Journal of Robotics Research (JRR)
Volume 2, Issue 2, Date: 31 - December - 2025
ISSN: 2978-4344, DOI: 10.64820/AEPJRR.22.17.29.122025

Power Augmentation and/or Rehabilitation for Human Upper Limb: A Review

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***Abstract*—Upper-limb exoskeletons are increasingly developed for rehabilitation and power augmentation, fucusing on important joints like the shoulder, elbow, and hand. To guarantee safe assistance, their design must comply with anatomical and biomechanical specifications. The three types of existing systems are soft pneumatic, hybrid, and rigid. While soft pneumatic solutions offer comfort and compliance with force output and control limitations, rigid systems offer precision and torque but are still large and misaligned. These trade-offs are intended to be balanced by hybrid systems. New developments in bidirectional actuation, smart sensing, and portable pneumatic sources have facilitated a move towards soft pneumatic actuators.**

Keywords— Upper-limb exoskeletons, rehabilitation, power augmentation, soft robotics, pneumatic actuators.

I. INTRODUCTION

The human upper limb is a highly complex kinematic chain that is necessary for a variety of sensory and motor activities that allow us to interact with our environment. It is made up of the upper arm and forearm segments, as well as the shoulder, elbow, and wrist joints, which together form the intricate hand architecture. The upper limb's coordinated movements depend on the complex interplay between its neurological and musculoskeletal systems. Wide range of motion made possible by this intricate design makes it possible to perform daily tasks requiring strength, dexterity, and flexibility, like firm grasping and delicate manipulation. Understanding the specific anatomical features of the hand, palm, elbow, and shoulder is essential, particularly in fields like rehabilitation where upper limb functionality is greatly impacted by disabilities brought on by illnesses like stroke. In order to restore functioning and improve quality of life, assistive and rehabilitative exoskeleton design primarily depends on mimicking natural movements and taking into account the complex biomechanics of joints. The human hand is extremely adaptable and necessary for daily tasks. Its numerous muscles and approximately 29 bones allow for complex movements [61]. Five fingers make up each hand, and each finger has multiple joints, including the proximal interphalangeal (PIP), distal interphalangeal (DIP), and metacarpophalangeal (MCP) joints. . The thumb is special because it has interphalangeal (IP), metacarpophalangeal (MCP), and carpometacarpal (CMC) joints. A significant number of degrees of freedom (DoF) are provided by this complex structure for a variety of tasks, including as manipulation and grasping (such as accurate, spherical, or cylindrical grasps). Motions such as flexion, extension, abduction, and adduction are essential [59].

The humerus, ulna, and radius articulate to form the complex hinge joint known as the elbow joint. The main functions include forearm flexion and extension, which are controlled by muscles such as the triceps brachii and biceps . Through the proximal radioulnar joint, the elbow makes pronation and supination motions easier . One important characteristic is that the elbow's axis of rotation is not fixed; rather, it can translate while in motion, which is essential for rehabilitation exoskeletons' ergonomic design in order to provide comfortable human-robot interaction [1][2].

It is widely accepted that the human shoulder has the greatest range of motion (ROM). Three bones the clavicle, scapula, and humerus as well as four distinct joints the glenohumeral (GH), acromioclavicular (AC), sternoclavicular (SC), and scapulothoracic (ST) joints make up the complex anatomy [5][8]. Flexion/extension, abduction/adduction, and medial/lateral rotation of the humerus are the three degrees of freedom for movement offered by the glenohumeral joint, a ball-and-socket joint. As seen in figure (2-1), the shoulder complex's substantial mobility is made possible by its variable instantaneous center of rotation (ICR), which varies with the movement of the upper limbs and shoulder complex [3].

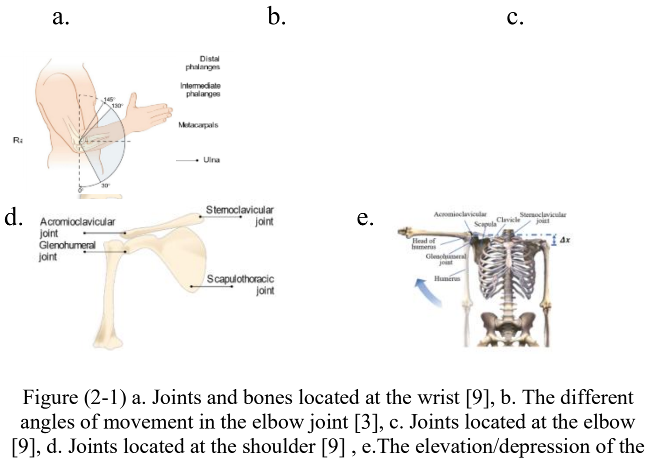

Figure (2-1) a. Joints and bones located at the wrist [9], b. The different angles of movement in the elbow joint [3], c. Joints located at the elbow [9], d. Joints located at the shoulder [9] , e.The elevation/depression of the

Received: 14-10-2025
Revised: 3-12-2025
Published: 31-12-2025

humeral head (the center of rotation) of the shoulder complex in abduction/adduction movement [8].

Exoskeletons, thus, delivering rigorous, repetitive, and reliable rehabilitation treatment important for enhancing motor recovery and plasticity [59], and giving workers with the assistive torque they need for high-intensity or overhead operations in order to reduce muscle strain and lessen fatigue. For patients to recover their freedom and for the working population's physical health to be protected, this technology must be successful [60].

II. Robotic Hand Exoskeletons in Rehabilitation and Assistive Technologies

The human hands are complex and essential for daily activities, with individuals performing over 1,500 grasps each day Stroke, spinal cord injury, multiple sclerosis, arthritis, and traumatic brain injury are all conditions that can make it hard to use your hands, which can greatly limit your independence and quality of life. Stroke is a major cause of disability around the world, and one of its most common effects is hand dysfunction.

Traditional therapy relies on repetitive exercises to restore finger movement; however, it is resource-intensive, time-consuming, and heavily dependent on therapists [13]. To solve these problems, robotic hand exoskeletons have been made to provide automated, intensive, and personalized rehabilitation [14]. These devices help with motor rehabilitation, encourage the use of damaged limbs, and help with everyday tasks outside of medical settings [12][16].

A. *Rigid Hand Exoskeletons*

The CyberGrasp, a well-known haptic glove that is not sold commercially, is a good example of a rigid device. It gives active force feedback in one direction to each finger (except the little finger). Even though it can control torque and position with high precision, it is described as big, heavy, and expensive, so it is mostly used in medical settings. The whole system, including the glove skeleton, weighed 640g, and the weight was mostly on the fingers, which could make it uncomfortable to wear for a long time. Hand of Hope This system uses straight-line motors and stiff parts to help people. It weighs about 700g (the part you wear; the total weight isn't given) and can squeeze with a force of 12 N. It helps all five fingers, lets the wrist move freely, and can push and pull . But a big problem is that its stiff parts and connections must line up exactly with the person's finger joints, which can make it bigger and not fit as well [12].

