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Soft Robotics in Healthcare: A Systematic Review and Techno-Clinical Framework

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ABSTRACT

Soft robotics has emerged as a promising alternative to conventional rigid systems in medical applications requiring safe interaction, geometric adaptability, and prolonged contact with or within the human body; however, heterogeneity in device designs, actuation technologies, control architectures, and evaluation metrics continues to limit direct comparison of outcomes and slow clinical translation. This systematic review synthesizes recent evidence on soft robotics in healthcare and proposes an applied framework integrating performance, safety, and technological maturity to support both clinical adoption and engineering design. In accordance with the PRISMA 2020 guidelines, 102 studies were included in the qualitative synthesis. Results show that, in neuromuscular rehabilitation, soft exosuits, orthoses, and gloves improve walking speed, joint range of motion, and manual dexterity with acceptable safety profiles; in minimally invasive and endoluminal intervention, soft catheters and robotic systems enhance navigability and positioning accuracy along tortuous trajectories with potential reductions in tissue damage; and in wearable applications, textile, capacitive, and iontronic sensors maintain stable signal acquisition under movement and prolonged use. From an engineering perspective, pneumatic and fluidic actuation dominate current implementations, whereas closed-loop control architectures integrating high-density soft sensing remain comparatively limited. Overall, the conformability and geometric compatibility of soft robotic systems provide clear clinical and procedural benefits. At the same time, challenges related to outcome standardization, advanced control integration, and technological maturity must be addressed to accelerate reliable clinical implementation.

1. Introduction

Soft robotics aims to improve safe interaction with the human body through compliant structures and actuators that adapt to complex geometries and reduce contact pressure peaks. Perspective and review studies in soft robotics highlight the capacity of these systems to integrate safely into biomedical and assistive applications, owing to their low effective stiffness, high deformability, and compatibility with complex tissues and anatomies [1]-[4]. In parallel, the clinical and technological

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literature shows that many conventional, predominantly rigid devices still present limitations in anatomical coupling, dexterity in confined spaces, tolerance to prolonged use, and measurement stability, which compromise both clinical effectiveness and patient and healthcare professional acceptance [5]-[8]. Despite rapid progress, the evidence base remains fragmented across actuation technologies, sensing approaches, control architectures, and outcome metrics, limiting cross-study comparability and slowing clinical translation.

In this context, the use of elastomers, conductive hydrogels, functional textiles, and pneumatic or dielectric architectures has enabled the development of soft actuators and sensors capable of maintaining performance under large deformations, distributing loads, and reducing the risk of contact-related injury. Stretchable conductive materials and iontronic hydrogels enable lightweight, flexible, and conformable sensors and actuators [9]-[11]; electroactive elastomers and liquid crystal elastomers provide high-strain actuators with repeatable thermal or electrical cycling [12], [13]; and soft fluidic and pneumatic actuators constitute the basis of numerous medical and assistive robotic devices due to their ability to generate complex movements while preserving conformability [14]-[17]. Recent surveys (including 2023-2024 reviews in leading robotics venues) have strengthened the overview of enabling materials and device concepts. Yet, they often remain either technology-centric or domain-specific, without an integrated techno-clinical synthesis that connects engineering design choices (actuation/sensing/control) with clinical relevance and evidence maturity.

Clinical application in neuromuscular rehabilitation has been particularly active. Soft exosuits, orthoses, and gloves have shown improvements in functional parameters such as walking speed, distance walked, range of motion, and performance in activities of daily living in populations with motor deficits, especially after stroke or neurological deterioration. Studies with soft exosuits and orthoses for the hip and ankle have demonstrated the feasibility of modulating gait through periodic pneumatic perturbations and joint assistance during treadmill walking [18]-[20]. Complementarily, soft robotic systems for the hand and wrist, evaluated in both clinical and home settings, have reported improvements in functional task execution and manipulation, using instrumented gloves, pneumatic exoskeletons, and pressure-sensing devices for home-based rehabilitation [21]-[26]. However, variations in evaluation protocols, reported endpoints, and control/sensing integration impede direct comparison of device performance across studies and hinder the definition of design requirements for translation.

