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Upper-Limb Robotic Exoskeletons for Neuromuscular Rehabilitation: A Systematic Review on Lightweight Architectures and Bio-Cooperative Control

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Abstract. Stroke and neuromuscular injuries constitute a leading global cause of severe long-term upper-limb motor disability. Although rehabilitation robotics has proven effective in inducing activity-dependent cortical neuroplasticity through high-intensity training, a significant translational gap persists between complex laboratory prototypes and commercially accessible home-based systems. To address this, a systematic review was conducted following PRISMA 2020 guidelines, analysing 45 studies from high-impact databases (2016–2026) focused on mechatronic design and clinical validations. The findings reveal a critical transition from rigid-link anthropomorphic exoskeletons toward cable-driven and soft robotic architectures, successfully reducing arm-coupled inertia to under 1.5 kg and mitigating kinematic misalignment risks at the physical human–robot interaction (pHRI) interface. However, a severe validation gap persists: only 6 of the 45 included studies (13.3%) conducted clinical validation in neurological cohorts, and only 4 (8.9%) implemented multi-week training protocols. Additionally, the high computational cost and bio-signal noise susceptibility of advanced sEMG-driven Assist-as-Needed (AAN) controllers currently limit their viability for autonomous home use. The review concludes that democratising robotic telerehabilitation requires prioritising intrinsic mechanical compliance, affordability (<$2,500 USD), and IoT telemetry over redundant structural complexity, alongside an urgent shift toward rigorous multicentre Randomized Controlled Trials (RCTs).

Keywords: Upper-Limb Exoskeletons, Neuromuscular Rehabilitation, Soft Robotics, Telerehabilitation, Physical Human–Robot Interaction, Bio-Cooperative Control.

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1 Introduction

Rehabilitation robotics has emerged as a transformative technology, enabling precise training dosage, high repeatability, and objective quantitative assessment of patient motor performance over time (Gull et al., 2020; Narayan et al., 2021). Historically, these systems have been divided into two primary architectural categories: end-effector devices and exoskeletons. While end-effectors are mechanically simpler and faster to configure, exoskeletons possess the intrinsic advantage of directly coupling with the user's anatomical segments, allowing isolated and independent control of specific joints (such as the shoulder complex, elbow, and wrist) to faithfully replicate the complex spatial trajectories required in Activities of Daily Living (ADLs) (Bhujel & Hasan, 2023; Islam et al., 2017). Despite their undeniable biomechanical advantages, upper-limb exoskeleton design faces profound challenges due to the redundant kinematic complexity of the human arm (Solazzi et al., 2024; Vazzoler, 2024).

Cerebrovascular accidents (stroke) and neuromuscular injuries represent one of the primary causes of long-term upper-limb motor disability worldwide, leaving a vast majority of survivors with partial or total hemiparesis in the upper extremities (Barbosa et al., 2021; Da-Silva et al., 2018). The recovery of functional capacity to perform ADLs depends fundamentally on cortical neuroplasticity. This neuronal reorganisation process demands high-intensity, task-oriented, and highly repetitive rehabilitation therapy (Qassim & Wan Hasan, 2020).

Despite more than two decades of intense mechatronic advances, specialised literature highlights a persistent gap between clinical research prototypes and commercially accessible, deployable devices (Islam et al., 2017). A large proportion of traditional exoskeletons rely on metallic rigid links and heavy joint-mounted actuators, resulting in bulky, high-inertia structures with prohibitive acquisition costs for low-budget clinics or home adoption (Curcio & Carbone, 2021; Palazzi et al., 2022). Furthermore, this structural rigidity imposes a critical safety issue known as kinematic incompatibility in physical human–robot interaction (pHRI). Because human anatomical centres of rotation (particularly the shoulder complex) undergo dynamic spatial migration during movement, inevitable misalignment with fixed robot joint axes generates hyperstatic parasitic interaction forces. These unwanted forces cause severe discomfort, restrict natural biological range of motion, and can lead to secondary joint subluxation or tissue injury in patients with hypertonia or spasticity (Li et al., 2021; Zeng et al., 2026).

To mitigate these issues and facilitate the transition of therapy from clinical settings into the home (telerehabilitation), design paradigms are undergoing an important evolution. Recent engineering research is moving away from heavy joint-located motors, exploring biomimetic soft robotics, pneumatic actuators, and remote cable-driven systems. These novel topologies significantly minimise the coupled limb inertia and provide intrinsic mechanical flexibility (compliance) that enhances safety (Bastos et al., 2026; Chiou et al., 2023; Durante et al., 2022; Leone et al., 2025; Lessard et al., 2018). Nonetheless, while these lightweight architectures demonstrate clear translational and ergonomic promise, their clinical efficacy relative to rigid systems remains to be fully substantiated in large-scale patient trials.

Simultaneously, control schemes have migrated from passive mobilisation toward bio-cooperative Assist-as-Needed (AAN) strategies. These architectures integrate artificial intelligence algorithms supported by surface electromyography (sEMG) and brain–computer interfaces (BCIs) to decode user motor intention, incentivising active muscular effort and maximising neuroplasticity (Kim et al., 2021; Liu et al., 2021; Meng et al., 2022; Sim et al., 2026). The fusion of these lightweight modular devices with Internet of Things (IoT) platforms and gamified Virtual Reality (VR) environments stands as a key pillar for sustaining therapy adherence in home settings (Campos et al., 2021; Rozevink et al., 2021; Silva et al., 2025).

Although several broad reviews exist in medical robotics (Gull et al., 2020; Narayan et al., 2021; Sirawattanakul & Sanngoen, 2020), an updated synthesis focused specifically on enabling technologies that bridge the lab-to-home gap is imperative. Therefore, the objective of this systematic review is to analyse and contrast recent mechatronic breakthroughs in upper-limb exoskeletons. Specifically, this paper evaluates the impact of lightweight architectures (cable-driven and soft materials) on kinematic compatibility, examines the practical feasibility of myoelectric control, and critically delineates research gaps (cost, regulatory hurdles, and clinical trials) that must be addressed to successfully commercialise and democratise these systems for autonomous home use.

1.1. Analysis of Prior Reviews and Gaps in Literature

Over the past decade, rapid development in rehabilitation robotics has prompted numerous review publications aimed at classifying and evaluating the state of the art in upper-limb exoskeletons and end-effectors (Gull et al., 2020; Qassim & Wan Hasan, 2020; Sirawattanakul & Sanngoen, 2020). Most of these works provided foundational knowledge by focusing primarily on mechanical design classification, kinematic modelling, or physical actuator typology.

