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Wrist Exoskeletons for Rehabilitation: Current State, Challenges, and Future Research Directions

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ABSTRACT

Exoskeletons have become a promising innovation in wrist and hand rehabilitation, providing targeted support, improved mobility, and individualized therapy for patients recovering from neurological damage, musculoskeletal conditions, or surgical procedures. This review outlines recent progress in mechanical structures, control approaches, and user-focused design, with emphasis on adaptive systems, force enhancement, and the integration of soft robotic elements. Despite these advancements, several barriers remain, including limitations in weight, portability, and energy efficiency, as well as issues related to usability, patient compliance, affordability, accessibility, and regulatory approval. Current research trends point toward the use of lightweight composites, artificial intelligence for therapy customization, wireless connectivity, Internet of Things (IoT) frameworks, remote rehabilitation platforms, and multimodal feedback systems to enrich patient experiences. These developments highlight the importance of collaboration among engineers, healthcare professionals, and policymakers to ensure that innovation aligns with safety, effectiveness, and user comfort. Looking ahead, wrist-focused exoskeletons are expected to advance into versatile, networked, and patient-centered solutions, creating opportunities for broader clinical adoption and at-home rehabilitation, ultimately contributing to more effective and inclusive therapeutic outcomes.

Keywords: Adaptive Robotics, Exoskeleton Rehabilitation, Patient-Centered Design, Wrist Therapy

1. INTRODUCTION

Loss of wrist and hand function is a common consequence of stroke, neurological disorders, and musculoskeletal injuries, often leaving patients with difficulties in carrying out everyday activities such as eating, writing, or holding objects. Conventional rehabilitation approaches, while valuable, are often limited by therapist availability, treatment intensity, and the repetitive nature of therapy that can be hard to sustain over long periods. These challenges have created a growing interest in robotic solutions, particularly exoskeletons, to support more consistent and effective recovery.

Wrist exoskeletons are designed to guide or assist natural joint movements, making it possible for patients to practice targeted motions with greater precision and frequency. Unlike conventional therapy alone, these devices can deliver structured, measurable, and intensive training, which is critical for motor relearning and neuroplasticity.

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The technology has also evolved to include both rigid and soft designs, wearable and non-wearable formats, and a range of control strategies from fully automated systems to adaptive models that respond to the patient's own efforts.

While these advances show great promise, challenges remain. Issues such as device weight, comfort, portability, affordability, and patient adherence continue to influence their real-world adoption. Balancing engineering innovation with user needs and clinical practicality is essential to ensure that these systems do more than replicate therapy and they must genuinely improve the rehabilitation experience.

This manuscript explores how exoskeleton-based wrist rehabilitation technologies have developed, the different design and control approaches in use, and the opportunities and challenges that lie ahead. The aim is to provide a clear picture of where the field currently stands and how these innovations may shape the future of rehabilitation, both in clinics and at home.

1.1 Basic Framework for Exoskeleton-Assisted Wrist Rehabilitation

Wrist exoskeletons represent robotic rehabilitation systems engineered to assist, guide, or restore functional movements of the wrist and hand in patients recovering from stroke, trauma, or neurological impairments. These systems operate by exerting controlled forces that replicate or enhance the natural biomechanics of the wrist and fingers, thereby enabling repetitive, task-oriented therapeutic interventions. Their classification can be delineated according to parameters such as device morphology, structural configuration, and control strategy.

Majority of wrist exoskeletons are wearable, enabling patients to undergo therapy in both clinical environments and at home without being restricted to stationary platforms. Wearable systems are generally categorized into rigid and soft configurations. Rigid exoskeletons, such as those proposed by Carbone et al. [1] Chen et al. [2], and Damarla et al. [3] rely on linkage mechanisms, servomotors, or linear actuators to deliver precise and mechanically constrained movement. Conversely, soft exoskeletons, exemplified by the works of Aghil et al. [4] Bagneschi et al. [5], and Biris et al. [6], utilize tendon-driven designs or pneumatic actuators embedded in flexible glove-like structures, emphasizing user comfort, adaptability, and reduced weight.