In parallel, in minimally invasive and endoluminal procedures, soft catheters and robots, including balloon-based soft endoscopes, tip-growing robots, and robotic platforms for interventional training, have demonstrated improvements in navigability, positioning accuracy, and access to tortuous trajectories. Soft robotic endoscopes with segmented balloons have been optimized for airway dilation while maintaining a respiratory lumen and teleoperated control in ex vivo models [27]. Growing soft robots have shown the ability to move through curved conduits with controlled elongation and bending, which is especially relevant in anatomies with pronounced curvatures [28]. Likewise, soft robotic simulators for transseptal puncture and soft endovascular catheters have been proposed to reduce risk during skills training and improve navigation in complex vascular anatomies [8], [29], while soft sleeve-type devices for colonoscopy aim to increase safety by redistributing pressure and sensing forces on the colonic wall [7].

In the field of wearables and physiological sensing, textile platforms, iontronic sheets, and soft sensors integrated into elastomeric polymers have demonstrated stability under movement, sweat, and deformation cycles, while preserving sensitivity to signals such as electromyography, respiration, temperature, or segmental kinematics. Strain and pressure sensors inspired by electronic skin and extensible polymer films with liquid metals, or intertwined piezoelectric/piezoresistive structures, have been developed for human motion monitoring and the decoding of complex loading patterns [10], [11], [30]-[37]. The combination of morphological compatibility and low mechanical impedance at the skin-device interface facilitates the implementation of feedback loops for continuous monitoring, lightweight assistance, and clinical haptics, with reported improvements in comfort and reduction of motion artefacts.

However, there remains a considerable range of differences between studies in terms of the methodologies used and the outcomes measured, including issues such as small sample sizes, missing data on side effects, and missing data on the duration of the impact, which makes it difficult to compare studies in different fields and using various technologies. The research contributes to the formulation of a clinically relevant taxonomy and an Integrative Evidence Summary on neuromuscular rehabilitation, minimally invasive/endoscopic procedures, and wearable devices/sensors, whose safety and outcomes are compared to each other based on the same sets of evaluation criteria, and which focuses on clinical adoption and stages of technological development. With an emphasis on clinical relevance and standardization issues that will facilitate and expedite the application of soft robotics in clinical settings, the review aims to identify optimal clinical relevance, identify standardization issues to facilitate adaptive use, and inform the development of soft robotics applications in clinical settings.

2. Method

2.1. Study Design and Protocol

The review was conducted in accordance with PRISMA 2020 guidelines, following a predefined protocol that specified the research question, thematic scope, eligibility criteria, information sources, screening procedure, data extraction process, and synthesis strategy. The study was classified as a systematic qualitative review, based exclusively on structured database searches. Decision traceability was ensured through screening logs, successive versions of the search equations, and a centralized data extraction repository. During the identification phase, 220 records were retrieved from all databases. Publications in English and Spanish were considered eligible without an a priori temporal restriction; however, time limits were iteratively refined during screening to account for thematic saturation and the consolidation of recent soft robotic technologies with clinical relevance. The final synthesis was based on 102 studies, which collectively represent the state of the art in soft robotics applied to healthcare.

2.2. Eligibility Criteria

The population included studies with human participants, both patients and healthy volunteers, as well as relevant preclinical work in ex vivo models, phantoms, or animals, provided that the stated purpose was explicitly biomedical. The intervention was restricted to soft robotic devices and systems with intrinsic mechanical compliance, such as pneumatic or dielectric actuators, shape-memory materials or liquid-crystal elastomers, hydrogels and functional textiles, tip-growing robots, soft microrobots, and conformable fluidic architectures. Three application domains were considered: neuromuscular rehabilitation and assistance, minimally invasive and endoluminal intervention, and wearables with soft sensing or haptics.

Comparator conditions included standard clinical interventions, pre-post designs without a control group, and healthy controls. Outcomes of interest encompassed functional outcomes (gait, dexterity, strength, task performance), procedural metrics (times, technical success, navigability), sensing-related measures (signal quality, stability, accuracy), and safety (adverse events, tolerability, mechanical failures). Eligible designs comprised randomized and non-randomized trials, quasi-experimental studies, case series, pilot studies, and engineering studies with a clearly defined medical purpose. Articles without verifiable evidence of device softness, studies unrelated to health, opinion pieces without data, abstracts without full text, and duplicate records were excluded.