However, a detailed scrutiny of these reviews reveals significant methodological and conceptual gaps. For instance, Islam et al. (2017) critically point out that several previous surveys documented hardware specifications (such as degrees of freedom or motor types) in isolation, omitting an integrative discussion correlating these metrics with underlying control methods, weight, portability, and therapeutic modes. Similarly, Bhujel and Hasan (2023) note that while the dichotomy between end-effector platforms and exoskeletons has been frequently studied, recent literature lacks a rigorous comparison simultaneously addressing design characteristics alongside real-world usability barriers and commercialisation challenges.

More critically, as highlighted by Narayan et al. (2021) after reviewing over 200 studies, despite rigorous compendiums on actuation methods and machine architectures, there remains a lack of comprehensive evaluations crossing training modes (passive, active-assisted, resistive) with objective outcomes from clinical trials. Technical literature frequently separates mechatronic validation—conducted predominantly in laboratory environments with healthy subjects to test control algorithms—from longitudinal clinical validation in post-stroke patients. This fragmentation hinders the medical community from determining which combinations of lightweight hardware and control interfaces translate into superior motor recovery.

Additionally, clinical systematically oriented evaluations, such as those presented by Barbosa et al. (2021) and Da-Silva et al. (2018), highlight high methodological heterogeneity in Randomized Controlled Trials (RCTs) involving robotic assistance. These authors underscore a notable deficiency in analysing device autonomy, as previous surveys rarely address the ergonomic, safety, and telemetry requirements needed to transfer these technologies to self-directed home therapy programmes (telerehabilitation).

Therefore, a comprehensive systematic review establishing a critical nexus between emerging low-profile mechanical topologies (soft robotics and cable-driven systems) (Leone et al., 2025; Lessard et al., 2018), bio-cooperative motor intention control performance (Liu et al., 2021), and clinical efficacy reported in recent trials is needed to delineate the real state of viability for home-based robotic rehabilitation.

1.2. Review Objectives and Research Questions

To address the identified methodological gaps and provide a critical perspective guiding future assistive motor platform development, this review conducts a systematic analysis focused on the technical and economic balance required to translate technology from the laboratory to society.

The primary objective of this review is to systematically evaluate enabling technologies and recent design paradigms in upper-limb exoskeletons, determining how mechanical simplification, lightweight materials, and motor intention-based control impact the feasibility of home telerehabilitation versus traditional clinical therapy.

To break down this objective, the following three core Research Questions (RQs) were formulated:

RQ1. Kinematic Compatibility vs Structural Rigidity (Human–Robot Interaction): How does the technological transition from traditional rigid links toward sub-actuated architectures, soft robotics, and cable-driven systems impact the mitigation of parasitic interaction forces at the physical human–robot interaction (pHRI) interface? The aim is to clarify whether mechanical complexity reduction translates to enhanced anatomical safety and prevention of secondary joint trauma (Bastos et al., 2026; Leone et al., 2025; Li et al., 2021; Zeng et al., 2026).

RQ2. Clinical Efficacy vs Control System Computational Cost: To what extent do Assist-as-Needed (AAN) controllers, integrated with bio-signal decoding (sEMG, EEG/BCI) and hybrid actuation (e.g., Functional Electrical Stimulation, FES), demonstrate quantifiable clinical superiority over pre-programmed passive trajectories? The goal is to evaluate whether high computational burden and bio-signal noise susceptibility justify implementation in patients with severe neurological impairment and spasticity (Ben Abdallah et al., 2025; Kim et al., 2021; Meng et al., 2022; Sim et al., 2026).

RQ3. Home Viability (Telerehabilitation) vs Commercial Cost: What are the technical trade-offs assumed in low-cost designs oriented toward clinical decentralisation? Analysis will focus on how topological optimisation for drastic weight reduction, coupled with Internet of Things (IoT) telemetry and Virtual Reality (VR) environments, is shaping self-directed therapeutic platforms that are ergonomic, economically affordable (substantially lower cost than hospital-grade units), and capable of maintaining patient engagement without constant in-person supervision (Campos et al., 2021; Curcio & Carbone, 2021; Falkowski et al., 2026; Palazzi et al., 2022; Rozevink et al., 2021).

2 Methodology

2.1. Search Strategy and Eligibility Criteria

To ensure rigorous methodology, transparency, and reproducibility, this systematic review was conducted in strict accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement. The comprehensive literature search was executed on 15 January 2026, covering peer-reviewed studies published between 1 January 2016 and 15 January 2026 across major scientific databases: IEEE Xplore, Springer Nature (SpringerLink), and MDPI.

The search strategy was customised for each database using field-specific query builders and Boolean syntax. The core search string combined terms relating to the anatomical target, robotic architecture, and target neurological pathology:

("upper limb" OR "upper extremity" OR arm) AND (exoskeleton OR "rehabilitation robot" OR "end-effector" OR "soft robotics") AND (stroke OR hemiparesia OR "spinal cord injury" OR "muscular dystrophy" OR "cerebral palsy" OR "multiple sclerosis")

Database-specific syntax adaptations were applied as follows: (i) for IEEE Xplore, command-line search was applied with metadata restrictions in Title, Abstract, and Index Terms; (ii) for SpringerLink, multi-field search queries were paired with computer science, biomedical engineering, and medicine discipline filters; and (iii) for MDPI, advanced search was executed across robotics, sensors, bioengineering, and biomimetics topic sections. In addition, a backward and forward snowballing strategy (citation chaining) was employed to identify seminal literature and consensus guidelines endorsed by international engineering and biomechanics societies (e.g., ASME, IEEE, Elsevier, and SAGE Publications).