HEXORR (Hand EXOskeleton Rehabilitation Robot) was made and tested as a hand exoskeleton for rehab and is listed as an example of a device that helps the upper arm. The sources don't give many details about its exact stiff design and what it adds, other than saying it's a hand exoskeleton [15], as shown in Figure (2-2).

Figure (2-2) One subject wearing the hand exoskeleton [15].

Intelligent Haptic Robot-Glove (IHRG), a special covering, carefully gives help to the human hand. Made to help those getting better from a cerebrovascular accident patient rehabilitation, it helps with grabbing things well. This glove, which uses robots and has five fingers, uses the natural mechanical compliance of human fingers. Its parts let it motion across various planes, which helps with pinching and opening and closing the hand. Everything is driven by a carefully thought out and precisely designed operating system. [17],as shown in Figure (2-3).

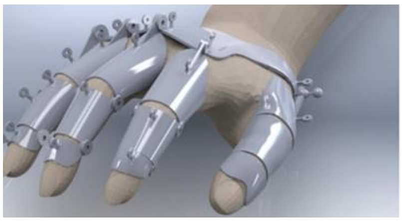

Figure (2-3) Intelligent Haptic Robot-Glove (IHRG) [17].

Iqbal et al. (2015/2016) This research looked at robotic hand exoskeleton systems that don't need to be controlled for every movement and can fit different hand sizes. While they tried to be adaptable, these early designs still often used stiff connections to move forces, which could make it hard to stay comfortable and avoid being misaligned [18][16]. Wearable Robotic Glove (Surface-Mounted Actuators) This new glove with robots has actuators expertly mounted on the arm surface. It uses multiple tendons woven onto the glove to emulate the functionalities of both intrinsic and extrinsic hand muscles. This lets the fingers natural finger motions including abduction, adduction, flexion and extension, with special cords for the thumb. The glove can be worn on any robotic hand skeleton, so it can be changed and used in many ways. A dual-layer tendon structure facilitates complex finger movements, which means the hand does not have to be longer, which is good for replacements and getting better [19] , As shown in figure (2-4) .

Figure (2-4) Anthropomorphic robotic hand with glove for external muscles and attached motors. (A) The front view of the robotic hand. (B) The rear view of the robotic hand.(C) A robotic hand equipped with flexible sensors for posture estimation. [19]

HandMATE is made as a motorized hand exoskeleton you can wear at home for stroke rehab. It uses straight-line devices to help each finger and the thumb bend and straighten. It has force-sensitive resistors (FSRs) to measure the force of grabbing and starting to straighten. Its control system uses a strategy where it responds to how the user moves. The source doesn't say "stiff links," but straight-line devices usually use stiff ways to move power, not flexible ones. The design tries to be small and look good on the back of the hand while keeping the right movements [20], As shown in figure (2-5).

Figure (2-5) HandMATE device. Individually actuated fingers and thumb shown. Electronics box is affixed to back of splint [20].

Even though they're strong, rigid hand exoskeletons have some big problems . Joint Misalignment and Discomfort, The stiff structure often has difficulty fitting the different shapes of human hands, since bone lengths and muscle sizes vary a lot from person to person [15][18]. A device that's one size would put the joint centers in the wrong place, making it work poorly and possibly causing discomfort or even pain for the user because the joints aren't lined up right [14]. These devices tend to be heavy and big, which makes them hard to carry around and for patients to wear during everyday activities or outside of a clinic . This size and weight really hurt how well people and machines work together and how comfortable it is to wear [18].

While they give strong help, their stiff nature can stop the hand's natural, complex movements and limit the kinds of grabs you can do without changing the device mechanically [18][21]. Most rigid hand rehab systems either don't do much or are too heavy and big, which makes them hard to wear as devices that help you [14].

B. Hybrid Systems

Hybrid robotic hand exoskeletons show advancement in design, using both rigid and soft parts. This plan tries to use the good things about rigid parts (like sending force well and strong movement) and soft materials (like bending easily, changing shape, and feeling good) while making their bad things less important. To overcome Rigid Design Drawbacks Hybrid designs are made to fix the big issues with only using hard exoskeletons [22].

SPAR Glove (SeptaPose Assistive and Rehabilitative Glove) by Rose and O'Malley (2018) as shown in figure (2-6) ,This device is a great example of a hybrid design, made to connect fully rigid and fully soft hand devices. It moves in a simple way, helping with seven hand positions used for most daily tasks. Key parts include new comfortable parts for sending power and features for putting it on and taking it off easily. The SPAR Glove uses rigid palm bars and parts that stop overextension for support and safety, while using soft connections to feel better. It has been shown to do as well as or better than what is needed for daily tasks for both movement range and grip force, especially being able to grip harder than similar devices while offering the most positions [14].

Figure (2-6) The SPAR Glove combines a novel glove-based exoskeleton with intent detection at the wrist [14].

Hybrid Robotic Exoskeleton Glove by Gerez et al. (2020) This system has a special design that includes a wire system to bend fingers, air-powered parts to move fingers apart, and an extra thumb that blows up to make gripping things steady. This design fixes a problem with many soft gloves, which is that they can't move fingers apart. The device doesn't weigh much, doesn't cost too much, and is simple to use. It has parts on the back of the glove that can change how stiff they are, which helps the fingers bend in different ways and keep the grip steady. The mixed design combines the small size and strong force of wire systems with the flexible nature of soft parts. Tests showed that this mixed glove really helps people grip things better, allowing them to use enough strength for many daily activities (like 13.8 N at 90° bending when not stiff, 12 N at 45° when stiff). It also showed that making parts rigid can make the fingers stronger at small bending angles, improving small grips and stopping fingers from moving around too much. Soft Robotic Exomusculature Glove by Delph et al. (2013) This soft robotic glove uses air and has sEMG sensors for hand therapy. It wants to help by sensing muscle activity, using soft movements with advanced control [21]. As the Figure (2-7)

Figure (2-7) The hybrid exoskeleton glove is equipped with a tendon-driven system for finger flexion, pneumatic actuators for finger abduction, and an inflatable, telescopic extra thumb for grasp quality enhancement. The soft glove is connected to the control box that houses the actuators [21].