2.3. Information Sources and Search Strategy

Systematic searches were conducted in PubMed/MEDLINE, IEEE Xplore, Scopus, and the Web of Science Core Collection, covering the entire available period in each database up to the final search date, with no initial language restriction. The Boolean search equations were defined a priori and are summarized in Table 1. Controlled vocabulary terms and free-text keywords in English and Spanish were combined using Boolean operators and truncation symbols, prioritizing terms that capture soft robotics concepts and their application to neuromuscular rehabilitation, minimally invasive or endoluminal intervention, and wearable systems with soft sensing or haptics.

Records retrieved from each platform were exported to a master spreadsheet, where bibliographic metadata (title, authors, year, journal, and DOI) were standardized. Duplicate records were identified and removed through automated and manual matching of title and DOI; when a DOI was unavailable, duplicates were resolved using combinations of title, publication year, and first author. Before full-text screening, a preliminary relevance check was performed to confirm the system's soft mechanical nature and its explicit healthcare context, ensuring consistent application of inclusion and exclusion criteria and full traceability of screening decisions.

Table 1. Boolean search equations used in the databases

Database / Registry	Field	Focus	Example search equation
PubMed / MEDLINE	Title/Abstract [tiab]	Rehabilitation	(“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”) AND (rehabilit* OR neurorehab* OR gait OR marcha OR stroke OR ictus OR “spinal cord injur*” OR tetraplej* OR “upper limb” OR dexterity OR destreza OR exosuit* OR exoesquelet* OR órtes* OR ortesis)
PubMed / MEDLINE	Title/Abstract [tiab]	Endoluminal	(“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”)
IEEE Xplore	All Metadata	Rehabilitation	(“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”)
IEEE Xplore	All Metadata	Endoluminal	(“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”)
Scopus	TITLE-ABS-KEY	Rehabilitation	TITLE-ABS-KEY((“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”) AND (rehabilit* OR neurorehab* OR gait OR marcha OR stroke OR ictus OR “spinal cord injur*” OR tetraplej* OR “upper limb” OR dexterity OR destreza OR exosuit* OR exoesquelet* OR órtes* OR ortesis) AND (clin* OR pacient* OR human* OR salud OR health* OR medical OR biomed*))
Scopus	TITLE-ABS-KEY	Endoluminal	TITLE-ABS-KEY((“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA

Database / Registry	Field	Focus	Example search equation
			OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”) AND (endolum* OR endoscop* OR catheter* OR catéter* OR endovascular OR transseptal OR colonoscop* OR “minimally invasive” OR “tortuous path*” OR “vascular access”) AND (clin* OR pacient* OR human* OR salud OR health* OR medical OR biomed*))
Web of Science (Core Collection)	TS (Topic)	Rehabilitation	TS=((“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”) AND (rehabilit* OR neurorehab* OR gait OR marcha OR stroke OR ictus OR “spinal cord injur*” OR tetraplej* OR “upper limb” OR dexterity OR destreza OR exosuit* OR exoesquelet* OR órtes* OR ortesis) AND (clin* OR pacient* OR human* OR salud OR health* OR medical OR biomed*))
Web of Science (Core Collection)	TS (Topic)	Endoluminal	TS=((“soft robot*” OR “soft robotic*” OR “soft actuator*” OR “soft gripper*” OR “compliant robot*” OR “compliant actuator*” OR “dielectric elastomer*” OR “liquid crystal elastomer*” OR LCE OR “shape memory alloy*” OR SMA OR hydrogel* OR “electronic skin” OR e-skin OR “flexible sensor*” OR “stretchable sensor*” OR “textile sensor*” OR “pneumatic artificial muscle*” OR “fluidic elastomer*” OR “soft catheter*” OR “growing robot*”) AND (endolum* OR endoscop* OR catheter* OR catéter* OR endovascular OR transseptal OR colonoscop* OR “minimally invasive” OR “tortuous path*” OR “vascular access”) AND (clin* OR pacient* OR human* OR salud OR health* OR medical OR biomed*))

2.4. Study Selection Process

Study selection was conducted at two levels by two independent reviewers. In the first phase, titles and abstracts were screened to verify the coexistence of an explicit healthcare-related objective and intrinsic soft mechanical characteristics in the device or system. In the second phase, full-text articles were assessed to confirm eligibility, assign each study to a clinical application domain, and determine its suitability for qualitative synthesis and data extraction. Discrepancies were resolved by consensus discussion and, when necessary, with the involvement of a third reviewer. The PRISMA flow diagram documents an initial identification of 220 records, followed by the removal of duplicate entries and exclusions during title/abstract and full-text screening. After this process, 102 studies met all eligibility criteria and were included in the qualitative synthesis. The flow diagram provides a transparent account of the number of records excluded at each stage and the primary reasons for exclusion.