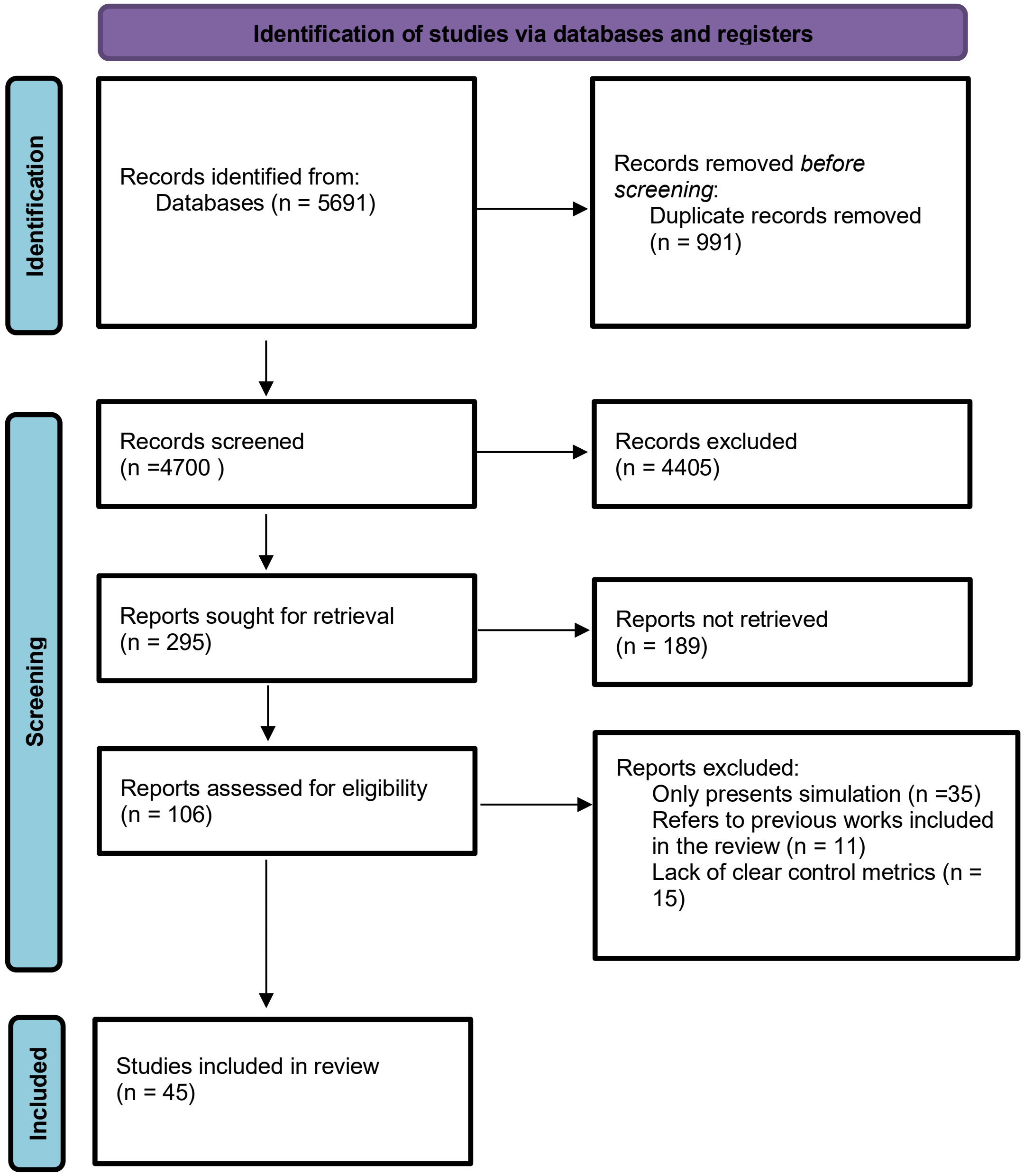
Inclusion criteria encompassed: (i) original peer-reviewed research and state-of-the-art review articles published in English or Spanish between 2016 and 2026; (ii) studies presenting mechatronic design, kinematic modelling, or physical prototypes of upper-limb robotic platforms; (iii) studies developing active control algorithms (e.g., pHRI impedance, AAN, sEMG decoding, or hybrid FES); and (iv) clinical or pilot validation trials involving neurological patient populations or healthy-subject benchmark cohorts. Exclusion criteria were defined as: (i) purely passive orthoses devoid of actuation or active sensorized feedback; (ii) robotic systems targeting exclusively the lower limbs; (iii) software-only kinematic simulations lacking physical prototype validation; (iv) duplicate publications or extended abstracts; and (v) studies lacking clear quantitative engineering or clinical performance metrics.

2.2. Search Results, Study Selection, and PRISMA 2020 Selection Flowchart

The initial database queries retrieved 5,691 records: 1,113 from IEEE Xplore, 319 from MDPI, and 4,259 from Springer Nature. All records were exported into reference management software, and 991 duplicate records were identified and removed. The remaining 4,700 titles and abstracts were independently screened by two reviewers (Y.V.G. and M.A.A.D.) against predefined eligibility criteria. A total of 4,405 records were excluded at the title/abstract screening stage due to irrelevant scope.

Subsequently, 295 reports were sought for retrieval, of which 189 were not retrieved. The remaining 106 full-text articles were assessed in duplicate for eligibility. Discrepancies between reviewers at the full-text stage were resolved through structured discussion and consensus adjudication by a third senior reviewer (A.R.L.R.), achieving 100% inter-rater agreement. Following full-text evaluation, 61 articles were excluded with specific reasons recorded: only presents simulation (n = 35), lack of clear control metrics (n = 15), and refers to previous works included in the review (n = 11). Consequently, 45 studies met all criteria and were included for qualitative synthesis, critical appraisal, and quantitative comparative analysis (Figure 1).

Figure 1. PRISMA 2020 Literature Selection Flowchart for Study Identification, Screening, and Inclusion.



3 Mechanical Architectures and Design

The clinical viability and biomechanical performance of a rehabilitation robotic system depend intrinsically on its mechanical architecture. The structural design dictates the physical human–robot interaction (pHRI) interface, assisted degrees of freedom (DoFs), reachable workspace, range of motion (ROM), and overall system mass and inertia. Systematic analysis of recent literature categorises upper-limb rehabilitation platforms into two primary paradigms: end-effectors and exoskeletons, with the latter showing a strong evolutionary trend toward hybridization with soft robotics, Bowden-cable transmissions, and pneumatic actuators to mitigate coupled inertia (Bhujel & Hasan, 2023; Lessard et al., 2018).

3.1. End-Effector Platforms

End-effector systems interact with the patient through a single distal attachment point, typically at the hand or wrist. These architectures do not require precise alignment with individual biological joint axes, simplifying donning/doffing, setup, and clinical preparation time (Bhujel & Hasan, 2023).