Exo-Glove PM by Yun et al. (2017) This device is described as mixing soft, air-powered parts with strong, solid links [14]. It is made to be a glove that helps people easily, using parts that can be changed out [18]. Using 3D-printed pieces inside the finger parts helps keep the parts at the right distance, making sure that big forces are moved strongly. This mix of soft and rigid parts helps it work well and change easily [23]. Soft Hand Exoskeleton by Bagneschi et al. (2023) This new soft exoskeleton helps people close and open their hands. Its big change is the way the wires are placed, folded to the sides of the hand, which adds "squeezing strength" when the exoskeleton is used. This design makes the glove much more steady, stopping it from slipping and the wires from coming off the palm when gripping. A single part that makes it work is put on the back of the hand, making the device small without needing wires to go somewhere else. The stretchy glove is made stronger by two hard plates (made with 3D printing) for the back and palm of the hand as shoen in Figure (2-8), which guide the wire covers. The stronger palm plate sticks to the palm better, making gripping better. The test model had an average of 37% between the strength of the grip and the strength of the motor [24].

Figure (2-8) Preliminary prototype of the compact soft exoskeleton. Actuator and tendon transmission are arranged around the palm and hand dorsum, with no remote Mechanical parts [24].

HSRexo (Hybrid Soft-Rigid Exoskeleton) by Chen et al. (2021) This device is made for helping people get their hand strength back after a stroke, using a simple spring system with three layers that slide. It tries to mix being flexible with being easy to understand how it moves, fixing the problem of not having good models in many mixed soft and rigid hand exoskeletons. The flexible spring parts in the spring system allow for small movements of the three natural bending/straightening finger joints by only 1 way of moving [22], Figure (2-9).

Figure (2-9) Preliminary prototyping of HSRexo worn on a user [22].

Body-powered Assistive Exo-glove The exo-glove that uses body power greatly enhances user grasping capabilities, being easy to use and not costly.It cleverly puts together a differential module a soft glove a tendon tensioner and a harness for the best work. Moving power from the user&039;s upper body like shoulders to the thumb index and middle fingers through a system. A differential mechanism ensures balanced force distribution which can lock to keep the tendon tight all the time. It is very lightweight at 335 g and costing merely 92 USD, and it can work for a very long time , [25] As the Figure (2-10).

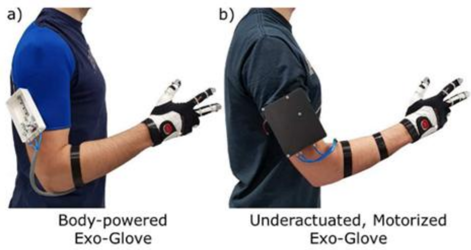

Figure (2-10). Side view of the proposed assistive devices (exo-gloves) [25].

HES (Hand Exoskeleton System) by Secciani et al. (2021) This system was developed from older models, with the goal of being fully wearable and easy to carry for help at home and remote rehab. It uses finger parts that are single-phalanx, single-DOF, stiff, and moved by cables. The way the hand and exoskeleton connect is made better by using a wrist support that fits well (a plastic that can be shaped with heat) that makes a firm base that connects to the forearm, and is made to fit each person's hand. This is to make sure it connects well and moves forces in a comfortable way. The system is made to handle forces up to 15 N on each finger's touch point, which is a normal amount for everyday tasks. It also has a sEMG band to wirelessly know what you want to do, so there are fewer annoying wires [26] , As the Figure (2-11).

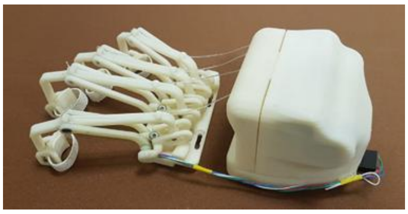

Figure (2-11) The figure shows the two blocks of the HES modular structure: on the left, the fingers' mechanisms module, and on the right, the motor and control one [26].

The Exo-Glove Shell is a robot you can wear that uses wires and both rigid and soft parts to help the thumb move and the fingers bend it cleverly uses a soft glove made of fabric for a comfy fit with strong metal pieces that guide wires to make sure force is sent well this robot smartly uses a simple system with only four motors to make three important basic hand movements possible its metal guides stop the robot from bending in the wrong ways making sure it works well and stays slim and trim the easy way it is made with three steps makes building it simpler and makes changing the design easier, making grip much better by 4.75 times [27]. Hybrid systems are becoming more common, as they try to get the best of both rigid and soft designs. They are more comfy and easy to wear than just rigid devices, while still often being better at moving forces and control than just soft devices.

While combined systems, such as the SPAR Glove [14], the Gerez et al. (2020) combined glove [21], or the Bagneschi et al. (2023) flexible exoskeleton[24], try to get the best of both types, they still use strong parts (like palm supports, plates, spacers, spring pieces) for strength or to send power

[22]. These strong parts, even when small, can still add weight, stop full flexibility, and maybe create focused pressure or pain, especially for patients who are very stiff, have delicate skin, or have very different body shapes [11].

C. Soft Robotic Gloves

Soft robotic gloves, also called exosuits, are a fast-growing type of wearable device that use very bendable materials like fabrics, rubbery materials, and bendy plastics [18]. This natural bendiness is very helpful for how people and robots work together, making them usually safer and better to use than rigid ones. In soft robotics, using air pressure to move things is a key way to make things move [28]. Soft Robotic Glove by Polygerinos et al. (2015) This important study showed a soft robotic glove using fluid-powered soft parts made to help and give therapy at home. A similar device, called the Rutgers Master II-ND (RMII-ND), had a wearable piece that weighed only about 3.5 ounces. It could create a force as strong as 3.6 pounds on each finger (except the smallest one) when closing. The system could react to a sudden signal in less than 0.2 seconds and stabilize after 2.2 seconds [18].

But, these air/fluid systems usually need an extra air pump or force, which makes them heavier and harder to move [12]. This means they work better in labs or hospitals. Fabric-Based Bidirectional Pneumatic Flexible Hand Exoskeleton by Yap et al. (2016/2017) This study looked at a soft robotic glove to help stroke survivors with their hand function, using plastic parts that fill with air [30]. One version of the wearable piece weighed about 5.3 ounces [18]. Their work showed that using fabric shapes could help fingers close and open [28]. They also made a version that could be used with magnetic resonance machines [16][18]. Synergy-Based Robotic Glove ,This gentle glove with robots is made to augment grasp capability and assist rehabilitation for spinal cord injury patients. It uses a underactuation strategy based on hand postural synergies, which helps with holding things in many ways using just one mover. The device is very lightweight adding only 85g to the hand and wrist, and it is easy to put on. It helps the active assistance for finger flexion of the thumb, index and middle fingers, and springs help the fingers go back out. The first postural synergy is cleverly embedded mechanically with a special pulley showing it works well [31] , As the Figure (2-12).

