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Research Progress on Mechanical Systems of Rehabilitation Robots from the Perspective of Mechanical Engineering

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Abstract. The demand for rehabilitation exoskeletons has outpaced the mechanical engineering required to make them truly wearable. Demographic aging and rising stroke incidence have expanded the candidate patient pool, yet most devices still stall at the laboratory door because their physical hardware cannot reconcile the conflicting requirements of daily use: every gram saved from the limb tends to cost torque, every fixed-stiffness transmission eventually misaligns with anatomical joints, and every rigid actuator introduces a failure mode that exposes the patient to injury. These problems are not independent; they trace back to a single design tension—structure, drive, and sensing are still optimized separately rather than treated as one coupled interface. This review therefore narrows its scope to the mechanical layer, tracing recent advances in biomimetic structures, actuation architectures, and embedded sensing integration. Rather than covering control algorithms or clinical trials in isolation, this paper examines how structural choices constrain drive options and how drive options, in turn, dictate what sensing and feedback can realistically achieve. Particular attention is given to two under-addressed engineering gaps: long-term wearing comfort under cyclic loading, and the accumulation of nonlinear kinematic errors across multi-joint chains. The next generation of hardware will need to move beyond single-subsystem optimization toward adaptive stiffness, intrinsic mechanical safety, and high physical integration—shifts that are as much about design culture as about component performance.

Keywords: Rehabilitation exoskeleton, human-robot interaction, variable stiffness actuator, lightweight design, mechanical system

1. Introduction

The demand for rehabilitation exoskeletons is driven less by demographic trends alone than by a specific mismatch: stroke survivors are discharged earlier, but home-based gait training still lacks hardware that is both light enough for daily wear and powerful enough for meaningful assistance [1]. Current devices can correct posture and support repetitive training, yet the gap between laboratory demonstration and unsupervised clinical routine remains wide [2].

The gap mentioned above is rooted in a single design tension rather than a checklist of independent problems. To deliver sufficient torque for gait support, engineers rely on motor-reducer assemblies or hydraulic drives; these are inherently bulky, and every kilogram added to the limb raises the patient's metabolic cost, shortening viable training sessions and confining use to supervised clinical settings [3]. To guarantee safety, most systems lock stiffness at a fixed value that cannot adapt to changing gait phases or recovery progress, which means the robot either resists the patient too much or offers too little support precisely when it is needed [4]. Meanwhile, integrating sensing and closed-loop control into a slim wearable frame remains difficult: conventional encoders are too voluminous and too fragile for limb modules, and compensating for nonlinearities in advanced actuators demands computational resources that further increase system weight.

These technical limitations translate directly into human-machine interface failures. When the robotic joint axis and the anatomical center do not align, shear forces during motion cause skin abrasion [5]; rigid, poorly fitted frames concentrate pressure on soft tissue during prolonged wear, producing discomfort that patients simply refuse to tolerate [6]; and because most systems lack mechanical fail-safes, an actuator malfunction during stance phase exposes the patient to uncontrolled collapse and secondary injury.

The common thread running through these challenges, is that mechanical structure, actuation, and sensing are still designed as three separable subsystems rather than one coupled physical interface. This review therefore examines the current state of research across these three dimensions, with particular attention to how choices in one domain constrain what is achievable in the others.

2. Advances in mechanical structure design of rehabilitation robots

This section reviews the system components and key technologies in rehabilitation robot design. It covers three main topics: degrees of freedom (DoF) design, biomimetics and human-robot fitting, and lightweight design.

2.1. Dof design for rehabilitation robots

DoF design in rehabilitation exoskeletons forces an immediate trade-off: more joints improve anatomical fidelity but explode control complexity and weight, while fewer joints simplify hardware yet may lock the limb into unnatural trajectories. The field has responded with three distinct mechanical philosophies, none of which fully resolves this tension.