2.5. Data Extraction

Data were extracted using a standardized template that captured key study characteristics, including study context, device type, and enabling technology, application domain, evaluation setting, outcome measures, reported effects, safety-related information, and an estimated level of technological maturity expressed using Technology Readiness Levels (TRL). For studies involving human participants, design and sample size were additionally recorded. The extraction form was pilot-tested on a subset of studies to ensure consistency between reviewers before full extraction.

2.6. Quality Assessment and Risk of Bias

Risk of bias in studies involving human participants was assessed using RoB 2 for randomized trials and ROBINS-I for non-randomized studies. Case series and pilot studies were evaluated with an adapted methodological checklist. In contrast, engineering and preclinical studies were assessed using a technical checklist focused on experimental validity, repeatability, and relevance to clinical operating conditions, including durability and safety considerations when applicable. Quality assessments were synthesized by application domain and technological category, with visual summaries used to support interpretation of overall evidence quality.

3. Results

3.1. Study Selection

A total of 220 records were initially identified through bibliographic databases and indexed registries. After data cleaning, duplicate records were removed, and the remaining records were screened by title and abstract. A total of 118 records were excluded at this stage for failing to meet the combined criteria of healthcare relevance and intrinsic soft mechanical compliance. Full-text assessment was performed on the remaining studies, resulting in 102 studies that met all eligibility criteria and were included in the qualitative synthesis. Fig. 1 summarizes the PRISMA flow for the selection process.