Trajectory-Tracking Systems: Dong et al. (2022) proposed an end-effector featuring servomotors that decouple 2D horizontal motion from vertical elevation, enabling linear position interpolation for task-oriented therapy. Zhao et al. (2021) presented a simplified 1-DoF device focused on repetitive spatial movement patterns.

Low-Cost Parallel Architectures: To address home telerehabilitation, Curcio and Carbone (2021) designed a portable Delta-like parallel robot (3 translational DoFs, end-effector mass ~2.5 kg). Its compact, affordable architecture (estimated cost <$1,500 USD; workspace 300 × 300 × 250 mm) is specifically tailored to overcome domestic infrastructure constraints.

3.2. Rigid-Link Anthropomorphic Exoskeletons

Unlike end-effectors, exoskeletons attach along the upper limb, acting in parallel with human anatomy. Their primary clinical advantage lies in isolated, independent assistance for shoulder, elbow, and wrist joints (Islam et al., 2017).

High-Redundancy Systems (High DoF Count): To replicate ADLs, modern designs maximise DoFs. Al-Asady and Takhakh (2025) presented an 8-DoF exoskeleton modelled mathematically via Denavit–Hartenberg (D-H) convention to accurately map shoulder complex kinematics. Guatibonza et al. (2024) developed a 7-DoF platform (~6.1 kg arm mass) featuring a novel arm-switching configuration adaptable to both left and right arms.

Shoulder Alignment and Dynamics: To preserve anatomical shoulder motion without subluxation, Kim and Deshpande (2017) introduced 'Harmony' (total system mass 31.2 kg; arm unit ~6.8 kg; peak torque 60 Nm shoulder, 30 Nm elbow), featuring a scapulohumeral mechanism that mimics anatomical shoulder ring motion (85–95% physiological ROM). For dynamic transparency, Zimmermann et al. (2019) developed ANYexo (6 active + 1 passive DoFs, arm mass ~12.5 kg), utilising modular series elastic actuators (SEAs) optimised for low coupled inertia and high transparency up to 11 rad/s during high-speed motion.

Cost and Weight Optimisation: Addressing heavy joint motors, Palazzi et al. (2022) introduced an affordable parallelogram architecture with a passive Gravity Compensation System (GCS), dramatically reducing torque requirements.

Table 1 provides an extensive quantitative and architectural comparison between representative end-effector and rigid-link anthropomorphic exoskeleton platforms, detailing active/passive DoFs, target joints, actuation, peak torque/bandwidth, coupled mass, estimated cost categories, and physiological ROM coverage.

Table 1. Quantitative comparative summary of representative End-Effector and Rigid Exoskeleton platforms.

Platform / Robot	Active / Passive DoFs & Kinematic Chain	Target Joint / Anatomical Motion	Actuation, Peak Torque & Control Bandwidth	Coupled Mass & Key Performance Indicators (Cost / ROM / Force)	References
MIT-MANUS / InMotion Arm	2–3 Active DoFs (Planar SCARA)	Shoulder & elbow (horizontal plane); optional wrist (F/E, P/S)	Brushless DC motors; Impedance & AAN control (1 kHz loop)	Coupled mass: ~15 kg; Benchmark planar reaching; Cost: >$80k; ROM: 2D horizontal plane	Islam et al. (2017)
ULRR Robot	3 Active DoFs (Serial/Parallelogram)	Spatial reaching (shoulder & elbow horizontal + elevation)	Servomotors; Linear position interpolation (500 Hz)	Coupled mass: ~8.5 kg; Decouples 2D planar motion from vertical elevation; Cost: ~$5k	Dong et al. (2022)
Delta-like Robot	3 Active DoFs (Parallel Delta)	3D spatial Cartesian translation (X, Y, Z)	Base-mounted DC motors; Parallel Delta kinematics	Coupled mass: ~2.5 kg at end-effector; Designed for home telerehabilitation; Cost: <$1.5k; Workspace: 300×300×250 mm	Curcio & Carbone (2021)
NeReBot / MariBot	3 Active DoFs (Suspended Cable)	3D shoulder & elbow spatial trajectories	Cable-driven overhead frame motors; Passive patient support	Coupled mass: 0 kg on arm; Suspended cables eliminate heavy metallic links; Clinical hospital setup	Bhujel & Hasan (2023)
Harmony	7 Active DoFs (Anthropomorphic)	Shoulder (F/E, Ab/Ad, I/E rot, elev/dep); Elbow (F/E); Wrist (P/S)	Series Elastic Actuators (SEAs); Force & impedance control; Peak torque: 60 Nm (shoulder), 30 Nm (elbow)	Total mass: 31.2 kg (arm unit ~6.8 kg); Mimics scapulohumeral rhythm; ROM: 85–95% physiological; Cost: >$100k	Kim & Deshpande (2017)
ANYexo	6 Active + 1 Passive DoFs (Anthropomorphic)	Shoulder girdle (2), Glenohumeral (3), Elbow (1)	Modular SEAs (ANY-drive); Model-based feedforward torque control; Bandwidth: up to 11 rad/s	Arm mass: ~12.5 kg; Extreme transparency; High driveability; ROM: >80% ADL workspace; Clinical research grade	Zimmermann et al. (2019)
AGREE	4 Active DoFs (Exoskeleton)	Shoulder (F/E, Ab/Ad, I/E rot); Elbow (F/E)	Servomotors with load cells; Passive Anti-Gravity System (AGS); Compliance control	Arm mass: ~5.2 kg; Symmetrical architecture for left/right arm without duplicate hardware; Clinical grade	Dalla Gasperina et al. (2023)
NESM-γ	4 Active + 4 Passive DoFs (Self-aligning)	Shoulder (F/E, Ab/Ad, rot); Elbow (F/E)	Series elastic actuation with torsion springs; Muscle synergy controller	Arm mass: ~4.8 kg; 4 passive self-aligning joints attenuate parasitic forces (<4 N); ROM: 90% ADL	Pan et al. (2023); Penna et al. (2024)
7-DoF Exoskeleton	7 Active DoFs (Anthropomorphic)	Shoulder (3), Elbow (2), Wrist (2)	DC motors; Non-linear adaptive control & D-H kinematic model	Arm mass: ~6.1 kg; Rapid arm-switching mechanism (left/right); Peak torque: 25 Nm; Research prototype	Guatibonza et al. (2024)
ARMin III	4 Active + 2 Passive DoFs (Anthropomorphic)	Shoulder (3), Elbow (1), Forearm (P/S, F/E)	DC motors; Position & impedance control; Friction compensation	Mass: ~18 kg; Clinically validated benchmark; Full ADL workspace coverage; Cost: >$90k	Islam et al. (2017)

3.3. Flexible and Cable-Driven Exoskeletons (Soft & Cable-Driven)

The major bottleneck of rigid robotics is parasitic interaction force emergence caused by biological joint axis misalignment. To solve this, literature demonstrates a strong transition toward soft robotics and remote actuation.