Jiang's 2-DoF five-bar knee mechanism attacks the problem through kinematic redundancy [1]. By adding a second independent input to the traditional four-bar linkage, it generates multiple instantaneous center of rotation trajectories rather than a single fixed path, allowing the joint to adapt to different patient limb sizes without mechanical redesign. The cost is increased linkage complexity.

Where Jiang adds degrees of freedom at the joint, Xu removes them at the finger. His 1-DoF linkage collapses the flexion/extension of three finger joints (MCP, PIP, DIP) into a single mechanical degree of freedom driven by one actuator [2], replacing control intelligence with mechanical intelligence through series elasticity. This cuts system cost and complexity dramatically and achieves 80% of daily grasping functions, but lateral grasping and other complex motions are inherently lost.

Wang's reconfigurable parallel ankle mechanism takes a middle path [3]. It switches between 2-DoF and 3-DoF modes to match rehabilitation stages, using parallel linkage topology to let the mechanical rotation center passively track the human ankle's instantaneous motion center in real time without algorithmic compensation. This improves comfort across varying body types, yet the parallel structure is mechanically more complex than serial alternatives, and adduction/abduction remain coupled in the 2-DoF configuration.

These three approaches represent a spectrum: Jiang adds adaptability through redundant linkages, Xu sacrifices dexterity for simplicity, and Wang stages complexity through reconfiguration. The unresolved question is whether any single hardware platform can traverse the full rehabilitation cycle—from the minimal assistance a bedridden patient needs to the multi-axis mobility a recovering ambulatory patient demands.

2.2. Biomimetic design and human adaptation

Biomimetic design and human adaptation are essential for human-robot integration. Biomimetic design has three aspects. Kinematics reproduces the changing instantaneous center of rotation rather than single-axis constraints. Biomechanics mimics muscle compliance and ligament non-linear stiffness. This enables dynamic stiffness adjustment. Structural geometry achieves lightweight and high strength.

Human adaptation depends on kinematic compatibility and human-machine interface. Kinematic compatibility requires real-time matching between exoskeleton DoF and human joint rotation centers. This prevents constraint forces and injuries caused by axis misalignment. The interface must balance effective force transmission and soft tissue compliance. This prevents pressure and slippage.

Li Hui's team developed a rolling-sliding biomimetic knee joint. It uses planetary gears and three-stage coupled gears. The knee motion is decoupled into rolling angle α and sliding angle β. This accurately reproduces the J-shaped instantaneous center of rotation trajectory. Transmission efficiency reaches 95.4%. The knee module weighs only 1.35 kg. ICR deviation is less than 10%. Sliding displacement is within 4.2 mm. Misalignment is reduced by 68.8% compared to single-axis hinges. The efficiency significantly exceeds five-bar linkages (88%), cams (89%), and cable drives (85%) [5]. Rigid meshing replaces flexible hysteresis. Biomimetic precision is higher than traditional hinges. Rigid transmission has no elastic delay and responds quickly. However, noise and comfort issues require material optimization and gear profiling.

Tian's shrimp-inspired elbow exoskeleton takes the opposite path from Li's rigid rolling-gear knee. Where Li pursues kinematic fidelity through metal meshing, Tian sacrifices some transmission efficiency for compliance and self-alignment. The device consists of six interconnected modules linked by rotating center screws, mimicking the joint membranes of shrimp abdominal segments to permit adaptive axis adjustment through a 0–140° flexion/extension range [6]. The most inventive feature is not the biomimetic segmentation itself but the dual crossed cables in an inclined layout: compared with traditional vertical single-cable arrangements that are prone to lateral deviation, the symmetric diagonal forces cancel torsional moments and stabilize the 0.6 kg module against unwanted rotation. This addresses a genuine failure mode of rigid exoskeletons—axis misalignment under load—by allowing the structure to shift passively rather than forcing perfect mechanical congruence.