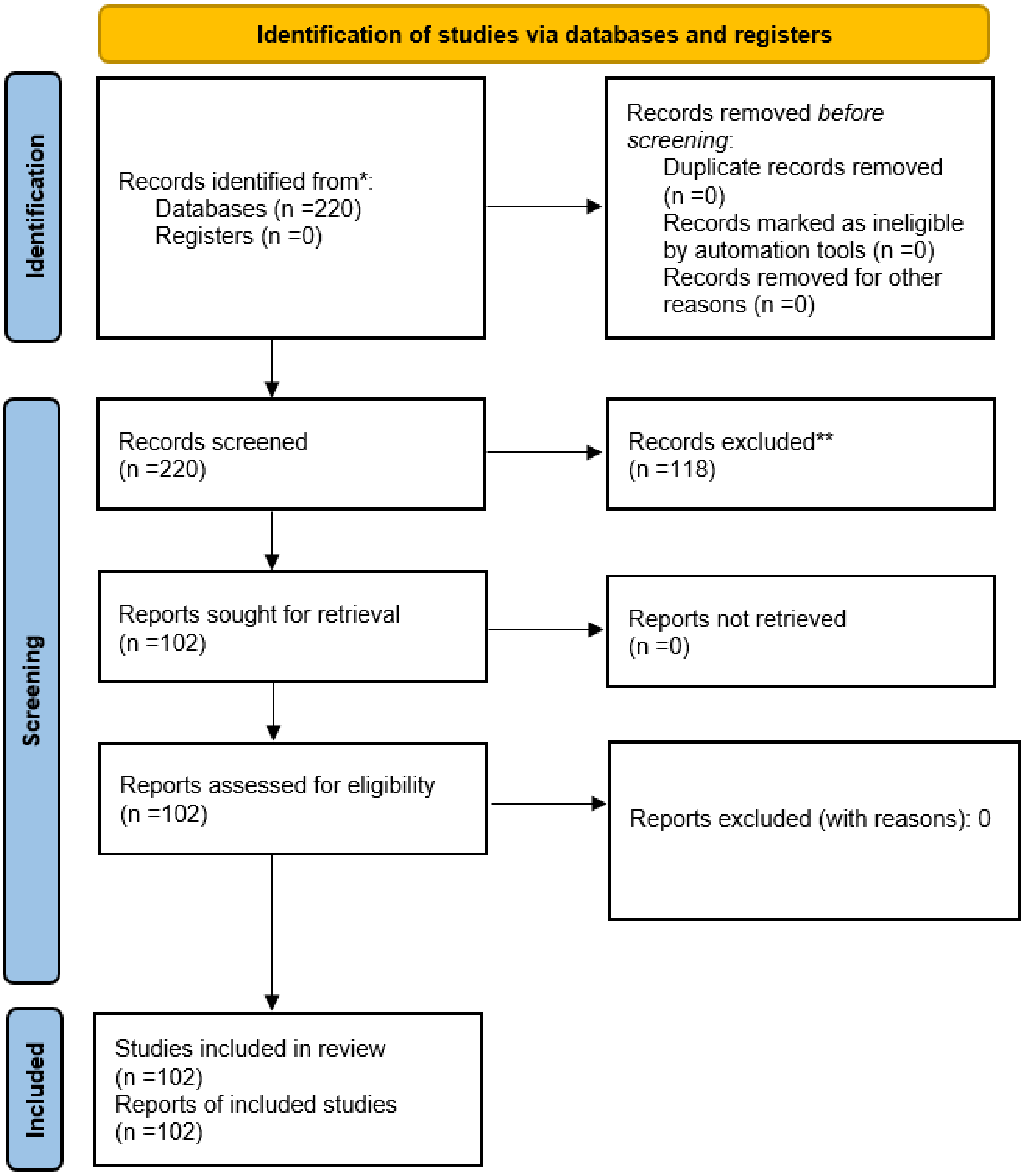

Fig. 1. PRISMA 2020 flow diagram for study selection

3.2. Corpus Characteristics

The overall characteristics of the corpus are summarized in Table 2, which groups studies by primary application domain and predominant evaluation environment. Table 3 presents a complementary technological classification, highlighting enabling technologies, device typologies, and levels of technological maturity (TRL) across domains.

Table 2. Distribution of included studies by primary domain/setting and predominant environment (n = 102)

Primary domain/setting	Number of studies (n)	Predominant environment	References
Neuromuscular rehabilitation and assistance	23	Mostly human participants (clinical, pilot, home-based) and some design/engineering work	[5], [18]-[26], [38], [39], [40]-[42], [51], [52], [54], [57], [62], [63], [66], [67]
Minimally invasive and endoluminal intervention	10	Mainly preclinical/engineering (bench, phantoms, anatomical models) with some initial/early-stage clinical applications	[7], [8], [27]-[29], [46], [48], [49], [64], [68]
Soft wearables and sensing/haptics	14	Mixed; predominance of human studies (monitoring, functional use) plus engineering validations	[6], [10], [11], [30]-[32], [34]-[37], [43], [44], [47], [50]
Enabling soft robotic technologies and foundations	55	Engineering and preclinical (development of actuators, materials, models, and conceptual reviews)	[1]-[4], [9], [12]-[17], [33], [45], [53], [55], [56], [58]-[61], [65], [69], [70]-[102]

Table 2 shows that a substantial proportion of the corpus is devoted to enabling technologies and foundational aspects of soft robotics, including actuators, materials, sensing solutions, control strategies, and modeling approaches. These studies underpin the clinical systems described in the other domains, reflecting the strong interdependence between technological development and healthcare-oriented applications. Neuromuscular rehabilitation represents the largest clinically oriented domain, while minimally invasive interventions and wearables address complementary needs for navigation in confined anatomies and continuous monitoring in real-world contexts.

Table 3. Technological/thematic classification of the included studies (n = 102)

Technological/thematic category	Brief description	Number of studies (n)	TRL
Soft robotics for neuromuscular rehabilitation	Soft exosuits and lower-limb orthoses, robotic gloves, hand and gait rehabilitation systems; clinical, pilot, and home-use studies	23	TRL 6–7
Soft robots and catheters for minimally invasive/endoluminal intervention	Tip-growing robots, soft catheters, sleeves, and endoluminal platforms for colonoscopy, endoscopy, and vascular procedures	10	TRL 4-6
Soft wearables and sensing (monitoring and haptic interfaces)	Wearable strain, pressure, and tactile sensors; textile platforms and electronic skin for physiological and movement monitoring	14	TRL 5-7
Actuators, smart materials, and foundations of soft robotics	Pneumatic/fluidic actuators, dielectric elastomers, liquid crystal elastomers, hydrogels, sensing materials, and control framework	55	TRL 2-5

Table 3 highlights the heterogeneous technological maturity across application domains. Systems evaluated with human participants, particularly in rehabilitation and wearable applications, generally exhibit higher TRL levels, whereas endoluminal systems and enabling technologies are predominantly validated in laboratory or preclinical settings. This heterogeneity reflects differing translational pathways and regulatory constraints across domains.

