Current Developments and Prospects for Soft Rehabilitation and Nursing-Care Robots

Dr. Monique Brown[1], **Dr. Rachel Wilson**[2]
[1]School of Nursing and Midwifery, University of Toronto, Toronto, Canada
[2]Department of Health Sciences, McMaster University, Hamilton, Canada

Received: 10-02-2025; Revised: 03-03-2025; Accepted: 20-03-2025; Published: 14-04-2025

Abstract

Healthcare technology has achieved a breakthrough through soft rehabilitation and nursing-care robots which deliver gentle adaptation during patient rehabilitation and elderly care. These robots reach their goal by combining soft materials with intelligent control systems as well as human-centric design to offer better patient comfort and improve both recovery rates and the quality of caregiver assistance. This article investigates modern soft robotic systems used for rehabilitation and nursing care by exploring developments related to mechanical systems and sensor integration as well as human-machine interfaces. The article addresses safety concerns together with customization problems and implementation expenses and regulatory framework issues. The paper concludes with a forward-looking perspective which combines interdisciplinary teamwork along with Artificial Intelligence components and bioinspired system development for improving accessibility and adaptability of soft healthcare robots.

Keywords: ***Soft robots, rehabilitation robotics, nursing-care robots, elderly care technology, human-robot interaction, soft actuators, patient-centered robotics, healthcare innovation, assistive robotics, future of nursing care.***

1.Introduction

The field of medical rehabilitation experienced substantial changes over the last few decades through the development of soft rehabilitation and nursing-care robots (SRNCRs). The new robotic systems pioneered a fundamental change from traditional robotic structures through the development of flexible and adaptable designs which mimic human characteristics(1). The ever-growing need for efficient accessible rehabilitation solutions matches the rising number of older people worldwide and mounting cases of mobility-limiting conditions. World Health Organization reports that stroke causes 6.2 million annual fatalities which exceed the deaths caused by AIDS, tuberculosis and malaria combined while stroke survivors need intensive rehabilitation because of their motor impairments. Traditional therapeutic methods deliver essential benefits yet they frequently encounter restrictions regarding availability and persistent care duration. The addition of soft robotic systems to modern therapeutic systems helps resolve multiple treatment obstacles while generating completely patient-oriented rehabilitation protocols.

A key difference exists between traditional robots used for rehabilitation and their soft versions and pertains to their components and structural ideas. Modern rehabilitation systems employ rigid actuators together with structures to guide movements with precision yet such devices restrict safety and user comfort and natural motion execution. Manufacturers of therapeutic devices use biological inspiration to develop compliant systems that work alongside rather than against human bodies based on human muscle and tendinous elasticities and octopus limb adaptability and elephant trunk motion capabilities. By implementing this biomimetic method SRNCRs fit onto patient-specific anatomical features and support human movement patterns in their natural variety.

Soft rehabilitation robots operate through two main technological paths which consist of tendon-driven actuation along with soft intelligent material actuation. Tendon-driven systems reproduce human tendon and ligament mechanics through the use of cables that often include Bowden cable technologies(2). This technology has produced outstanding results to direct rehabilitation exercises because it assists patients during upper and lower limb recovery. Therapists can adjust assistance levels for their patients based on personal needs through customizable payloads and diverse routing options of this system according to its design philosophy. Soft tendon routing adds value to Exo-Glove systems alongside AirExGlove development using antagonistic driving principles and fabric-based bidirectional soft gloves that assist both flexion and extension movements.

Soft intelligent rehabilitation robots represent the major revolutionary advance in the field over tendon-driven alternatives. The conversion of electrical and thermal and pneumatic stimuli into controlled physical displacement is enabled through materials found in these systems. Pneumatic fiber braids together with elastomeric polymers serve as the base components for pneumatic artificial muscles whose contractions resemble biological tension. Rehabilitation devices that respond to temperature develop through the use of Shape memory alloys (SMAs) and polymers (SMPs) which demonstrate outstanding strain capability upon heating. Electronic polymers called EAPs undergo form changes under electrical stimulation which duplicates natural muscle operations. Hydrogels demonstrate great potential to develop entirely biocompatible rehabilitation systems because of their outstanding biological compatibility features(3). The varied use of materials has extended soft rehabilitation robots' clinical scope into facial remedies and oral treatments and unique procedures which were previously out of reach for standard robotic methods.

There are numerous advantages to safety built into soft robotic systems. The therapeutic benefits of traditional rigid rehabilitation robots remain significant although their risks include patient injuries when machines malfunction because their rigid structures do not yield under such circumstances. Soft rehabilitation robots reduce these associated risks thanks to their adaptive structures that will bend when a robot encounters excessive forces while also matching patient body shapes. Patients can participate more actively in treatment activities because of this safety configuration which simultaneously decreases potential harm throughout rehabilitation sessions. Patients exhibit decreased anxiety upon interacting with these safe machines thereby accelerating their therapeutic progress because psychological concerns receive substantial benefits from this advanced safety profile.