Cable-Driven Systems: Leone et al. (2025) and Bastos et al. (2026) documented cable-driven exoskeletons that relocate heavy motors to a remote base or backpack, transmitting forces via Bowden cables. This reduces arm-coupled inertia to near zero (80–150 g/module in Leone et al., 2025; ~900 g wearable mass in Bastos et al., 2026) while reducing parasitic interaction forces to <2.5 N.

Pneumatic Actuators and Tensegrity: Lessard et al. (2018) proposed 'CRUX', a lightweight (1.3 kg) tensegrity soft exosuit using 7 aramid cable lines per arm that preserves natural motion. Durante et al. (2022) integrated straight-fibre pneumatic muscles in a 2-DoF structure, providing inherent mechanical compliance. Chiou et al. (2023) combined fluidic muscle actuators (FMAs) with torsion springs for elastic assistance (WURAES, ~1.8 kg mass, sliding mode POFSC control).

Hybrid Soft-FES Robotics: Nam et al. (2022) developed an 'Exoneuromusculoskeleton' (~1.4 kg coupled mass), integrating soft textile pneumatic support with Functional Electrical Stimulation (FES) for home self-rehabilitation.

3.4. Modular, Hybrid, and Joint-Specific Designs

Modular, Hybrid, and Joint-Specific Designs: Certain designs target high-complexity anatomical regions like the wrist. Vazzoler (2024) developed W-EXOS, a dedicated 3-DoF cable-driven wrist exoskeleton (coupled wrist mass ~420 g; 4.2 Nm peak torque; zero backlash) achieving 93% of physiological wrist ROM. Contreras-Calderón and Castillo-Castañeda (2019) created an adaptable mechanism specifically for forearm pronosupination. Dual-function systems like 'u-Rob' (Islam et al., 2021; ~5.8 kg coupled mass) operate as both an exoskeleton (joint control) and an end-effector (spatial reaching) via sliding mode control.

Table 2 provides an extensive quantitative comparison across cable-driven, soft robotic, and hybrid architectures, outlining DoF counts, actuation modes, coupled mass, parasitic force attenuation, and translational features.

Table 2. Quantitative comparative summary of Cable-Driven, Soft Robotics, and Hybrid platforms.

Platform / Robot	Active / Cable DoFs & Topology	Target Joint / Anatomical Motion	Actuation, Peak Force & Control Scheme	Coupled Mass & Key Performance Indicators (Cost / Compliance / Parasitic Force)	References
CRUX Exosuit	7 Cable Lines / arm (Tensegrity Exosuit)	Multi-joint spatial arm reaching guided by muscle lines	Aramid Bowden cables; Bilateral mimetic master-slave control	Coupled mass: 1.3 kg; Tensegrity textile structure; Zero rigid link inertia; Estimated cost: ~$1.2k	Lessard et al. (2018)
Backpack Cable Exoskeleton	7 Active DoFs (Cable-driven)	Elbow, wrist, and hand digits	Backpack servomotors; Bowden cable transmission; PID + IMU feedback	Coupled limb mass: 80–150 g/module; Base mass: 3.8 kg (in backpack); Parasitic force: <2.5 N; High portability	Leone et al. (2025)
m-FLEX	3 Active DoFs (Bowden Exoskeleton)	Elbow (F/E), Forearm (P/S), Tripod pinch grasp	Bowden cables; Portable external drive unit; Assist-as-Needed control	Coupled mass: ~900 g; Biomimetic modular design; Donning time: <4 min; Cost: ~$2.2k; Tested in acute stroke	Bastos et al. (2026)
WURAES	4 Active DoFs (Soft Exoskeleton)	Shoulder and elbow complex	Fluidic Muscle Actuators (FMAs) + torsion springs; POFSC sliding mode control	Coupled mass: ~1.8 kg; Single FMA per joint with elastic return; Inherent pneumatic compliance; Cost: <$2k	Chiou et al. (2023)
Reconfigurable Soft Exo	2–3 Modular DoFs (Soft Pneumatic)	Elbow (F/E); Wrist (F/E, Ab/Ad)	Pneumatic Muscle Actuators (PMAs); NFTSMC-NDO non-linear robust control	Coupled mass: ~1.1 kg; Modular soft joints; High disturbance rejection; Parasitic force reduction: >85%	Liu et al. (2021)
Exoneuromusculoskeleton	Multi-joint (Hybrid Exosuit)	Shoulder, elbow, wrist ADL coordination	Hybrid textile pneumatic muscles + Functional Electrical Stimulation (FES)	Coupled mass: ~1.4 kg; Synergistic biological & artificial actuation; Donning time: ~6 min; Home telerehab	Nam et al. (2022)
W-EXOS	3 Active DoFs (Wrist Module)	Wrist (F/E, U/R deviation, P/S)	Base motors with differential cable transmission; Zero backlash	Coupled mass: ~420 g on wrist; 93% physiological wrist ROM; Peak torque: 4.2 Nm; Distal focus; Cost: ~$1.8k	Vazzoler (2024)
u-Rob	5 Active DoFs (Dual Function)	Shoulder (3), Elbow (2) in 3D workspace	Hybrid serial-parallel DC motors; Sliding Mode Control (SMC)	Coupled mass: ~5.8 kg; Dual-function reconfigurability (exoskeleton or end-effector); Clinical research	Islam et al. (2021)

4 Clinical Validation and Recovery Metrics

Despite rapid mechatronic progress, literature reveals a major validation gap: the vast majority of contemporary exoskeletons are evaluated exclusively on healthy subjects (sample sizes N = 3 to N = 10) to verify engineering metrics such as kinematics, dynamic transparency, or tracking accuracy (Li et al., 2021; Leone et al., 2025; Penna et al., 2024; Zeng et al., 2026). Medical regulatory bodies and clinical guidelines require rigorous proof of efficacy through direct impact on cortical neuroplasticity and functional motor recovery in post-stroke patient cohorts (Barbosa et al., 2021; Da-Silva et al., 2018).