The trade-offs are specific and nontrivial. The Bowden cable transmission introduces a 0.07-second delay from friction and elastic hysteresis, which creates instability in force transmission during rapid voluntary movement [6]. More fundamentally, the six-module segmented architecture, while biologically plausible, pushes manufacturing and maintenance costs well above those of conventional single-hinge designs. It is noted that Tian's prototype validates the concept on a single elbow joint; whether the shrimp-inspired segmentation scales to multi-joint chains—where module-to-module error might accumulate—or survives the repetitive loading of a full rehabilitation protocol remains an open question.

These two studies illustrate a tension running through the entire biomimetic design literature. Li's rolling-gear mechanism achieves 95.4% efficiency and an ICR deviation below 10% by trusting rigid precision [5]; Tian's soft segmented shell achieves anatomical adaptation by trusting biological compliance [6]. Neither fully resolves the underlying dilemma: human joints migrate their instantaneous center of rotation through both rolling and sliding, yet current exoskeletons must choose between mechanisms that do one well and mechanisms that do neither precisely but adapt gracefully. The next step is not to declare one approach superior but to identify which patients—and which rehabilitation stages—benefit more from precision than from compliance, or vice versa. That patient-specific mapping, rather than abstract biomimetic fidelity, should guide future mechanical design.

2.3. Lightweight design and structure optimization

Lightweight design in rehabilitation exoskeletons presents a specific mechanical paradox: the patient feels only the mass that moves with the limb, yet engineers must keep structural strength, actuator power, and safety margins intact. In practice, the field has pursued three parallel tracks. Material substitution—aluminum alloys and carbon fiber in place of steel—improves specific strength and stiffness, though biocompatibility standards often demand wall thicknesses that partially cancel the weight savings. Topology optimization and serial-parallel hybrid configurations reduce moving-part inertia by concentrating mass near the torso, but the resulting geometries complicate manufacturing and joint alignment. Drive relocation—moving motors proximally and using cable or compliant transmission to decouple actuator mass from the joint axis—has produced the most dramatic limb-weight reductions, at the cost of longer transmission paths that introduce elasticity, backlash, and control delays.

This paper emphasizes that these strategies are usually validated separately: a frame is weighed on a bench, a motor is tested for torque density, a cable is measured for friction loss. How the combined system behaves over a full rehabilitation session—whether the patient's metabolic cost actually drops, or whether proximal motor mass disrupts balance and seated posture—receives far less attention. Until lightweight design is evaluated against the complete wear cycle rather than isolated component metrics, the gap between laboratory mass reduction and clinical wearability will persist.

Simone Leone's team developed a portable integrated exoskeleton for elbow, wrist, and finger. It uses cable-driven parallel structure. Seven motors are concentrated in a backpack unit. The limb module weighs only 80-150g. Total weight is 1.2-1.5kg. This significantly reduces limb inertia. A unidirectional cable drive strategy is used. Assistance is provided only for the main movement direction. Return motion relies on gravity and tissue elasticity. This simplifies structure and control. Main components are 3D printed with TPU base plates. This enables low-cost rapid customization. Tests with eight healthy subjects showed EMG results. Active muscle activation decreased by 21.3% on average. Radial wrist flexor activation decreased by 23.4%. This confirms effective muscle effort reduction [7]. Compared with traditional rigid exoskeletons with motors at joints, this design sacrifices bidirectional control force. It gains extreme lightweight, low cost, and multi-joint integration. It is suitable for daily home assistance and light rehabilitation. Traditional rigid/bidirectional cable drives are better for high-precision clinical training. Soft robotic solutions are better for extreme compliance requirements.

Hamed Vatan's team developed a lightweight shoulder exoskeleton [8]. It supports three DoF: shoulder abduction, flexion, and horizontal adduction. It solves problems of traditional exoskeletons being heavy, having insufficient DoF, and being unsuitable for home use. It uses biomimetic tendon drive. Motors in the backpack module transmit force to the arm through Bowden cables. This reduces arm load by about 2kg. Total weight is only 2.09kg [8]. The prototype went through three material iterations: PLA, aluminum, and carbon fiber. Carbon fiber was finally selected for strength and lightweight balance. Mathematical modeling, simulation, and experiments validated the system. It shows excellent performance in assistance precision, load capacity, and wearing comfort. This provides important insights for practical wearable rehabilitation robots. Compared with traditional rigid exoskeletons with motors at shoulder joints or arms, this design uses backpack-mounted drive. It concentrates 2kg motors on the back. The arm end has no motor load. Only lightweight cables and carbon fiber supports remain. This significantly reduces limb inertia and metabolic cost.