Figure (2-12) The soft, synergy-based robotic glove for grasping assistance [31] .

AirExGlove by Stilli et al. (2018) As the Figure (2-13).This device is a new, light, inflatable soft exoskeleton made for people who have clenched fist problems after a stroke. It gives a lot of therapy that changes to fit the person and happens little by little. The AirExGlove is said to be cheap (all parts cost less than £10), can fit any hand size, and isn't bothersome.

It uses air-powered parts on the back of the hand to help open it, while cords along the palm limit how far it can open. This makes a stable balance for hand positions in between. Tests showed that a force range of 0–5 N was enough to copy MAS scores from 0 to 3, showing it works well for people with muscle stiffness after a stroke [30].

Figure (2-13) Overview of the AirExGlove: (a) hand dorsal side of the system (pneumatic chambers pressurized), (b) hand palm side (tendon channel seams visible in white) and (c) side view of the system (thumb side) when grasping a plastic bottle [30].

McKibben-type Actuation by Bartlett et al. (2015) This system uses McKibben-type air-powered artificial muscles with a fabric glove, elbow sleeve, and a way to tighten it for wrist therapy [23]. Fabric-Based Pneumatic Actuators by Ge et al. (2020) This study focuses on creating, modeling, and testing air-powered parts made from knitted materials and fabrics for soft wearable gloves that help [32]. This shows a trend of using soft robotics with fabric engineering for designs that feel more natural and are easier to wear. Cable-Based Remote Actuation System (RAS) made by Dittli and others, made to run a fully wearable assistive soft hand exoskeleton for use outside of labs. This system has a pull-pull Bowden cable transmission, using specially made flat steel covers and very thin plastic (PE) wires to lower friction and wear, making it last longer and work better. The whole part that makes it move, which powers the fingers and thumb, weighs 560 grams and is made to be worn like a backpack or put on a wheelchair. It lasted for over 20,000 grasp cycles before any parts broke and worked very well, reaching 97% when straight and 87% when bent at 180°. People said they were very happy with how comfy and light it was, rating it 4.0 out of 5 on a scale for comfort [33] , As the Figure (2-14).

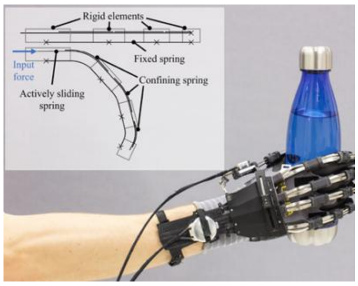

Figure (2-14) Cable-Based Remote Actuation System (RAS) [33].

Cable-Driven This is a popular way to make flexible hand exoskeletons because they are simple, flexible, light, easy to put together, and cheap [18]. The devices that make them move are often placed far away or on the back of the hand to make the fingers weigh less.

SNU Exo-Glove (In et al., Kang et al.) This wearable robotic hand, made of a type of plastic and driven by tendons, can help move the hand in both directions. It weighs 194g and can apply a pinch force of 20 N with three fingers. Flexo-glove by Mohammadi et al. (2018) This soft exoskeleton glove, created with a 3D printer, is powered by a motor and cable and designed to be customizable and easy to carry [18]. It allows the fingers to move in both directions, weighs 330g (with its battery), and can produce a pinch force of 22N and a power grasp force of 48N.

It can sense what the user intends to do using wireless sEMG or a smartphone app [10]. Portable Exoskeleton Glove (Graspy Glove) by Popov et al. (2017) This soft exoskeleton, driven by cables, helps move three fingers and the thumb. It allows both bending and straightening while letting the wrist move freely. It has one of the best power-to-weight ratios of all portable glove systems (16 N pinch force, 340g total system weight) because the motors are placed directly on the back of the hand, which makes the power transfer more efficient [11].

SAFE Glove (Sensing and Force-Feedback Exoskeleton) by Ma and Ben-Tzvi (2015) This wireless device, a self-contained haptic exoskeleton, is worn on the back of a bare hand. It gives haptic force feedback to each finger and can fit many finger sizes without limiting how much they can move. The glove uses small DC motors with high reduction ratios and cables routed in opposite directions [12]. The whole system weighs only 180g [13]. It is meant to measure and learn how people grasp things and then copy those movements to help people with weak hands [29]. RobHand by Cisnal et al. (2021) This inexpensive robotic hand exoskeleton, driven by real-time EMG signals, is made for rehabilitation on both sides of the body. It has an open palm design and uses five linear actuators to bend and straighten the thumb and fingers, with movements linked together. The system showed it could detect hand gestures with 97% accuracy and respond quickly enough. It is inexpensive because it uses a custom-made system to get EMG signals and flexible actuators that do not allow reverse movement [34]. Shape Memory Alloy (SMA) Driven SMA materials can create force by shrinking after being heated. This is good because they are flexible, simple to operate, lightweight, easy to carry, quick to respond, and have a high-power ratio, making them a possible material for artificial muscles [18]. Glove-SSCS by Xie et al. (2023) This bendable glove that can be worn is powered by a soft structure made of SMA (SSCS). It helps move all five fingers back and forth, only weighs about 4 ounces, and has a design that can be taken apart, with power, sensors, and performance all in one. The SSCS tries to fix the problems of stress on cable drives and the difficulty of moving pneumatic actuators, aiming to be flexible, light, easy to power, have a strong power ratio, and many ways to move. While it can move in two directions, the bend in the current model isn't very big [18]. Knitted SMA Exoglove by Lee and Park (2024) This brand-new, bendable glove that can be worn uses knitted SMA as a flexible way to move for help with getting better. Made specifically for people who have half their body paralyzed, it showed joints could move 13.71% more and grip strength increased by 55.01% compared to before. People could put the glove on and take it off by themselves, and it gave off heat through electrical resistance [32].

Soft robotic gloves provide flexibility and safety but encounter significant limitations: inadequate force output, reduced control accuracy due to material deformation, instability under load [24], Movement is often unidirectional, requiring additional components. [18]. Research indicates a distinct transition from rigid to soft and hybrid devices to enhance comfort, portability, and usage [16]. Designers prioritize customizability through customizable and 3D-printed components [13] , bidirectional actuation for comprehensive rehabilitation , and integrated sensors (EMG, force, flex) for collaborative control [12]. My suggested pneumatic soft glove effectively addresses these deficiencies by removing rigid components, facilitating safe bidirectional actuation solely with soft materials, incorporating compact air actuation for mobility [10], and integrating intelligent soft sensors for adaptive control [19]. This device, in contrast to previous ideas like the AirExGlove [31], seeks to provide complete dexterity, comfort, and utility for daily activities while maintaining a lightweight and inherently safe profile.