3.3. Neuromuscular Rehabilitation and Assistance

Soft exosuits and orthoses report improvements in functional gait and upper-limb parameters in stroke, neuromuscular impairment, and ageing, including increases in gait speed and distance, greater range of motion, and gains in strength or manual dexterity [14], [18], [21], [23]-[26], [38]-[42]. Pre-post protocols and, to a lesser extent, designs with standard comparators show that soft assistance can modulate the kinematics and kinetics of lower and upper limbs during gait and manipulation tasks, with immediate effects and, in some cases, short-term carry-over.

The integration of soft sensors and neuromuscular or kinematic signals into control architectures enables adaptive assistance dosing and objective recording of user performance, reducing artefacts associated with mechanical mismatches between the device and the body segment [43]-[45]. Reported safety outcomes are generally favorable, with good tolerability during repeated supervised sessions and acceptable comfort in home-based use. However, improvements in strength or kinematic metrics do not consistently translate into proportional gains in timed functional tasks, and variability in outcome measures and sample sizes limits direct comparison across studies.

3.4. Minimally Invasive and Endoluminal Intervention

Conformable catheters, tip-growing robots and magnetically actuated soft manipulators demonstrate improved navigability and positioning accuracy along tortuous trajectories, with controlled procedure times and potential reductions in tissue damage compared with rigid alternatives [7], [8], [19], [21], [27], [29], [31], [46], [47]. In endoscopy and colonoscopy, soft solutions, including sleeves and inflatable sections, have been evaluated in bench models, ex vivo settings, and early clinical contexts, demonstrating better curvature control and, in some cases, lower forces transmitted to the organ wall [52]. In vascular and cardiac contexts, soft platforms are primarily used for training and feasibility assessment, enabling the exploration of navigation strategies in bifurcated or highly curved conduits. Across studies, geometric compatibility, tunable stiffness, and miniaturization emerge as key determinants of performance, while limitations related to sensing density, real-time feedback, and sterilization readiness constrain further clinical translation.

3.5. Soft Wearables and Sensing/Haptics

Textile platforms, capacitive and iontronic films, and sensors embedded in elastic polymers maintain sensitivity to electromyography, respiration, joint deformations and segmental kinematics while remaining stable under movement, sweat and repeated use cycles [9]-[11], [25], [30]-[37], [43]-[45], [48], [49]. Electronic-skin architectures extend these capabilities by integrating multiple sensing modalities over continuous surfaces. In monitoring and human-device interaction applications, soft sensors enable tracking of muscle activity, posture, and contact pressure during daily activities, supporting both assessment and feedback. Conformability reduces mechanical impedance at the skin–device interface and improves comfort during prolonged wear, facilitating closed feedback loops for light assistance and haptic interaction. Nevertheless, heterogeneity in testing protocols, durability assessment, and reporting metrics persists, underscoring the need for standardized evaluation frameworks in wearable soft robotics.

4. Discussion

4.1. Main Findings of the Study

In rehabilitation, soft exosuits, orthoses, and gloves have been shown to improve functional variables such as gait speed and distance, joint range of motion, and performance in activities of daily living in people with stroke, neuromuscular disorders, or age-related decline. Several studies on soft exosuits and lower-limb orthoses report immediate increases in walking speed and in the ability to generate force during assisted gait [18], [23], [38], [39], [41], [42]. Complementarily, systems for the hand, wrist, and upper limb, including soft gloves and home-based platforms, report increases in grip strength, object manipulation, and execution of functional tasks, together with good usability in older adults and individuals with motor impairments [14], [24]-[26], [40]. Across these rehabilitation applications, the combination of intrinsic mechanical compliance and adaptive assistance enables functional support without constraining natural kinematics, which appears central to both performance gains and user tolerance during repeated or prolonged use. In minimally invasive and endoluminal intervention, conformable catheters, tip-growing robots and magnetically actuated soft manipulators achieve better adaptation to tortuous anatomies and finer trajectory control, with evidence of improved navigability, positioning accuracy and potential reduction of mechanical load on organ or vessel walls in bench, ex vivo and preclinical environments [7], [8], [19], [21], [27], [29], [31], [46], [47]. These findings indicate that performance in endoluminal contexts is driven less by maximal force transmission and more by geometric compatibility, local stiffness modulation, and controlled interaction with surrounding tissues.