3. Advances in drive systems

This section reviews drive systems for rehabilitation robots. It covers two aspects: performance comparison of mainstream drive types, and application potential of piezoelectric motors in exoskeletons.

The drive mechanism of rehabilitation robots directly determines system weight, dynamic performance, compliance, and wearing comfort, representing the core aspect of lightweight design and structural optimization. Currently, five mainstream drive approaches prevail in clinical and research settings: motor drive, hydraulic drive, pneumatic drive, soft drive, and cable drive, exhibiting significant disparities in power density, compliance, control precision, and lightweight potential. The selection among these alternatives exerts a decisive influence on robotic system design [9] (Table 1).

Table 1. Performance comparison of mainstream drive approaches for rehabilitation robots [9]

Drive Type	Power Density	Compliance	Control Accuracy	Lightweight Potential	Typical Applications
Motor drive	Medium	poor	High	Low	lower limb exoskeleton
Hydraulic drive	High	Medium	Medium	Extremely low	Fixed rehabilitation equipment
Pneumatic drive	Medium-low	Excellent	Low	Medium	Hand Rehabilitation
Flexible Drive	Medium-low	Excellent	High	High	Lightweight Exoskeletons
Cable Drive	Medium	Medium	Medium	Extremely High	Upper Limb & Hand Lightweight Exoskeletons

Choosing a drive for a rehabilitation robot is less about finding the best actuator than about matching the actuator's physical character to what the patient can actually tolerate at each recovery stage. This paper organizes the discussion around three clinical snapshots rather than five technical categories, because the engineering trade-offs only make sense when viewed from the patient's side.

Early-stage passive training demands high force with minimal patient effort. Motor-reducer assemblies and hydraulic systems remain the default here: motors offer predictable control and sufficient torque for gait support, while hydraulics deliver the highest power density for fixed-platform or heavy-load mobilization. The problem is not that these drives are ineffective, but that their rigid transmissions add several kilograms of distal or proximal mass. Clinics have reported that patients tolerate only 20–30 minutes of continuous walking before fatigue sets in, which suggests that the "output capacity" advantage is partly cancelled by the metabolic cost of wearing the device. For bedridden or severely impaired patients, this trade-off is acceptable; for anyone expected to transition toward active participation, it becomes a hard ceiling.

Recovery-stage training shifts the priority from force to compliance. Pneumatic drives use the natural compressibility of air to create inherent softness, and when paired with artificial muscle structures they can mimic the fiber-like behavior of human muscle—an attractive feature for hand and soft-glove rehabilitation. Yet the same compressibility that gives pneumatics their safety also makes stiffness control imprecise, and the need for a continuous air supply tethers the patient to infrastructure. Soft drives—series elastic actuators and shape memory alloys—introduce compliance through elastic elements and cut inertia substantially, which is why they have dominated recent lightweight exoskeleton research. However, their output force is modest, their dynamic models are complex, and their controllers are demanding; in practice, they have been confined to assistive roles or single-joint actuation rather than full-limb recovery protocols.

Home and community use imposes a different constraint entirely: the device must be donned without clinical assistance and worn for hours. Cable drives address this by parking motors on a proximal frame or backpack and transmitting power through Bowden cables, reducing the moving mass at the arm or leg to a few hundred grams. Leone's upper-limb system and Vatan's shoulder exosuit both exploit this geometry. The cost is precision: cable elasticity and backlash introduce positioning errors that grow with transmission distance, and maintaining tension over long cycles requires either mechanical compensation or hybrid actuation at the joint.