III. Elbow Exoskeleton Modules for Upper Limb Rehabilitation and Power Enhancement

The elbow joint is crucial for upper-limb movement, facilitating daily activities through the coordinated flexion and extension primarily by the biceps and triceps muscles [8]. The intricacy and common utilization render it susceptible to accidents and ailments such as epicondylitis, fractures, and stroke-related disabilities, frequently resulting in discomfort and restricted mobility [7][3]. Limited range of motion (75°–120°) Reduces independence, with only Approximately 50 per cent of those affected are able to perform basic tasks. Traditional therapy is successful yet resource-demanding, underscoring the necessity for robotic alternatives. Exoskeletons offer repetitive, rigorous, and measurable training, mimicking natural joint movement while delivering assistive or resistive torques. Rigid and soft pneumatic elbow modules have been created to improve rehabilitation results and increase functional strength [7].

A. *Rigid Elbow Exoskeletons*

Rigid exoskeletons for upper limb rehabilitation use mechanical frameworks composed of inflexible components, typically attached to the user's arms, with actuators delivering exact torques at the joints. These systems have been rigorously evaluated for their ability to provide highly regulated and stable movements, generate significant torque, and handle substantial loads, making them suitable for applications requiring force amplification or precise control over joint trajectories [7][3]. Their longevity and movement precision have been a primary focus in the earlier designs [4] .

NEUROExos This motorized elbow exoskeleton, developed by Nicola Vitiello and his team, was designed exclusively for post-stroke arm rehabilitation. It features a compact and lightweight mechanical design, utilizing double-shelled linkages to alleviate pressure on the skin . A crucial advancement is its four-degree-of-freedom (4-DOF) passive mechanism that relieves the elbow joint of undesired loads by preserving the alignment of human and robotic joint axes . This exoskeleton, supported by European Union initiatives like NEUROBOTICS and EVRYON, represents an initial effort to integrate ergonomic design with powered assistance [1] As the Figure (2-15) .

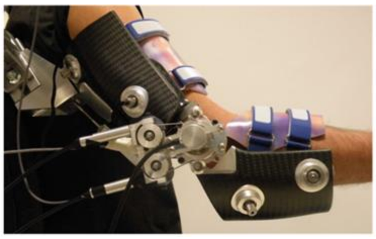

Figure (2-15) NEUROExos [1].

The ARMin, developed by Nef et al., is a significant rehabilitation robot designed for patient-assisted arm therapy. The ARMin exoskeleton has shown effective in improving motor recovery through repetitive guided arm motions in stroke patients. The design emphasizes interaction and adaptation to patient needs, indicating a transition towards more developed control strategies in rigid systems [1]. The IntelliArm by Ren et al. developed a 10-degree-of-freedom upper limb rehabilitation exoskeleton, consisting of 8 active and 2 passive degrees of freedom [35] .The multi-DOF arrangement offers a broad range of motion, leading to increased total volume and enhanced complexity [7] .

ETS-MARSE This robotic system for upper limb rehabilitation, driven by Maxon motors, features 7 degrees of freedom [34]. Like other rigid systems, it enables accurate control due to its motor-driven actuation [35]. EXO-UL8 This exoskeleton provides upper-limb support aimed at augmenting strength for rehabilitative and assistive purposes [3]. The CADEN-7 Created by the University of Washington in 2007, this seven-degree-of-freedom exoskeleton was employed for the rehabilitation of shoulder and elbow injuries . The several degrees of freedom led to an augmented total bulk, a more complex auxiliary apparatus, and heightened production expenses. The HARMONY A dual-arm exoskeleton created by the University of Texas, HARMONY utilizes the kinematic basics of human joints to facilitate therapeutic movements of the shoulders and elbows Due to its big size and high cost, it is firstly employed for scientific research [7]. The ANYexo 2.0 (as figure (2-16) Developed by the Swiss Federal Institute of Technology Zurich, this is a fully actuated upper limb exoskeleton including 9 degrees of freedom under active control .The objective is to ease joint-centric training across all recovery stages, use three six-degree-of-freedom force/torque sensors for ongoing monitoring [36]. However, its high energy consumption and cost limit widespread use.

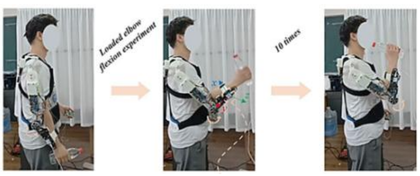

Figure (2-16) The ANYexo 2.0 [36].

Rigid exoskeletons, Although their accuracy, have significant disadvantages like as rigidity, safety issues, exorbitant mass (e.g., Hardiman at 680 kg), and limited portability [4][35][8]. Their inflexible design frequently results in a misalignment with normal elbow kinematics, restricting comfort, and precise motor control [3]. Elevated manufacturing expenses and maintenance requirements further diminish accessibility, rendering them unfeasible for routine usage or domestic repair. These concerns underscore the necessity for gentler, more adaptable options.

B. Soft Pneumatic Elbow Exoskeletons:

Designing and New Problems As soft robotics has grown, it has completely changed the way wearable rehabilitation devices are made, giving us a great option to rigid exoskeletons. Soft exoskeletons, also called exosuits, are made of materials and structures that are bendable and can be shaped, like soft motors and pliable fabrics. This built-in flexibility makes it much more comfortable, useful, and mobile, without putting strict limits on the user's normal range of motion. The main way that soft exosuits move, mostly through fluidic muscle actuators (FMAs) or pneumatic muscle actuators (PMAs), is through pneumatic actuation, which makes up 52% of these devices. [2].

Fluidic artificial muscles (FMAs), also known as McKibben muscles, are favored because to their flexibility, lightweight structure, enhanced strength, and greater safety compared to traditional motors . They are considered "clean" actuators because of their cost, swift response times, and high power-to-volume/weight ratios. An FMA consists of a slender elastic rubber tube enclosed within a mesh-like rigid fiber framework. As air pressure increases within the FMA, the inner tube expands, leading to a decrease in axial length and producing a tensile force comparable to that of human muscle . Conversely, as air pressure decreases, the FMA returns to its initial state [37]. PMA devices offer numerous advantages, such as superior safety, elevated compliance, lightweight construction, and affordability. WURAES (Wearable Upper-Limb Rehabilitation Assistance Exoskeleton System) This advanced 4-DOF system is designed for upper-limb injury rehabilitation, emphasizing safety, user-friendliness, and motion compliance (as figure (2-17).