Non-wearable alternatives often consist of bench-mounted robotic arms or platform-based systems that guide wrist motion while the forearm is secured. Although effective in laboratory rehabilitation settings, these devices lack portability, limiting their suitability for home use. With respect to control methodology, exoskeletons are commonly classified as active, passive, or assist-as-needed. Active systems employ actuators to generate movement in response to patient inputs such as electromyography (EMG) signals . [6], foot commands [2] or manual triggers. Passive systems, which offer guided mechanical support without powered actuation, are less frequently implemented in contemporary designs. Assist-as-needed approaches, as surveyed by Kapsalyamov et al. [7] dynamically adjust support levels to encourage patient participation while minimizing device dependency.

This classification underscores the diversity of design strategies in exoskeleton-based wrist rehabilitation, illustrating how choices in form factor, structural architecture, and control strategy directly affect usability, therapeutic impact, and patient adherence. The wrist itself is a complex joint system that is integral to positioning and orienting the hand for functional activities. Primarily composed of the radiocarpal and midcarpal joints, it enables two key degrees of freedom: flexion–extension and radial–ulnar deviation. Additionally, forearm pronation–supination—though anatomically linked to the radioulnar joints—is often incorporated into wrist rehabilitation protocols due to its critical role in grasping and manipulation. The coordination of these motions supports essential daily functions, including writing, eating, and handling objects.

From a rehabilitation standpoint, the biomechanical design of wrist exoskeletons must align with the natural range of motion (ROM) of the joint—typically 70–90° in flexion, 70–80° in extension, 20–25° in radial deviation, and 30–40° in ulnar deviation—while also maintaining coordinated movement with the metacarpophalangeal and interphalangeal joints during grasping activities. For instance, Carbone et al. [1] employ multi-linkage mechanisms to replicate human kinematics, whereas soft exoskeletons, such as those proposed by Bagneschi et al. [5], utilize tendon-driven pathways to reproduce natural motion trajectories without rigid mechanical constraints. An additional challenge lies in accounting for joint synergies during functional tasks. Wrist extension typically accompanies finger flexion to enhance grip strength, while wrist flexion is often coupled with finger extension during object release. Rehabilitation systems that integrate these natural couplings—either through mechanical structures or adaptive control algorithms—are more effective in supporting neuroplasticity and motor relearning. In contrast, devices that neglect physiological movement patterns risk reinforcing maladaptive compensations, potentially hindering recovery.

Thus, effective exoskeleton design requires a comprehensive understanding of joint kinematics, soft tissue dynamics, and load-bearing capacities to ensure that therapy is both biomechanically accurate and clinically beneficial.

Control strategies further define how wrist exoskeletons generate, guide, and adapt movements during therapy. These approaches—classified as active, passive, or assist-as-needed—differ in their degree of automation, adaptability, and patient involvement. Active systems rely on actuators to drive motion, often incorporating bio-signal inputs such as electromyography (EMG) for intention detection, as demonstrated by Biris et al. [6] in a fluid-actuated soft exoskeleton. Alternative control interfaces include foot gestures [2] and smartphone-based platforms [4] which broaden accessibility. Passive systems, though less prevalent, use springs, dampers, or mechanical linkages to provide unpowered guidance. While they are generally lighter and more cost-effective, their limited adaptability reduces suitability for intensive neurorehabilitation. Assist-as-needed systems, such as those discussed by Kapsalyamov et al. [7], provide adaptive support by monitoring patient effort through sensor feedback and adjusting actuation in real time, thereby encouraging active participation and minimizing device dependency. Ultimately, the choice of control mechanism significantly influences therapeutic intensity, patient engagement, and rehabilitation outcomes. Active approaches deliver precise and consistent assistance, passive systems prioritize simplicity and affordability, while assist-as-needed designs strike a balance by fostering independence alongside safety and movement quality.