It is not suggested to see these five drive types as a menu of options but as a set of mutually exclusive strengths. Rigid drives win on force but punish the wearer with mass; soft drives win on compliance but resist precise tuning; cable drives win on weight but degrade accuracy over distance. Because no single modality satisfies the full rehabilitation cycle—from passive bed training to active home walking—recent literature has converged on hybrid architectures that combine, for example, a rigid motor for gross motion with a soft elastic element at the joint. This paper emphasizes that most of these hybrids remain at the bench-test stage; how they perform under patient-specific variability and long-term cyclic loading is still largely unreported.

4. Sensing and closed-loop control

This section reviews research progress in sensing and closed-loop control. It focuses on two core topics: mainstream sensing systems and closed-loop control strategies.

4.1. Mainstream sensing systems

Sensors on rehabilitation exoskeletons have multiplied, and that creates a bulk problem. Early devices used single channels—an encoder for angle, a force plate for gait—but EMG drifts with sweat, IMU accumulates error, and pressure pads cannot tell intent from passive weight. The real headache is cramming several sensors into a limb module that remains slim enough for home use.

Choi et al. avoided the hardware problem by working in software [10]. Their deep heterogeneous transfer learning fuses sEMG, FSR, and IMU for upper-limb intent detection, borrowing features across modalities so the model needs less fully annotated data. That matters because patient-specific EMG is a nightmare to label at scale. Still, the method presumes all three sensors are already mounted and synchronized; it says nothing about where they actually fit on a lightweight frame.

Bu Lingyu's group attacked the opposite end [11]. Their 8×8 flexible thin-film pressure array costs about one-tenth of conventional force sensors, bends into 3D-printed sleeves, and captures spatial pressure without rebuilding the robotic arm. Replacing multiple sEMG electrodes with one conformable patch cuts setup time and patient discomfort—critical for unsupervised home use, less so for lab demonstrations.

The split is clear. Choi makes better use of sensors that are already there; Bu makes the sensors themselves less intrusive. Both help, but neither closes the gap. Choi's gains vanish if the exoskeleton cannot host three clean signal channels; Bu's patch maps pressure well but misses the neuromuscular information EMG carries. A home-use device probably needs both—Bu's minimal hardware and Choi's cross-modal processing—but currently, no single prototype has married the two.

4.2. Closed-loop control strategies

Mainstream closed-loop control for rehabilitation robots includes PID, impedance/admittance, adaptive, and robust control. PID adjusts based on error. It is simple and fast but has poor adaptability. It is mostly used for low-level control. Impedance/admittance control establishes virtual mechanical models. It achieves compliant human-robot interaction. It has high safety but requires precise models. It is the mainstream interaction strategy. Adaptive control adjusts parameters in real time. It has strong personalization but high computational load. Robust control handles uncertainties. It has high stability but sacrifices precision. Most use position and force sensor feedback to achieve precise tracking and safe assistance.

Aichaoui's team proposed cascade genetic algorithm adaptive backstepping impedance control. It separates outer-loop impedance planning and inner-loop adaptive backstepping tracking [12]. It requires no precise mechanical model. Improved adaptive laws eliminate model dependence. Genetic algorithms were first used for offline parameter optimization. An adaptive gain function dynamically adjusts priorities between trajectory tracking and environment compliance. Persistent position errors are solved. This strategy provides a more robust, flexible, and easily implemented interaction control solution for rehabilitation robots. It effectively solves limitations of traditional model-based control methods regarding model uncertainty and environment interaction.

Rosales-Luengas's team designed a dual-loop cascade control architecture for compliant joint lower limb exoskeletons. The inner loop uses robust sliding mode control for precise joint torque tracking. The outer loop also uses sliding mode control to ensure trajectory tracking [13]. This design achieves force-position decoupling and coordinated control. Series elastic actuators filter high-frequency chattering. Improved sliding mode algorithms strictly guarantee system stability. It unifies force control precision and trajectory tracking without modeling. It solves adaptability problems of traditional model-based control in strong patient-robot coupling systems. It is more suitable for clinical multi-patient rotation needs.