It uses a torsion spring mechanism with a single FMA to activate each joint, hence decreasing the number of actuators and pressure regulating valves (PRVs) compared to traditional dual-FMA antagonistic setups, thereby lowering cost, weight, and volume . The WURAES consists of two shoulder and two elbow FMAs, measuring 310 mm and 400 mm in length, respectively, with a maximum contraction rate of 25% . The torsion spring ensures that the joint returns to its initial position when the power is turned off [37].

Figure (2-17). Photograph of the designed WURAES [37].

Soft Elbow Rehabilitation Trainer , This device uses soft pneumatic actuators as flexion joints specifically engineered for elbow rehabilitation . It has adaptive capabilities and self-alignment, significantly speeds up device adjustment . The trainer provides adaptive assistance and enhances human-robot interaction (HRI) without the need explicit torque and stiffness information, hence simplifying control [3]. Silicone Rubber-Based Elbow System, Researchers have developed a lightweight and cost-effective robotic system made of 100% silicone rubber to enhance elbow mobility. This system features Specially designed motor for comfortable wear on the arm and forearm, secured by silicone bands . It facilitates elbow flexion and extension by pneumatic air control, including a pressure sensor for real-time feedback and a webcam to monitor angles for precise movements [3] As the Figure (2-17).

Figure (2-18) Silicone Rubber-Based Elbow [3].

Soft Elbow Exosuit (Hosseini et al.) This exosuit utilizes twisted string actuators for elbow assistance, Show diversity of soft actuation systems beyond traditional pneumatic inflation [38]. Pneumatic Actuated Tennis Augmentation Device (Ogawa et al.) This device, while not solely intended for rehabilitation, use pneumatic actuation to improve bat swing assistance in baseball (as figure (2-19)). The novel technique of employing the tennis player's weight to create pressure from a pump in their shoes efficiently addresses the challenge of air supply weight [2].

Figure (2-19) Pneumatic Actuated Tennis Augmentation Device [2] .

"Carry" Pneumatic Elbow Exoskeleton This lightweight, active device is designed to assist with carrying tasks and reduce localized muscle fatigue [36]. Soft Shoulder-Elbow Therapy Exoskeleton (Proietti et al.) This wearable soft exoskeleton employs textile pneumatic actuators for assistance and rehabilitation [38].

Obstacles and Suggested Remedies for Soft Pneumatic Exoskeletons Soft pneumatic exoskeletons encounter numerous constraints, such as decreased force production attributed to pressure limitations (about 0.5 bar), non-linear control difficulties including Deceleration, and unwieldiness resulting from compressors and pneumatic circuits [4][3][37]. Multi-DOF systems frequently Show great weight and complexity, resulting in a trade-off between mobility and portability, while the fabrication of soft composites can also be complicated. Although they offer comfort, flexibility, and safety [3].

These problems are solved by a pneumatic soft elbow module in my project, which is built around a single pivotal joint. As compared to rigid designs, this method makes the system smaller and easier to carry, with references showing devices weighing less than 2 kg. It also makes the system more in line with the natural biomechanics of the elbow. Better pneumatic circuits and the addition of small compressors make it easier to use outside of clinical settings. The module effectively gets rid of force limitations by using pneumatic muscles that produce enough torque for activities like bending and straightening the elbow (for example, lifting about 470 grammes at 200 kPa). This bio-inspired design imitates how muscles work naturally, making rehabilitation safer, more comfortable, and more effective while also making it easier to move around and use in everyday life.

IV. Shoulder Exoskeleton Modules for Upper Limb Rehabilitation and Power Enhancement

The human shoulder joint is a great example of biomechanical engineering that is important for many upper-limb movements and interactions with the environment. The glenohumeral, sternoclavicular, acromioclavicular, and scapulothoracic joints make up a complex structure that allows for a wide range of motion (ROM), which lets you do everything from light lifting to heavy lifting [39]. However, because of its complexity, the shoulder is also more susceptible to overexertion, repetitive motion injuries, and work-related musculoskeletal disorders (MSDs) [40]. One of the main causes of acute or chronic pain and injury is prolonged, excessive muscle activity that results in exhaustion and an increase in internal joint force or torque. Workers frequently experience musculoskeletal issues affecting the upper extremities, especially the shoulders, which can lead to disability and financial hardship. Additionally, for stroke survivors, Upper-extremity dysfunction is a common symptom that makes daily life and quality of life very difficult [42]. More and more people want technology that can help, support, or rehabilitate the shoulder joint because it is so important for maintaining functional autonomy and occupational efficacy. Because they can move both passively and actively with help, exoskeleton robots have become a possible solution to these problems. By making it easier to move, requiring less effort, and making people feel less tired, these wearable technologies improve human performance. This lowers the risk of work-related musculoskeletal disorders and helps patients recover or learn new motor skills. [40][42]. Two categories will be explored of shoulder exoskeletons rigid and soft, particularly pneumatic systems.

A. *Rigid Shoulder Exoskeletons*

Rigid shoulder exoskeletons are characterized by their robust, independent structures that operate autonomously while sending out significant support forces. These systems often have many actuators, enabling significant external control of the exoskeleton to perform diverse assistance tasks. Their primary applications include muscle healing, rigorous industrial processes, and stroke rehabilitation therapy [43][40] .

A few well-known examples show how rigid shoulder exoskeletons are made and what they do: Ecso Bionics Holdings, Inc. called EVO This exoskeleton for the upper limb has been used in research situations and offers three levels of passive support. The mechanical design is made up of a "tower" shape with seven joints and two adjustment links on each side. The EVO has six passive joint configurations that control closed-kinematic loops and any misalignment between the person and the exoskeleton. This makes it easier for the body to fix itself. A system of five revolute joints and elastic ropes acts like weak springs and limits movements that aren't wanted. The elevating device of the exoskeleton uses a compressed spring to help the upper arm move.as in figure (2-20) [40].

Figure (2-20) The EVO (Ekso Bionics Holdings Inc, California, USA) upper limb exoskeleton is used as a wearable device with three levels of passive assistance [40].

ARMin II and ARMin III are whole-arm exoskeletons with seven degrees of freedom (DoF) that have electric motors built right into their active joints. The glenohumeral joint (CGH-joint) may move linearly thanks to the ARMin II, however its complicated design includes three active and ten passive joints. Backdrivability may be hampered by this intricacy, which necessitates a large amount of area and a significant moving mass. Force/torque sensors with admittance controllers are also required. The ARMin III eliminates the need for additional passive joints by enabling circular motion of the CGH-joint with a simpler mechanical construction. Impedance control is possible on all ARMin III axes, and the device may be quickly reoriented for left- or right-side use without the need for any equipment. Both ARMin variations offer improved ergonomic shoulder guidance, despite being more sophisticated than many cutting-edge robots. [39].