In summary, the effectiveness of exoskeleton-based wrist rehabilitation is shaped by both biomechanical design and control strategy. Devices must accommodate the natural range of motion and replicate physiological joint synergies to ensure movements are therapeutically relevant and biomechanically accurate. At the same time, the choice between active, passive, and assist-as-needed control directly influences patient engagement, adaptability, and long-term recovery outcomes. Rigid and soft wearable systems, along with non-wearable alternatives, each present distinct advantages and limitations in terms of precision, comfort, and portability. Collectively, these design and control considerations underscore the need for a careful balance between engineering innovation, clinical applicability, and user-centered design to optimize rehabilitation effectiveness and promote sustainable functional recovery.

2. CONTROL ARCHITECTURES AND SENSOR INTEGRATION FOR WRIST EXOSKELETONS

Electromyography (EMG) has become a cornerstone in the design of assistive and rehabilitative technologies, particularly for enhancing hand and upper limb function. Khamis et al. [8] presented a control framework that combined EMG with flex sensors for a hand-grip assistive device aimed at older adults experiencing muscle weakness. Their system supported both semi-active and active operation modes, integrating safety mechanisms such as emergency stop switches, though it also highlighted practical challenges associated with EMG signal variability due to sensor placement. To improve reliability and user comfort, Liu et al. [9] developed a flexible surface EMG (sEMG) acquisition platform using graphene-based electrodes, achieving wireless operation and nearly 99% accuracy in predicting muscle strength through an LSTM model. Similarly, Zhao et al. [10] advanced the field by merging EMG with electrocardiography (ECG) in a wearable robotic glove, enabling real-time physiological monitoring and adaptive pressure control during training. Collectively, these studies emphasize the versatility of EMG from intention detection to fatigue monitoring while also underscoring ongoing concerns related to signal stability and long-term usability.

Surface EMG remains the most widely applied sensing modality in wrist exoskeletons because it directly reflects muscle activation and user intent. Various strategies employ sEMG from either the impaired limb or a contralateral healthy limb to drive actuation. Chen et al. [11], for example, developed a bilateral training glove that mirrored motion from the unaffected hand to the impaired side, while Cheon et al. [12] demonstrated a simplified single-sensor glove capable of detecting power grasp across multiple postures. More advanced designs, such as those by Birouaș et al. [16] and Yoo et al. [13] employed multi-sensor EMG arrays to control underactuated or 3D-printed orthoses. Adaptive approaches have also emerged; Siu et al. [14], integrated EMG with Learning-from-Demonstration (LfD) techniques to accommodate user variability, while Vangi et al. [15] combined sEMG with deep learning models (CNN-LSTM) to improve motion prediction accuracy. These hybrid approaches highlight the growing role of biosignal–AI integration in achieving refined and personalized rehabilitation control.

Electroencephalography (EEG) is another powerful modality in rehabilitation research, particularly for patients with severe motor impairment. Unlike EMG, EEG bypasses the peripheral nervous system, enabling direct detection of motor intent from cortical activity. This capability has made EEG-based brain–computer interfaces (BCIs) increasingly relevant in stroke rehabilitation, where patients may struggle to generate sufficient muscle signals.

Jacob et al. [16] proposed the Artificial Muscle Intelligence with Deep Learning (AMIDL) system, which linked EEG activity to transcutaneous electrical nerve stimulation (TENS) for muscle activation. The system decoded six hand postures using Walsh–Hadamard Transform (WHT) feature extraction combined with deep learning, achieving classification accuracies above 80%. It also integrated EEG–EMG correlation, adaptive stimulation, and even gesture-to-voice functions to improve rehabilitation outcomes and patient–caregiver communication. In parallel, Araujo et al. [17] designed a low-cost, textile-based, 3D-printed exoskeleton actuated by Bowden cables, translating EEG signals into motion commands for post-stroke therapy. While EEG-BCI offers unique opportunities, it remains technically demanding, requiring robust noise suppression, signal processing, and user training to achieve clinically reliable performance.