Guo's healthy-side reference strategy treats the unaffected limb as a dynamic mirror rather than imposing fixed trajectories on the affected side [14]. By comparing bilateral stiffness differences through an online endpoint model fed by EMG and interaction force, the system maps the patient's own normal characteristics onto the impaired limb. An inner-outer cascade handles this: the outer loop adjusts variable impedance through stiffness mapping, while the inner loop compensates pneumatic delays with dynamic feedforward PD control. The merit lies in using the patient's own unaffected side as a personalized reference that outperforms generic forced movement. The limitation is that the approach assumes a functional contralateral limb—a condition not met by all stroke patients.

5. Engineering challenges and future trends

It is observed that the push from hospital to home is blocked by a stack of mutually reinforcing problems. Intention recognition is too noisy for unsupervised use; sensor fusion drains portable batteries; no drive architecture delivers both precision and light weight. These limits translate into interface failures—joint misalignment causes injury, and the absence of mechanical fail-safes leaves patients exposed. Multi-DoF coordination remains difficult under patient-specific variability. Cost and uneven insurance coverage then complete the barrier, but they are symptoms of underlying engineering immaturity rather than independent obstacles.

This paper suggest that the near-term future converges on a single requirement: the hardware must become mechanically autonomous enough that control complexity can be reduced rather than increased. Variable-stiffness actuators, pancake motors, and micro-pumps point toward lighter, more integrated joints; fatigue-adaptive control and biomimetic structures that passively align to the patient will do more for home use than adding AI layers or VR interfaces. Remote monitoring and brain-computer interfaces are valuable adjuncts, yet they depend on solving the physical integration problem first.

6. Conclusion

This review deliberately focuses on the mechanical layer, as that is where the gap between laboratory promise and clinical reality is widest. Structurally, biomimetic five-bar knees and reconfigurable parallel ankles have made exoskeletons anatomically more compatible than earlier single-axis hinges, and pairing underactuated linkages with series elastic actuators has cut both weight and control complexity. Yet these advances remain piecemeal: no existing platform adapts seamlessly across upper- and lower-limb tasks with identical hardware, and the trade-off between degrees-of-freedom redundancy and underactuation is still settled ad hoc for each patient cohort rather than solved systematically.

The actuation literature has likewise moved past the question of which drive is best to the harder problem of how to combine them. Motor and hydraulic drives deliver force but burden the wearer with mass; pneumatic and soft actuators provide compliance yet resist precise tuning; cable drives reduce distal weight but introduce elasticity that degrades accuracy over long transmission paths. Because every modality fails on at least one clinical requirement, hybrid architectures—rigid motors coupled with soft joint elements, or cable transmissions paired with local force sensing—have become the most frequently proposed solution, even though few have progressed beyond bench testing.

Sensing and control research is richer in algorithmic innovation than in hardware integration. Multi-sensor fusion has improved the robustness of intention recognition, and cascade impedance or adaptive backstepping strategies have handled model uncertainty and patient-specific coupling better than fixed-gain PID. Guo's healthy-side reference approach is particularly promising because it personalizes assistance to the patient's unaffected limb rather than imposing a generic trajectory. Still, nearly all of these controllers are validated on small healthy cohorts or short sessions; how they perform when the limb module is stripped to home-use weight limits and left unsupervised remains largely unreported.

This paper identifies two gaps that deserve closer scrutiny. First, long-term wearability data—skin pressure over weeks, metabolic cost across months, joint alignment drift after repeated donning—remain scarce, because prototype evaluation rarely extends beyond laboratory gait trials. Second, the mechanical, drive, and control communities publish in largely separate venues, so the system-level integration that clinical translation demands is rarely attempted in a single study. Closing that gap will require not merely better components, but a design culture that treats structure, actuation, and sensing as one coupled physical interface rather than three independently optimizable subsystems. Until that happens, rehabilitation robots will remain promising laboratory devices that hesitate at the clinic door.

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