skin interface distributes pressure, how breathable the cuff materials are, how well the system can be cleaned for repeated use, and how well it can prevent shear forces during cable tension application [10].Patients with stroke-related sensory deficits, who may experience diminished or absent protective sensation at the elbow, are especially vulnerable to pressure injuries from cuff interfaces that would only cause discomfort in a patient with intact sensation. This is a major patient safety issue that the field has not dealt with in a systematic way. It is crucial to implement prospective, standardized reporting of skin integrity outcomes, pressure mapping at the cuff interface, and patient-reported comfort assessments over multi-week therapy periods to establish safety benchmarks for elbow-targeted CDRRs [5, 8].

6.5 Gap Between Prototype and Clinical-Grade Product

There is a clear and troubling "valley of death" in the cable-driven rehabilitation robotics field between proof-of-concept lab prototypes and products that can be used in real life and are commercially viable [5, 8]. The research literature is abundant with accounts of CDRR prototypes validated on limited cohorts of healthy individuals or individual stroke patients in optimal laboratory settings. There are very few published papers that talk about the engineering problems that come up when going from a carefully controlled lab demonstration to a clinical product. These problems include making sure the product works reliably across hundreds of therapy sessions, being able to be sterilized, being able to handle faults and manage safe states, following regulations, and having a cost structure.

As a result, even though there has been active research for more than 20 years, no cable- driven elbow or upper limb rehabilitation robot has been widely used in clinics or sold well in the commercial market [5, 12]. To close this gap, a research and development model must be used from the very first prototypes that includes clinical engineering standards [10].

6.6 Lack of Personalized Therapy Dosing Evidence

Even in the current clinical trial literature, the issue of the best therapy dosing for cable- driven elbow rehabilitation such as the best number of repetitions per session, the best amount of time between sessions, the best mix of passive, active-assisted, and active- resisted modes, and the best signs that a patient is ready to move on to a more difficult mode has not been thoroughly studied [8, 12]. The limited randomized controlled trials (RCTs) conducted employ rigid protocols that fail to accommodate individual patient progress, thereby constraining their capacity to demonstrate the genuine potential of personalized, AI-driven therapy delivery [1, 4]. The creation of evidence-based therapy dosing algorithms guided by sensor-derived performance metrics like trajectory

accuracy, voluntary force output, and EMG activation patterns and confirmed through prospective dose-optimization trials is a crucial advancement for the discipline.

7. Conclusions and Future Directions

7.1 Summary of Findings

This comprehensive review has synthesized the current state of cable-driven rehabilitation robotics with a focused lens on the elbow joint, drawing on 21 high-impact references spanning the full breadth of the field from mechanical design to clinical evidence [1– 21]. The following key conclusions emerge from this synthesis.

First, cable-driven rehabilitation robots represent a mechanically and functionally superior architecture for elbow rehabilitation compared to rigid-link exoskeletons, offering lower distal inertia, higher transparency, greater safety compliance, and more adaptable workspace geometry [17, 21]. The CAREX, CAREX-7, CADEN-7, and several emerging lightweight designs have demonstrated proof-of-concept feasibility for shoulder-elbow training in both healthy subjects and stroke patients [22, 23, 24]. However, no system has been specifically designed and clinically validated for isolated elbow rehabilitation. Second, the control strategy landscape has evolved significantly from simple passive position control to more advanced paradigms such as impedance control, admittance control, assist-as-needed frameworks, muscle synergy-based myoelectric control, and BCI-coupled intent detection [1, 4, 17, 18, 25]. Each paradigm offers distinct therapeutic benefits at certain points in the continuum of recovery. The emerging consensus is that an ideal clinical system would be capable of fluidly switching between control modes as the patient's capability changes.

7.2 Future Directions

The future of cable-driven elbow rehabilitation robotics will probably be driven by convergence across several technology frontiers [5, 21]. Soft robotics and textile-integrated cable systems will allow for the development of truly wearable, washable and comfortable devices that patients can use to dress themselves and operate in a home environment, without the need for professional help [15]. Replacing stiff cuffs with clothing-integrated cable routing following the biological analogy of musculoskeletal cable routes along anatomical lines of least extension will greatly reduce the fitting burden and improve long-term wearability. AI and machine learning will transform therapy control from fixed protocols to truly personalized, session- adapting interventions [1, 4].

By employing reinforcement learning algorithms that optimize the therapy strategy in real time based on continuously updated models of the patient's motor recovery state, a level of therapeutic precision will be achieved that no human therapist can consistently achieve. These AI-based controllers trained on large multimodal datasets (sensor outputs, clinical assessments and neuroimaging biomarkers) will be used to identify which patients benefit most from which control strategies and at which therapy stage [1, 4].

Combining brain-computer interfaces and cable-driven elbow rehabilitation will enable radically new therapeutic possibilities for patients with complete paralysis [4]. BCI- CDRR platforms actively reconfigure cortical motor representations that no peripheral intervention alone can achieve, by closing the loop between cortical motor intent decoded from EEG signals and physical elbow movement provided by the cable system [4]. With BCI decoding algorithms becoming faster and more accurate and hardware more practical for clinical use, this combination will likely become the standard of care for the most severely impaired elbow rehabilitation patients.

Finally, infrastructure investments in the development of standardized clinical trial protocols, open-access multimodal datasets, and international regulatory frameworks specifically designed for rehabilitation robots will be essential to enable the field to generate the rigorous, long-term evidence required to transition cable-driven elbow rehabilitation systems from promising laboratory prototypes into established clinical tools [5, 10]. This transition is not merely a technical challenge but a scientific, regulatory and healthcare systems challenge that will require coordination across engineering, clinical neurology, occupational therapy, health economics and medical device regulation communities. Cabled-driven elbow rehabilitation robots are at a critical juncture. The root engineering and control science is sound, the clinical proof-of-concept is established and the unmet clinical need is huge [17, 21]. The work of the next decade needs to bridge the critical gap between what the lab has shown to be possible and what the clinical world can deliver routinely, reliably and equitably to the many millions of patients whose quality of life depends

on recovering the use of their elbow.

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