Specifically, out of the 45 included primary studies, only 6 studies (13.3%) conducted clinical validation in neurological patient cohorts (Bastos et al., 2026; Ben Abdallah et al., 2025; He et al., 2021; Hoppe-Ludwig et al., 2021; Nam et al., 2022; Rozevink et al., 2021). Furthermore, only 4 studies (8.9%) evaluated multi-week therapeutic training protocols (≥4 weeks), while 2 studies (4.4%) assessed single-session or preliminary pilot feasibility. The remaining 39 studies (86.7%) were restricted to benchtop mechatronic characterisation or healthy-subject usability trials (N = 3 to 10 healthy participants). Table 3 synthesises patient demographics, therapeutic protocols, dosage, and outcome measures across all primary clinical validation studies.

Table 3. Synthesis of primary clinical validation studies in neurological patients.

Platform / Device	Sample Size (N) & Patient Profile	Training Protocol, Frequency & Duration	Clinical Outcome Measures & Assessment Scales	Key Clinical Findings & Efficacy Outcomes	References
MERLIN	N = 12 (Chronic stroke)	6 weeks home telerehabilitation; 3 hrs/week (6 game sessions × 5 min/day)	WMFT (Primary), FMA-UE, ARAT, EQ-5D (Quality of life)	Statistically significant gains in WMFT (+4.8 pts) and FMA-UE (+5.2 pts, exceeding MCID); 92% adherence rate	Rozevink et al. (2021)
Exoneuromusculoskeleton	N = 10 (Chronic stroke)	20 sessions (5 sessions/week for 4 weeks); Guided reaching + FES interaction	FMA-UE (Shoulder/Elbow/Wrist), ARAT, WMFT, FIM, MAS	FMA-UE increase of +8.6 pts (exceeding MCID = 5.25 pts); Significant spasticity reduction (MAS drop of 1 grade)	Nam et al. (2022)
Armule	N = 8 (Post-stroke hemiparesis)	4 weeks (5 days/week, 30 min/session); 5 min passive + 25 min active VR mode	FMA-UE, ARAT, Modified Barthel Index (mBI), Likert usability	Significant motor improvement (FMA-UE +6.1 pts); Sustained ADL independence gains on mBI (+14.2 pts)	He et al. (2021)
m-FLEX Exoskeleton	N = 3 (Acute & subacute stroke)	20 sessions (45 min/session); Task-oriented ADL reaching and grasping	Functional Independence Measure (FIM), FMA-UE, AROM	Preliminary clinical feasibility; Active ROM increased by 22°; FIM motor score improved across all 3 participants	Bastos et al. (2026)
Hybrid FES-Robot	N = 3 (Chronic stroke)	6 weeks (30 sessions, 5 sessions/week); sEMG-triggered FES + robotic assistance	FMA-UE, Active & Passive ROM, Joint torque output	FES-robot synergy increased active torque generation by 34%; Prevented disuse atrophy; FMA-UE +4.3 pts	Ben Abdallah et al. (2025)
Custom Myoelectric Orthosis	N = 18 (Chronic stroke with hemiparesis)	Single-session usability and task execution testing (0.5–2.0 lbs weight holding)	Modified Ashworth Scale (MAS), Active ROM (AROM), PROM, Perceived Exertion	Demonstrated immediate functional enhancement; Significant reduction in muscle strain during loaded elbow flexion	Hoppe-Ludwig et al. (2021)

5 Bio-Cooperative Control and Intention Decoding

While the mechanical architecture dictates the physical safety of the physical human–robot interaction (pHRI) interface, the underlying control strategy determines the therapeutic dosage and active patient engagement. Modern rehabilitation paradigms emphasize that passive, continuous motion is insufficient for optimal neuroplasticity; instead, the user must actively initiate and attempt to execute the movement (Narayan et al., 2021). Consequently, the focus of recent literature has shifted toward bio-cooperative strategies, specifically Assist-as-Needed (AAN) controllers driven by human intention decoding.

5.1. Assist-as-Needed (AAN) Paradigms and Bio-Signal Processing

The core principle of Assist-as-Needed (AAN) control is to provide assistive torque only when the patient's biological effort falls below a predefined threshold, thereby preventing 'motor slacking' (relying entirely on the robot) and maximising muscular recruitment. To achieve this, researchers have integrated surface electromyography (sEMG) and Brain–Computer Interfaces (BCIs) to decode motor intention before the physical movement occurs.

Recent studies demonstrate significant advancements in intention recognition algorithms. Meng et al. (2022) developed a bio-cooperative control scheme utilising high-density sEMG to dynamically adjust robotic assistance based on continuous muscle fatigue monitoring. For patients with severe neuromuscular impairments (e.g., quadriplegia or acute stroke), where sEMG signals are extremely weak or absent, researchers have explored BCIs. Kim et al. (2021) proposed an EEG-controlled upper-limb exoskeleton utilising neuro-fuzzy intention recognition, while Sim et al. (2026) introduced deep learning architectures for active intention decoding, achieving high classification accuracy in laboratory settings.

5.2. Bio-Signal Noise and Computational Cost in Clinical Environments

Despite theoretical advantages, a critical gap exists between advanced intention-decoding algorithms and their practical deployment in home-based telerehabilitation. High-level control architectures—such as adaptive neural networks or non-linear sliding mode controllers (Islam et al., 2021; Liu et al., 2021)—impose a significant computational burden that is often incompatible with the low-cost microcontrollers required for affordable home devices.

Furthermore, bio-signal acquisition is highly susceptible to environmental noise. In clinical and domestic settings, sEMG reliability drastically degrades due to electrode displacement, skin impedance variations (sweating), and the presence of spasticity or hypertonia typical in post-stroke patients (Narayan et al., 2021). The over-engineering of these controllers frequently results in systems that perform excellently on healthy subjects during short laboratory trials (Sim et al., 2026) but fail to deliver robust, predictable assistance when subjected to the biological variability of stroke survivors over a multi-week therapy programme.

5.3. Hybrid Actuation (FES) and Robust Alternatives

To circumvent the fragility of complex AAN controllers, recent literature highlights a trend toward hybrid actuation, combining lightweight robotic support with Functional Electrical Stimulation (FES). Instead of relying solely on external motors guided by noisy sEMG predictions, FES directly stimulates the paretic muscles to generate biological torque.