ShoulderX (SuitX) A passive shoulder exoskeleton that can be bought in stores and weighs 5.3 kg. It was designed to help shoulder pain while doing chores that are higher. It has a high assistive torque of 15 Nm at its strongest. In controlled, one-on-one tasks, studies show that ShoulderX can lower the activity of the upper trapezius muscle by as much as 46%. While it still worked, it was much less effective in the real world, with reductions hitting only 8%. One big problem with ShoulderX is that its spine frame isn't very flexible. This has been linked to more upper body pain and unhappy users [45].

Figure (2-21) The shoulder exoskeletons evaluated during this study were (a) ShoulderX V2 (SuitX, Emeryville,United States) and (b) Skelex V2 (Skelex, Rotterdam, The Netherlands) [45].

MATE (Comau) This low-power shoulder robot weighs 3.5 kg and provides 5.5 Nm of help [46]. One interesting design feature is that the actuation system is placed laterally at the arms. This may make the exoskeleton's lateral size bigger, which could make it harder to move around in tight work spaces. [48] .

PAEXO (Ottobock) A passive exoskeleton that weighs 1.9 kg and is defined by having a force-generating part on the user's back . The goal of this design is to solve problems that come with having heavier arms. PAEXO has been shown to effectively reduce deltoid muscle activations during virtual minimally invasive surgery (MIS) tasks, with decreases of 8.33% in posterior activations and 14.55% in medial activations. and front by 21.0%) and in stopping arm trembling by 9.85%. It was originally made for overhead jobs, but the fact that it is used in surgical settings shows how flexible [50] .

Shoulder Exoskeleton Robot (Atkins et al.) This is a hybrid active-passive upper-body exoskeleton including a four-bar mechanism. This device is essential for relocating the exoskeleton's center of mass from the shoulders to the user's lower back, thereby improving balance and alleviating fatigue caused by the robot's weight. It incorporates a dual-function gravity correction mechanism that sustains the exoskeleton's weight while partially alleviating the wearer's arm weight . A unique 6-DoF compliant misalignment compensation mechanism (SCAM) is incorporated to facilitate natural shoulder translation, consequently alleviating joint discomfort. The apparatus has a mass of 9.83 kg [44] .

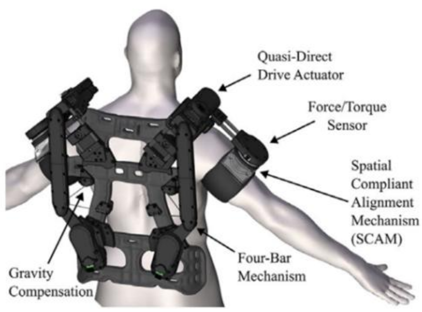

Figure (2-22) Shoulder Exoskeleton Robot (Atkins et al.) [44].

Despite its usefulness, rigid shoulder exoskeletons have a number of drawbacks, including restricted natural motion and misalignment. These designs' inflexible links can make it difficult for people to move naturally and nconstrained human movements, particularly during everyday activities. Kinematic alignment between robotic systems and the human arm is made more difficult by the complicated nature of the human shoulder, which is characterised by a non-static centre of rotation. The shoulder is seriously misaligned when oversimplified, such as when it is only shown as a ball-and-socket joint. This can cause pain, discomfort, and even serious injuries such bone fractures or joint dislocations [44]. Because of its actuators, batteries, and complex gearbox systems, active rigid exoskeletons are usually large, unwieldy, and require a significant amount of energy and processing power. Even passive stiff exoskeletons can be cumbersome, adding to the user's weight and increasing their overall effort [40].

Workspace Restrictions Some rigid exoskeletons may have a limited workspace, particularly those that are cable-driven. Motions beyond this practical range could make the robot uncontrollable and pose a potential safety hazard [52].

B. Soft Shoulder Exoskeletons

Soft shoulder exoskeletons show a unique approach in wearable robotics, lightweight, adaptable designs that closely fit to the user's movements. In contrast to their inflexible counterparts, these devices generally depend on the wearer's skeletal structure for support and transmit mobilizing forces by applying external tensile forces, frequently via exotendons, to generate moments across joints and ease the strain on biological muscles . A lot of soft exoskeletons are moved by cables and made of flexible materials like textiles, webbing, artificial tendons, and elastomers. [51].

There numerous unique instances of soft shoulder exoskeletons, especially those use pneumatic actuation, demonstrate their functionalities and how they tackle certain challenges:

LUXBIT (Samper-Escudero et al.) A textile-based, cable-driven exosuit utilizing deformable components for bilateral shoulder and elbow support. It incorporates an innovative deformable mechanism that facilitates the natural elevation of the arm. LUXBIT has demonstrated a reduction in muscular activation during upper limb flexion by as much as 13.17% and enables users to maintain exhausting postures for 62.91% longer .One important new feature is its unique pivoting system, which makes it more compatible with different body types by letting the cable move around with the arm. As a result, stresses are spread out better. It's possible that biceps and deltoid muscle action will go down by 9.63% and 3.99%, respectively, while hold time will go up by 49.61%. It's important to note that the activity of the trapezius muscle dropped by 16.63% during loaded abduction. The link made of textiles is designed to be comfortable, putting pressure only on the skin when help is given. Its structure is removable, which makes it easier to do yourself and keep up. [43] .

Noda et al.'s Shoulder Exoskeleton as in figure (2-23). A big part of this system is the pneumatic artificial muscles (PAMs), which are moved by Bowden wires and help raise the shoulder. It was specifically made for rehabilitation that starts with Brain-Machine Interfaces (BMI), with a focus on serious problems with the upper limbs. The robot has a Modular Exoskeletal Joint (MEJ) and improved Nested-cylinder PAMs (NcPAMs) that work together to make enough force to fight gravity and inertia. In clinical feasibility studies with stroke patients, improvements in upper-extremity function were very strong, as shown by an average increase of 1 point in FMA-UE A scores and an increase of 11.2 degrees in maximal voluntary shoulder flexion angle. The method made the elbow flexion ratio much better, which means that abnormal moves happened less often. The study showed that there were no side effects or shoulder pain, which shows that the system is safe and that its ideal assist rate is right. [53][41].

Figure (2-23) Shoulder elevation-assisted exoskeleton robot [41].