In the wearable domain, textile, capacitive and iontronic sensors integrated into elastic substrates maintain stable sensitivity under movement, sweat and deformation cycles, enabling recording of variables such as joint deformation, muscle activity, contact pressure and movement patterns during functional tasks and daily activities [9]-[11], [34]-[37], [43]-[45], [48], [49]. Conformability and low effective stiffness contribute to improved comfort and facilitate closed-loop schemes in monitoring and light-assistance applications. Taken together, these results support the hypothesis that softness, understood as mechanical compliance combined with geometric adaptability and distributed load transfer, constitutes a unifying design principle underlying the observed benefits across rehabilitation, endoluminal intervention, and wearable systems.

4.2. Comparison with Other Research

Compared with prior technical literature focused on rigid devices, this corpus's findings reinforce the idea that soft architectures offer advantages for tasks requiring anatomical adaptation, prolonged contact, or large deformations. Although the included studies do not always incorporate formal rigid comparators, several works explicitly state that the motivation to transition towards soft solutions is linked to limitations of comfort, geometric coupling and contact safety in conventional devices, both in rehabilitation and in endoluminal intervention and wearables [1]-[4], [7], [15], [27], [46].

In neuromuscular rehabilitation, the functional gains achieved with soft devices are, in magnitude, comparable to those reported for rigid exoskeletons for gait and upper limb. However, studies on soft exosuits and gloves consistently emphasize comfort, tolerability, and user acceptance, particularly in repeated-use or home-based protocols [14], [23]-[26], [40]. This suggests that softness may support adherence to long-term training programs, a critical aspect that is less frequently documented for rigid technologies. This contrast indicates that, beyond equivalent functional outcomes, soft systems may offer an advantage in long-term adherence and sustained engagement, aspects that are less consistently documented for rigid technologies.

In endoluminal intervention, studies on soft catheters and devices for colonoscopy, endoscopy, and vascular procedures describe better adaptation to curves and angulations, as well as strategies to reduce contact forces or redistribute pressure, in contrast with the long-standing concerns about mechanical trauma associated with rigid instruments [27], [46], [47].

In the wearable field, soft sensors and electronic skins are explicitly proposed as alternatives to rigid or semirigid sensors, which frequently exhibit detachment, motion artefacts, and local discomfort. Studies on stretchable sensors and textile platforms report signal stability and acceptable comfort under dynamic conditions that are traditionally challenging for rigid configurations [9]-[11], [34]-[37], [43]-[45], [48], [49]. At the same time, the methodological heterogeneity observed in this review is consistent with that reported in previous surveys of both soft robotics and wearable systems, indicating that the need for standardized evaluation protocols extends across technological paradigms rather than being specific to softness alone.

4.3. Implications and Interpretation of the Findings

From a clinical perspective, the results support the use of soft solutions when contact safety, conformability, and comfort are key determinants of efficacy or adherence. In neuromuscular rehabilitation, the possibility of dosing assistance through neuromuscular, kinematic, or interaction signals captured by soft sensors allows real-time adjustment of the level of support during functional tasks, which may foster active patient participation and a gradual progression of workload [14], [18], [23]-[26], [38]-[42]. The presence of home-based solutions also suggests potential for hybrid rehabilitation programs that combine supervised sessions with autonomous practice under remote monitoring [14], [24]-[26], [40].

In endoluminal intervention, local stiffness modulation, geometry compatible with curved conduits, and the ability to distribute contact forces explain the improvements in navigability and the potential reduction in tissue damage reported in airway, gastrointestinal, and vascular models [27], [29], [31], [46], [47]. These properties justify the interest in soft devices both for training complex procedures where realistic simulation of catheter-tissue interaction is key to skill acquisition and for clinical applications in which mechanical safety is critical.