Beyond bioelectrical signals, mechanical sensing modalities play a key role in ensuring safe and adaptive rehabilitation. Force and torque sensors integrated into exoskeleton joints or fingertips provide continuous feedback on applied loads, preventing overexertion and supporting closed-loop control. Similarly, motion tracking technologies such as inertial measurement units (IMUs) and optical systems capture limb trajectories, improving accuracy in assist-as-needed control modes. These sensing methods are often combined with EMG or EEG inputs, creating multimodal control frameworks that enhance robustness against signal dropout and variability.

Adaptive and intelligent control strategies are increasingly used to personalize therapy in real time. These approaches dynamically adjust assistance levels based on the patient's voluntary performance, encouraging active participation and promoting neuroplasticity. Siu et al. [14]

implemented an adaptive EMG controller with learning-from-demonstration, allowing systems to anticipate user motion despite inconsistent sensor placement. Meanwhile, AI-based methods such as CNN-LSTM regression models (Vangi et al. [15]),can process complex sEMG data to predict fine-grained joint trajectories, providing more responsive and precise assistance. Such integration of machine learning not only enhances motion accuracy but also enables automated progression in therapy difficulty, a critical factor in long-term rehabilitation.
In summary, EMG-based control continues to dominate rehabilitation research due to its balance of reliability and usability, while EEG-based BCI systems hold promise for patients with severe impairments who cannot generate stable EMG signals. Force and motion sensors complement these methods by enhancing safety and precision, and adaptive AI-driven algorithms are shaping the next generation of intelligent, patient-specific rehabilitation systems. Together, these innovations reflect a shift toward multimodal, responsive, and user-centered exoskeleton control architectures.

3. INTEGRATION OF EXOSKELETONS IN ROBOTIC REHABILITATION

Robotic rehabilitation and exoskeleton technologies are inherently interconnected, as exoskeletons represent one of the most practical wearable applications of robotics for restoring upper-limb motor function. By embedding robotic control principles into human-interfacing structures, exoskeletons guide, assist, or resist patient movements with high precision. Rigid exoskeletons [18] [19] for instance, align robotic joints directly with human anatomy to deliver controlled flexion–extension and abduction, enabling repetitive and intensive therapy sessions. In contrast, soft robotic gloves [20] [21] provide a more flexible form of exoskeleton, offering lightweight and safer assistance but often with reduced force capacity and limited bidirectional motion. Hybrid tendon-driven designs [22] attempt to balance these trade-offs by reducing mechanical complexity while preserving natural hand synergies. The integration of bio-signal inputs such as EMG and EEG further reinforces the connection between robotics and exoskeletons, enabling intelligent systems that not only facilitate movement but also adapt dynamically to user intent and recovery progress [23] [24]. Thus, although all exoskeletons can be categorized as robotic systems, not all robotic rehabilitation devices qualify as exoskeletons, with the key distinction being their wearable, human-coupled structure. Nevertheless, ongoing research suggests a convergence of the two domains, with future rehabilitation systems likely to emerge as robotic–exoskeleton hybrids that combine the precision of robotics with the comfort and accessibility of exoskeletal designs.

Exoskeletons are increasingly recognized as essential components in robotic rehabilitation, as they provide structured, wearable support that fuses mechanical actuation with user motor intent to restore functional movement. Recent work demonstrates that these systems not only aid physical performance but also stimulate neural recovery. For example, Kim et al [24] showed that robotic mirror therapy (RMT) using a sensorized soft robotic glove produced stronger and more balanced motor cortex activation compared with conventional mirror therapy or robotic therapy alone, highlighting the role of exoskeletons in enhancing neuroplasticity through multisensory feedback. Similarly, Duanmu et al. [25] developed guided bending bellows actuators (GBBAs) within a soft rehabilitation glove, generating sufficient bending force to overcome spasticity and enable independent finger motion—critical for precise, adaptable therapy. Complementing this, Yuan et al. [26] reported that a bidirectional fabric-based soft robotic glove improved stroke patients' ability to perform activities of daily living (ADLs), strengthening grip and boosting confidence by reducing reliance on external support. Further advancing soft wearable designs, Elmoughni et al. [27] introduced seamless knitted pneumatic actuators, delivering lightweight, durable, and customizable gloves with strong actuation performance and improved wearability. Collectively, these innovations underscore the pivotal role of both rigid and soft exoskeletons in bridging biomechanics with neural engagement, offering promising patient-centered pathways for rehabilitation.