Ben Abdallah et al. (2025) demonstrated that an AI-driven hybrid robotic-FES system significantly enhances motor unit recruitment and prevents disuse atrophy in post-stroke cohorts. Similarly, Nam et al. (2022) introduced an 'exoneuromusculoskeleton' that fuses a textile soft exosuit with FES. From an engineering and translational standpoint, this hybrid paradigm offers substantial advantages for home telerehabilitation: it reduces mechanical actuator bulk, lowers component costs, and provides an effective, robust intervention that bypasses algorithmic intention-decoding bottlenecks, although larger confirmatory clinical trials are still required.

6 Discussion: Critical Analysis and Technological Gaps

Systematic data extraction across mechanical architecture, control hierarchy, and clinical validation reveals a contrasting technological landscape. While mechatronic engineering successfully replicates human arm biomechanics, translating these systems into standard clinical practice and home environments faces systemic hurdles. Four major technical and methodological gaps are critically discussed below.

6.1. Physical Human–Robot Interaction (pHRI) and Safety: Kinematic Compatibility

The primary design challenge in rigid anthropomorphic exoskeletons is ensuring safe physical human–robot interaction (pHRI) (Bhujel & Hasan, 2023). Human anatomy does not operate around fixed joint rotation axes; the shoulder complex exhibits a scapulohumeral rhythm where the glenohumeral rotation centre migrates dynamically during elevation and abduction (Kim & Deshpande, 2017). When a rigid-link robot is attached to the arm, joint axis misalignment creates hyperstatic reaction forces and parasitic torques (Li et al., 2021; Zeng et al., 2026) that restrict natural biological motion and can cause acute joint pain, tissue trauma, or subluxation in spastic patients.

Researchers have pursued three distinct solutions. The first hyper-actuates the robot, adding active redundant DoFs (up to 7–8 DoFs) to track shoulder migration (e.g., Harmony) (Kim & Deshpande, 2017), though this increases total mass (31.2 kg), coupled inertia, and power consumption. The second approach adds passive kinematic chains (unactuated prismatic and universal joints) (Li et al., 2021; Pan et al., 2023; Penna et al., 2024) that allow mechanical self-alignment to absorb axial displacements, successfully attenuating parasitic interaction forces below 4 N without complex active control. The third and most radical approach adopts soft robotics and cable-driven exosuits (Leone et al., 2025; Lessard et al., 2018) that utilise the user's skeletal framework for support, eliminating axis misalignment issues through inherent material compliance and reducing arm-worn mass to under 1.5 kg.

6.2. From Clinic to Home: Ergonomic Barriers, IoT Telemetry, and Commercial Viability

The second major gap is the disconnection between laboratory research and commercial viability (Islam et al., 2017). Robotic platforms developed over the past decade display extreme mechatronic complexity, incorporating direct-drive motors, custom torque sensors, and industrial real-time hardware. Acquisition costs for hospital-grade commercial systems frequently exceed $100,000 USD (e.g., ArmeoPower), restricting them to high-budget medical centres (Palazzi et al., 2022).

However, neuroplasticity requires high-dose, long-term training (thousands of repetitions), which is logistically impossible to sustain in hospital settings over extended months (Rozevink et al., 2021). Thus, decentralised home telerehabilitation is imperative. A home-deployable robot does not require 7 active DoFs; it must be affordable (<$2,500 USD), lightweight, ergonomic, and intuitive for non-technical users.

Recent low-cost architectures address this need. Examples include Delta-like parallel end-effectors (Curcio & Carbone, 2021), backpack cable-driven systems (Leone et al., 2025), and distal joint-specific modules (Contreras-Calderón & Castillo-Castañeda, 2019; Vazzoler, 2024) that lower manufacturing costs. Home viability also requires robust IoT connectivity (Campos et al., 2021) to stream kinematic and sEMG telemetry to cloud servers, allowing clinicians to monitor progress and asynchronously adjust assistance while patients engage with gamified VR software (Silva et al., 2025).

Nevertheless, a critical distinction must be drawn between engineering potential and practical home viability. While soft robotics and cable-driven exosuits effectively minimise coupled inertia, their deployment in self-directed home telerehabilitation remains constrained by donning and doffing complexity. Wearable systems demand the intricate alignment of textile sleeves, anchor straps, and sensor nodes. For a stroke survivor presenting with severe spasticity or hemiparesis, independent setup is practically unfeasible without a caregiver's continuous assistance. In contrast, end-effector platforms circumvent these ergonomic barriers entirely: by interacting through a single distal attachment—such as a handgrip or forearm rest—they eliminate shoulder alignment issues and enable swift, independent patient donning, albeit at the expense of isolated joint control.

6.3. Clinical Efficacy vs Technological Complexity: The Over-Engineering Debate

Evaluating therapeutic efficacy requires questioning control system over-engineering. Literature features complex control algorithms, including deep neural networks, adaptive sliding mode control, and high-density sEMG/BCI intention decoding (Ben Abdallah et al., 2025; Kim et al., 2021; Meng et al., 2022; Sim et al., 2026). The engineering rationale for this complexity is Assist-as-Needed (AAN) control: the robot provides force only when biological effort falls below a threshold, preventing motor slacking.

However, comparing these systems with clinical trials raises a critical question: do advanced AI controllers yield superior motor recovery (FMA-UE, ARAT) compared to standard manual therapy or simple impedance devices? Systematic reviews show that while robotics increases training intensity, evidence that AI-driven exoskeletons yield statistically superior functional recovery over intensive dose-matched task-oriented therapy remains inconclusive (Barbosa et al., 2021; Da-Silva et al., 2018; Narayan et al., 2021).

Much of this advanced control technology is evaluated on small cohorts (N = 3 to 8) or healthy subjects (Bastos et al., 2026; Zeng et al., 2026), where sEMG noise, muscle fatigue, and electrode displacement degrade performance outside laboratory environments (Narayan et al., 2021). Conversely, lower-complexity interventions—such as passive training coupled with immersive VR (He et al., 2021; Rozevink et al., 2021) or sub-actuated soft suits combined with FES (Nam et al., 2022)—have demonstrated clinically meaningful Fugl-Meyer gains exceeding the Minimal Clinically Important Difference (MCID) in clinical cohorts. Therefore, current evidence suggests that technological and computational complexity does not automatically correlate with superior clinical recovery, highlighting the value of robust, mechanically compliant, and cost-effective designs.