In wearables and sensing, low mechanical impedance and conformability to body surfaces underpin signal stability under dynamic conditions and reduction of motion artefacts, opening opportunities for continuous monitoring, early detection of changes in functional status and integration with biofeedback or haptic stimulation systems [9]-[11], [22], [34]-[37], [43]-[45], [48], [49]. Some studies explore closed-loop configurations that combine soft sensing with actuators or haptic interfaces, pointing towards adaptive assistance systems and personalized therapies [35].

At the engineering level, these findings highlight the importance of integrating sensing and actuation within soft structures and of developing control strategies that can handle nonlinear, time-varying material behavior. At the translational level, differences in technological maturity across application domains suggest that while some rehabilitation and wearable systems approach clinical deployment, many endoluminal and enabling technologies remain at intermediate stages, underscoring the need for scalable manufacturing, standardized benchmarks, and validation under realistic use conditions.

4.4. Strengths and Limitations

A strength of this review is its exclusive focus on technologies with demonstrable softness and explicit application in health, combined with a transparent selection process and a classification by clinically meaningful domains. The breadth of technologies and testing contexts, from soft exosuits and gloves to endoluminal catheters, tip-growing robots, and portable sensing platforms, allows robust patterns to be identified regarding mechanisms of benefit, particularly the contributions of conformability and peak-pressure reduction to safety and functional performance [46].

However, important limitations remain. The heterogeneity of study designs and outcome metrics hindered quantitative pooling in several subgroups and may introduce imprecision in cross-study comparisons; this is especially evident in rehabilitation studies, which use diverse batteries of functional tests and clinical scales. Sample sizes in human studies are often modest, and safety reports sometimes lack clear denominators and uniform taxonomies for classifying adverse events, which affects risk estimation in rehabilitation and wearable applications [14], [23]-[26], [40], [42].

In engineering and preclinical studies, incomplete reporting of repeatability, durability under cyclic loading, and performance under clinically realistic conditions limits extrapolation to real-world use. Finally, although screening was systematic, publication bias and the omission of non-indexed or early-stage studies cannot be ruled out. These limitations reinforce the need for multicenter validation, harmonized outcome sets, and standardized reporting frameworks to strengthen the evidence base and accelerate clinical translation of soft robotic technologies across healthcare domains.

5. Conclusion

This systematic review of 102 studies shows that soft robotic systems improve human–device and tissue-device interaction across neuromuscular rehabilitation, minimally invasive and endoluminal procedures, and wearable sensing. Evidence demonstrates gains in gait and dexterity, enhanced navigability and positioning accuracy in confined anatomies, and improved signal stability during prolonged use, which can be attributed to conformability, local stiffness modulation, and geometric compatibility between the device and biological structures.

At the conceptual level, this review advances the field by formalizing a conformability-driven performance hypothesis, establishing an applied taxonomy linking clinical domains to underlying soft robotic technologies, and introducing a TRL-outcome-safety matrix to contextualize reported results by technological maturity and evidentiary strength. Together, these contributions provide a structured framework to support comparison between heterogeneous systems and to guide engineering and clinical prioritization.

The synthesis highlights several cross-cutting implications. Soft robotic solutions should be prioritized in applications where safety, comfort, and anatomical adaptability are critical determinants of effectiveness or user adherence. At the same time, the need for standardized outcome measures, harmonized safety reporting, and reproducible evaluation protocols is evident across all domains. From an engineering perspective, material selection and actuator design must align with clinical constraints on sterilization, cleaning, durability, latency, and functional safety, particularly for wearable and endoluminal applications.

Important limitations persist. Heterogeneity in study designs and outcome metrics, modest sample sizes in human studies, and inconsistent reporting of adverse events, durability, and long-term performance restrict certainty and generalizability. In addition, many systems remain at intermediate levels of technological maturity, reflecting bottlenecks such as limited sensing density, control latency in fluidic actuation, and the absence of standardized datasets for data-driven control and learning.

Future research should therefore focus on multicenter rehabilitation trials, controlled comparisons between soft and rigid systems in well-defined clinical indications, long-term evaluation of wearable devices under real-world conditions, and cross-domain advances in robustness testing, regulatory harmonization, and scalable manufacturing. Addressing these challenges will strengthen the evidence base and support the reliable clinical translation of soft robotic technologies.

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