Surface electromyography (EMG) remains dominant for detecting voluntary muscle activation, supporting unilateral and bilateral training [28] [11] [12] [29] [13] [14] [15] whereas electroencephalography (EEG)-based brain–computer interfaces (BCIs) provide alternative pathways for individuals with profound motor impairment by bypassing peripheral musculature [17]. In parallel, hybrid adaptive systems that integrate biosignals with AI are emerging, enabling real-time modulation of assistance and personalized rehabilitation [14] [15]. This classification not only illustrates the diversity of current strategies but also highlights future opportunities for multimodal sensor fusion to improve rehabilitation outcomes.

Electromyography (EMG)-based strategies remain the predominant control paradigm, capitalizing on muscle activation signals to deliver intuitive and responsive assistance. This is evident in both multi-sensor systems designed for fine-grained motion control [11] [29] and simplified single-sensor frameworks developed to improve ease of use [15]. In contrast, electroencephalography (EEG)-driven Brain–Computer Interface (BCI) systems, while less widely implemented, provide a critical pathway for patients with profound motor impairments by bypassing peripheral muscular activation altogether [17]. Complementing these modalities, adaptive and AI-driven algorithms including learning-from-demonstration approaches [14] and deep learning regression models [15] have been introduced to enhance motion prediction accuracy and accommodate inter-individual physiological variability. Across the literature, exoskeletons are realized in rigid, soft, and hybrid configurations, frequently incorporating mechanisms such as Bowden cable transmissions or pneumatic actuators to achieve a balance between effective force output and user comfort. Taken together, these developments highlight the growing potential of combining multimodal sensing with intelligent control architectures to advance rehabilitation toward more personalized, efficient, and clinically impactful solutions.

4. FUTURE-ORIENTED ENGINEERING CHALLENGES IN WRIST REHABILITATION ROBOTICS

To address current limitations and accelerate the clinical adoption of wrist exoskeleton technologies, future research should concentrate on four interrelated domains that collectively hold the potential to transform these systems into practical, scalable, and widely accessible rehabilitation solutions.

The adoption of soft robotic components including pneumatic actuators, shape-memory alloys, and tendon-driven compliant mechanisms can substantially reduce the mass and rigidity of exoskeletons, thereby improving comfort while retaining sufficient force generation. Designs such as Vertongen et al.'s [30] dorsal-mounted prototype could be enhanced through textile-based actuators or bio-inspired materials that better conform to human anatomy. Such strategies may overcome the mechanical complexity and bulk observed in earlier designs like Triolo et al. [44] and Wei et al. [31] rendering devices more practical for prolonged use. Likewise, lightweight composites can provide structural durability while reducing weight, a critical feature for individuals with muscle weakness or those engaged in long-term rehabilitation.

Artificial intelligence offers unprecedented opportunities for individualized rehabilitation. Building upon the CNN-based movement-intention recognition framework of Xia et al. [32], AI algorithms could dynamically tailor therapy parameters including actuator force, resistance, and movement trajectories in real time, adapting to biomechanical performance, fatigue, and recovery progression. Machine learning models can integrate multimodal inputs (e.g., EMG, IMU, and grip-force data) to generate evolving patient-specific therapy profiles, ensuring optimal challenge levels while minimizing risks of overexertion.