Minimalistic Soft Exosuit (Joshi et al.) This is a passive soft exosuit with a single stretchy exotendon attached to the waist and arm that goes around the shoulder. A key improvement is the use of a biomechanics-aware optimisation system to find the best exotendon parameters (rest length, attachment position) so that the wearer doesn't have to use as much muscle. The prototype is very light—it weighs only about 600 grams—and has low-friction parts on the shoulder that allow the exotendon to move smoothly. Experiments confirmed what the model said it would happen, showing that both the deltoid and trapezius muscles were less active [51]. Exo4Work (Rossini et al.) A passive cable-driven occupational shoulder exoskeleton weighing 3.8 kg, engineered with 6 degrees of freedom to guarantee kinematic compatibility with the shoulder joint . The Passive Remote Actuation System (pRAS), powered by compression springs, provides assistive torque amounting to one-third of the arm's gravitational torque (3 Nm) . The torque profile is designed to maximize at higher angles (90-130 degrees) and minimize at lower angles to avoid obstructing users during activities such as walking that do not necessitate assistance . The Exo4Work exhibited a decrease in anterior deltoid activity of up to 22% and the start of anterior deltoid fatigue was sped up by up to 41%. As a result of the remote actuation system moving the exoskeleton's weight to the user's back, the arm has a smaller size and less weight [54][48]. As figure (2-24).

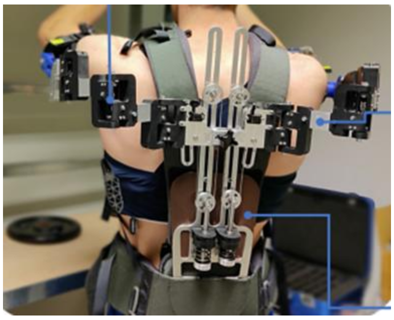

Figure (2-24) Exo4Work (Rossini et al.) [48] .

Passive Shoulder Exoskeleton (Lee et al.) Link chains and magnetic spring joints are used in this new design to make a small structure. The link chains provide extra degrees of freedom, which lets the exoskeleton adapt to and copy shoulder movements that go from side to side. The magnetic spring joint generates force without the need for extra, bulky gearbox parts. This design is made to cut down on power loss by letting the user change the installation height and starting angle of the magnetic spring joint to match their shoulder height. All of the equipment weighs 1.9 kg, and the upper arm only has to hold 400 g of inertial load. It reduced the activity of the anterior deltoid muscle by more than 30% during overhead drilling and box lifting with only 2.5 Nm of help, which is the same amount of help as exoskeletons providing more torque [49]. Passive Shoulder Exoskeleton (Ding et al.) as Figure (2-25). By placing its torque generator on the user's back, this novel passive exoskeleton uses Bowden cables to remotely activate the shoulder joint. Because the arm framework only weights 0.2 kg on each side, or 6% of the total device weight, this design significantly reduces the load that the human arms can support. It provides a maximum assistive torque of 10 Nm at 105 degrees of shoulder flexion by addressing nonlinear torque demands using a unique spring-cam mechanism. Studies found that repetitive and continuous shoulder flexion tasks resulted in a significant 14% decrease in upper trapezius activity and a 25% decrease in mean and maximum EMG signals of shoulder-associated muscles. Additionally, the technique suggests reducing spinal loading [47].

a. b.

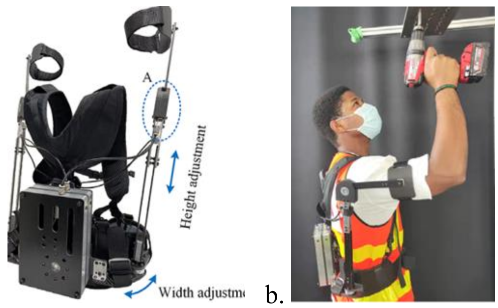

Figure (2-25): a) SE prototype and structural details. b) A user wears the SE to work [47].

Cable-Driven Shoulder-Elbow Rehabilitation Robot (Shi et al.) Designed for rehabilitation, this cable-driven device uses a Dynamic Adaptive Structure (DAS) to maximise workspace and tension effectiveness. To achieve a high force bandwidth and low output inertia, it incorporates a Distributed Active Semi-Active (DASA) system with magnetorheological (MR) clutches. In order to improve overall workspace and cable efficiency, the DAS effectively eliminates singularities in the internal and external rotation degrees of freedom. By reducing parasitic pressures, the system aims to improve comfort and safety while addressing potential risks in the Activities of Daily Living (ADLs) workstation. With a force bandwidth of about 35 Hz, the DASA system works better than the human force bandwidth [52] .

When you compare rigid and soft shoulder exoskeletons, you can see that comfort and force ability are two things that are not always equal. Rigid systems can make a lot of things and give precise control, but they are limited by being big, uncomfortable, misaligned, and using too much energy. They also don't have a lot of long-term proof. [46] . Soft and cable-driven systems diminish weight and enhance conformance; yet, they continue to encounter challenges related to anatomical adaptation, internal friction, and restricted torque efficiency [52] [43]. My research, which focusses on pneumatic soft actuators, overcomes these limitations by being flexible, lightweight, and compliant. Pneumatic systems maintain natural biomechanics while reducing parasitic forces and improving comfort. Their portability makes them more useful outside of lab environments.. Customisable "assist-as-needed" torque patterns make muscles work harder and keep them from getting tired for longer. Pneumatic soft actuators are the next generation of efficient, portable, and easy-to-use rehabilitation tools that improve safety and movement quality.

V. CONCLUSION

The hand, elbow, and shoulder are all parts of the upper arm. They are biomechanically complex systems that need advanced ways to heal and improve them. In the past, rigid exoskeletons have been good at accurately controlling torque and position. However, they have big problems like being uncomfortable, bulkiness, and misalignment with normal joint kinematics . Hybrid systems that include rigid and soft components have arisen to address these limits, enhancing flexibility and comfort while still transferring enough force. [24] . However soft robotics and pneumatic exoskeletons look like the most hopeful path forward. These technologies naturally offer safety, portability, and compliance. Soft robotic gloves are more comfortable to wear because of their lightweight, fabric-based pneumatic actuation. Elbow and shoulder modules that use pneumatics to simulate natural muscle contractions help with bio-inspired recovery. Despite many drawbacks, such as nonlinear control, reduced force output, and the requirement for an external air source [19] . According to the literature, there is a slow shift from rigid to flexible and pneumatic devices, with a focus on patient-centered adaptation, mobility, and ergonomic design. This shift makes it easier to create next-generation exoskeletons that enhance rehabilitation results, restore autonomy, and blend in seamlessly with daily life. [2][5] .

In the future, using smart sensors,, adaptive control, and lightweight materials make arm-support devices even easier to use of upper-limb exoskeletons. Continuous collaboration between clinicians and engineers will guide designs that truly match patient needs. Ultimately, these advancements will pave the way for more accessible, affordable, and personalized rehabilitation solutions [37].

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