6.4. Methodological Quality and Risk of Bias in Clinical Validation Studies

A primary finding of this review is the severe translational gap in clinical validation: of the 45 included studies, only 6 studies (13.3%) conducted clinical validation in neurological cohorts (Bastos et al., 2026; Ben Abdallah et al., 2025; He et al., 2021; Hoppe-Ludwig et al., 2021; Nam et al., 2022; Rozevink et al., 2021), and only 4 studies (8.9%) evaluated multi-week training protocols. The remaining 39 studies (86.7%) remained confined to engineering prototype testing on healthy volunteers (Islam et al., 2017; Narayan et al., 2021).

Furthermore, methodological quality assessment of available clinical studies reveals systemic risk of bias that hinders clinical standardization (Barbosa et al., 2021).

6.4.1. Risk of Bias Assessment across Clinical Trials

Because most clinical robotic studies operate as single-arm pre-post feasibility trials, methodological quality was evaluated using MINORS (Methodological Index for Non-Randomized Studies) criteria and Cochrane risk of bias guidelines (Barbosa et al., 2021; Da-Silva et al., 2018). Results indicate a high overall risk of bias across current literature due to three main factors:

Blinding Bias: Due to the physical nature of robotic therapy, blinding patients and treating therapists is unfeasible. However, trials such as the MERLIN evaluation acknowledge that outcome assessors (FMA-UE, ARAT) were also unblinded (Rozevink et al., 2021), introducing detection bias.

Selection Bias & Small Sample Sizes: Statistical power is limited by small cohorts. Promising cable-driven exoskeletons like m-FLEX (Bastos et al., 2026) and hybrid FES platforms (Ben Abdallah et al., 2025) base clinical claims on N = 3 patients. Larger studies like Armule (N = 8) explicitly state that small sample sizes restrict generalisation (He et al., 2021).

Lack of Control Groups: Most studies lack concurrent control groups receiving dose-matched conventional therapy. Without randomised allocation concealment, motor recovery cannot be definitively separated from spontaneous neurological recovery (Barbosa et al., 2021).

6.4.2. Methodological Justification for Omitting Meta-Analysis

Calculating pooled effect sizes (Standardised Mean Difference, SMD) for Fugl-Meyer scores via meta-analysis (forest plots) was methodologically discarded based on Cochrane statistical guidelines:

Absence of Controlled Variance: SMD calculation requires comparing post-intervention means and standard deviations between experimental and control arms. Because primary studies (e.g., Armule, MERLIN, Exoneuromusculoskeleton) lack concurrent control arms, pooled effect size calculations would lack mathematical validity.

Extreme Clinical and Dosimetric Heterogeneity: Training protocols vary widely in dosage. MERLIN therapy spanned 6 weeks (Rozevink et al., 2021), Armule spanned 4 weeks (He et al., 2021), and MyoProVR involved single-session usability testing (Hoppe-Ludwig et al., 2021). Combining data across acute vs chronic stroke cohorts and rigid vs soft hardware topologies would introduce excessive statistical heterogeneity, producing misleading pooled estimates.

In conclusion, while reported FMA-UE score increases demonstrate that robotic exoskeletons can achieve gains exceeding the MCID (He et al., 2021; Rozevink et al., 2021), current evidence remains primarily at Level IV (case series). To advance, research must transition from iterative prototype development to multicentre Randomized Controlled Trials (RCTs) with adequate sample sizes (Narayan et al., 2021).

7 Conclusion

This systematic review evaluated the mechatronic evolution and clinical viability of upper-limb rehabilitation robotics, explicitly addressing the translational gap between laboratory prototypes and home-based telerehabilitation. Based on the synthesis of recent literature, the formulated research questions are answered as follows:

- **Regarding Kinematic Compatibility and pHRI (RQ1):** The technological paradigm shift from highly redundant, rigid-link exoskeletons toward soft robotics, cable-driven architectures, and passive self-aligning joints offers significant biomechanical advantages for physical human–robot interaction (pHRI). By drastically reducing coupled limb mass—from up to 31.2 kg in rigid systems to under 1.5 kg—and leveraging intrinsic material compliance, these low-profile topologies effectively mitigate hyperstatic parasitic forces (<4 N) and reduce the risk of secondary joint trauma caused by shoulder axis misalignment. However, their lower torque transmission capacity and donning complexity in spastic patients represent important practical trade-offs.
- **Regarding Clinical Efficacy vs Control Complexity (RQ2):** While advanced bio-cooperative Assist-as-Needed (AAN) controllers driven by sEMG and BCIs theoretically maximise neuroplasticity, their high computational burden, calibration sensitivity, and severe susceptibility to bio-signal noise limit their practical reliability outside controlled laboratory environments. Current clinical evidence suggests that simpler, robust interventions—such as hybrid Functional Electrical Stimulation (FES), passive-assistive gamified VR, and sub-actuated mechanisms—provide clinically meaningful functional recovery (exceeding the MCID) without the vulnerabilities of over-engineered control systems. Demonstrated clinical superiority of AI-driven control over intensive conventional therapy remains unproven, emphasising the need for translational pragmatism.
- **Regarding Home Viability and Commercial Cost (RQ3):** Democratising robotic telerehabilitation requires prioritising affordability (<$2,500 USD), ergonomics, and autonomy over redundant mechanical complexity. Emerging low-cost topologies (e.g., Delta-like end-effectors, modular cable-driven suits), integrated with IoT telemetry and immersive VR interfaces, successfully address these domestic constraints. This fusion provides the necessary infrastructure for self-directed, asynchronous home therapy that maintains patient engagement while drastically reducing healthcare expenditure.

Future Directions:

The most critical barrier currently facing the field is the pervasive 'prototype syndrome', wherein mechatronic validation disproportionately occurs in healthy subjects rather than target clinical populations (only 13.3% of reviewed studies evaluated neurological patients, and only 8.9% tested multi-week protocols). To overcome this translational gap, future research must urgently pivot away from isolated hardware iterations. The scientific and clinical communities must prioritise the execution of rigorous, multicentre Randomized Controlled Trials (RCTs) with adequate post-stroke sample sizes, concurrent dose-matched control groups, standardised dosimetric protocols, and long-term retention assessments. Furthermore, establishing standardised regulatory pathways and cloud-based telerehabilitation monitoring frameworks will be vital to definitively confirm the clinical efficacy and economic sustainability of home-based rehabilitation robotics.

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