Transitioning from tethered systems to fully wireless, battery-optimized platforms would markedly improve usability and encourage home-based rehabilitation. Incorporating IoT connectivity would allow devices to log performance data, synchronize with secure cloud services, and provide clinicians with real-time progress dashboards. Wei et al.'s [31] teleoperation framework exemplifies the foundation of this approach; the incorporation of low-latency wireless protocols could eliminate restrictive cabling while facilitating predictive maintenance through automated alerts of potential system failures.

The integration of exoskeletons into tele-rehabilitation ecosystems could extend therapy access to underserved or remote populations. Through VR- and AR-based environments, patients could perform gamified, task-specific exercises that promote motivation and adherence. Clinicians would gain the ability to remotely monitor performance, adjust treatment plans, and provide live feedback. Multi-sensory feedback incorporating haptic, auditory, and visual cues could further enhance neuroplasticity, engagement, and motor relearning.

Evidence from recent studies supports these trajectories. Meng et al. [33] and Nava-Téllez et al. [34] highlighted the growing emphasis on lightweight and modular architectures, while Nazari et al. [35] showcased EMG-driven control systems that anticipate future AI-enabled personalization. Nishida et al. [36] and Peperoni et al. [37] emphasized novel kinematic alignment methods, laying groundwork for multimodal feedback integration, while Santos et al. [38] demonstrated the feasibility of IoT-enabled rehabilitation through the Nuada Glove. Collectively, these contributions illustrate a transition toward devices that are not only mechanically optimized but also digitally integrated, patient-specific, and clinically scalable.

In summary, the trajectory of research underscores that the next generation of wrist and hand exoskeletons will be defined by the convergence of lightweight hardware, adaptive AI control, wireless connectivity, and immersive tele-rehabilitation frameworks. Progress in these areas requires sustained interdisciplinary collaboration spanning robotics, materials science, neuroscience, data science, and clinical practice. By advancing these four directions; lightweight soft robotic design, AI-driven personalization, IoT-enabled mobility, and tele-rehabilitation integration, future exoskeletons can evolve from experimental prototypes into clinically viable, widely accessible rehabilitation technologies. Ultimately, these innovations hold the promise of not only improving recovery outcomes but also democratizing access to rehabilitation, thereby enhancing long-term quality of life for patients worldwide.

5. BRIDGING CURRENT LIMITATIONS THROUGH PROPOSED RESEARCH IN WRIST EXOSKELETONS

One of the central challenges in advancing wrist exoskeletons lies in balancing functional precision with portability. High-performance systems, such as the five-fingered powered exoskeleton developed by Triolo et al. [39] demonstrated substantial gains in grip and pinch assistance, reducing muscular load by nearly 67%. However, reliance on rigid ABS plastic, multiple actuators, and integrated batteries increased bulk and reduced comfort for extended use, limiting practicality in home-based rehabilitation. Similarly, Wei et al. [31] achieved accurate motion tracking and force reproduction through adaptive teleoperation, yet their servo-motor–driven architecture added considerable weight and complexity. These limitations highlight a pressing research need for lightweight, high-strength materials, compact actuation systems, and energy-efficient power supplies that maintain therapeutic efficacy without compromising wearability. Moreover, current tendon-driven designs such as that of Silva et al. [40], while promising in natural motion replication, still fall short in grip force and fine motor precision. Future research must prioritize bio-inspired actuation mechanisms and miniaturized power solutions to overcome these constraints.

Although existing prototypes demonstrate technical feasibility, their long-term usability remains uncertain. Studies such as Rojek et al. [41] emphasize the need for broader clinical validation beyond simulations to assess device effectiveness in diverse patient populations. Hybrid systems by Jiazheng et al. And [42] Gerez et al. [43] often deliver high accuracy but depend on rigid frameworks and complex actuator arrangements, which hinder portability and ease of use. Even when functional improvements are reported, as in Claudia et al. [44] reliance on contralateral assistance and limited comfort restrict user independence. For future development, emphasis should be placed on simplified donning and doffing mechanisms, minimal calibration requirements, and adaptive user interfaces that reduce setup burden and encourage consistent home use. Moreover, highly advanced CNN-based systems like Xia et al. [32] illustrate the potential of AI-driven precision but simultaneously raise concerns about maintenance, robustness, and accessibility for non-technical users. Research must therefore address human factors engineering and patient-centered design principles to ensure that advanced control technologies translate into practical, everyday solutions.

The high cost of advanced exoskeletons remains a critical barrier to widespread adoption, particularly in resource-limited healthcare systems. Soft robotic designs, such as those by Rudd et al. [45], provide a more affordable alternative but are often constrained by limited force output and battery endurance. The expense of high-grade actuators, complex sensor arrays, and custom fabrication further restricts scalability. To address this, future studies should explore low-cost manufacturing techniques, modular designs adaptable to different anatomies, and sustainable material solutions that reduce production costs without compromising performance. Developing standardized design templates and open-source hardware/software frameworks could also help democratize access to exoskeleton technology, particularly in underserved regions.

Beyond engineering and cost considerations, regulatory frameworks remain underdeveloped. Devices such as HandMATE by Sandison et al. [46] illustrate the potential of app-integrated rehabilitation but also highlight challenges in long-term validation and clinical adaptability. The absence of harmonized standards for safety, performance testing, and clinical outcome metrics creates barriers to large-scale trials, regulatory approval, and insurance reimbursement. Addressing this gap will require collaborative efforts to establish global benchmarks for efficacy, reliability, and patient safety, enabling developers, clinicians, and policymakers to align expectations. Future research should not only focus on technical refinement but also engage with regulatory bodies, clinical stakeholders, and industry partners to create a standardized evaluation ecosystem that accelerates clinical translation.

Despite the substantial progress made in the design and development of wrist and hand exoskeletons, the challenges outlined in terms of technical constraints, usability, cost, and regulatory gaps highlight the pressing need for continued research. Addressing these barriers requires not only mechanical refinement but also the integration of emerging technologies such as lightweight soft robotics, adaptive artificial intelligence, and wireless connectivity. Moreover, greater emphasis must be placed on clinical validation, user-centered design, and scalable manufacturing strategies to ensure that these systems can transition from laboratory prototypes into real-world, widely accessible rehabilitation tools. Building on the current limitations, the following section outlines proposed research directions that have the potential to redefine the future of wrist exoskeleton rehabilitation and accelerate their adoption in both clinical and home-based settings.

6. CONCLUSION

Wrist and hand exoskeletons have progressed from conceptual prototypes into increasingly sophisticated rehabilitation systems that merge mechanical design, intelligent control, and patient-centered usability. This review highlights the breadth of current approaches, spanning rigid, soft, and hybrid architectures, each with distinct advantages in force generation, comfort, and adaptability. Control strategies leveraging EMG, EEG, and multimodal sensing augmented by adaptive and AI-driven algorithms demonstrate the potential for highly personalized and responsive therapy. At the same time, challenges remain in reducing weight and complexity, ensuring long-term usability, and achieving cost-effective scalability for broader clinical and home-based adoption. Looking ahead, advances in lightweight and bio-inspired materials, integration of soft robotics, AI-based personalization, wireless IoT-enabled architectures, and tele-rehabilitation platforms represent promising avenues to overcome existing barriers. The convergence of these technologies suggests a trajectory toward exoskeletons that are not only therapeutically effective but also practical, wearable, and accessible across diverse care settings. Achieving this vision will require sustained interdisciplinary collaboration among engineers, clinicians, material scientists, neuroscientists, and regulatory bodies to ensure that innovation is aligned with safety, clinical efficacy, and patient needs. Ultimately, next-generation wrist exoskeletons hold the potential to transform rehabilitation, bridging robotics and neuroscience to deliver more adaptive, inclusive, and impactful recovery solutions.

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