The development of control approaches for soft rehabilitation robots presents novel critical issues to engineering research. Soft material properties exhibit strong nonlinearity along with time variations which standard control systems find challenging to manage. The development of soft system control frameworks consists of three main strategies which include model-based finite element-Lagrangian and PID methods and model-free approaches based on machine learning technologies. Distribution patterns show that tendon-driven systems initially adopted model-based and model-free approaches but soft intelligent material systems now prefer model-free methods due to their nonlinearity characteristics.

Research from clinical applications shows that soft rehabilitation robots produce beneficial results when used in different therapeutic areas. Soft robotic gloves provide benefits of up to 40% stronger grip strength along with improved motion accuracy which leads to better completion of functional daily tasks. Stroke patients receive better walking speed and stability together with improved gait symmetry through lower limb applications involving soft exosuits and pneumatic orthoses(4). The initial research shows that soft robots in rehabilitation can boost patient participation in therapy since their assistance delivers more natural support than conventional techniques.

Most obstacles continue to stand in the way of making these developments clinically universal. The majority of soft robotic rehabilitation devices exist only within laboratory environments because their market-ready mature products remain scarce in commercial markets. Current systems face financial obstacles because they demand expensive equipment for their operation. The degradation of soft materials during regular therapeutic applications burdens clinical equipment lifespan because materials lose their durability too quickly. The response capabilities as well as motion control precision and accuracy require further advancements that diminish the performance gap between rigid robotic systems. Development center will focus on incorporating next-generation sensor systems to establish seamless robotic-human communication abilities. Succeeding in therapy and determining cost-effectiveness will require extensive clinical evidence validation of new systems with fully sized patient groups under prolonged follow-up periods.

2. Mechanical Design Principles and Innovations in Soft Rehabilitation Robotics

Soft rehabilitation and nursing-care robots need fundamental mechanical engineering design changes which diverge from traditional robotic engineering principles. Traditional robotics relies on rigid components with precise joints along with determinist microbehavior functions yet soft rehabilitation robotics uses flexible shapes and biomimetic principles alongside decentralized mechanical attributes. Modern designs of soft robotic rehabilitation devices have produced a need for pioneering methodologies regarding motions systems alongside structural frameworks materials study and user interface technologies(5). These newly developed systems create new possibilities to conduct secure rehabilitation treatments that serve multiple patient groups within various therapeutic environments.

Tendon-Driven Actuation Systems: Mimicking Biological Function

The cable systems used in tendon-driven soft rehabilitation robots recreate human tendon and ligament biomechanical operations. Several special benefits make this approach suitable for rehabilitation implementations. Cable-driven systems achieve complex multi-DOF movements through their routing diversity which produces motions resembling human natural movement patterns. These systems derive their payload capacity from cable quality because it enables to calibrate assistive forces precisely for various stages of patient rehabilitation needs.

The progress demonstrated by tendon-based rehabilitation glove development showcases fast developments in this field. The initial robotic exomusculature glove prototype developed by Delph proved the potential of cable-based assistance for grip recovery by delivering up to 15N of assistance force(6). The team of Nycz along with their colleagues built upon this idea to develop complete upper limb expressive rehabilitation exoskeleton devices that added actuation of elbows and finger movement assistance capabilities. The Exo-Glove achieved a major design advance through its creators at In et al. who replaced mechanical pulleys with fabric tapes and Teflon tubes to establish a low-friction routing system that boosted wearability. This design produced excellent hand function parameters which included 20N of pinch force and 46°/48° metacarpophalangeal/proximal interphalangeal joint motion while enabling the user to hold objects of up to 76mm in diameter.

The AirexGlove demonstrates a noteworthy advancement in tendon-based designs through its antagonist system which utilizes balanced opposing cable networks like human agonist-antagonist muscle functions. The controlled operation of antagonistic systems allows users to perform hand movements naturally while gaining better management of complex functions(7). The EMG-integrated soft hand sheath by Guo features bionic fin-ray structures along with self-tightening mechanics which eases patient care for those with restricted hand mobility.

Lower limb rehabilitation has observed equal levels of innovation since adopting tendon-driven system designs. Post-surgical patients can attain 27° ankle movement following dorsiflexion and plantarflexion and inversion and eversion movements through Park’s robotic device which duplicates biological muscle-tendon-ligament functionality. The advanced soft exosuit developed by Bae and colleagues uses strategically placed Bowden cables to assist unilateral walking motions for stroke patients as it enhances both temporal symmetry and timed propulsive forces for their paretic limb.

Soft Intelligent Materials: Revolutionizing Rehabilitation Actuation

The implementation of soft intelligent materials within rehabilitation robots introduces a more basic change to existing tendon-driven systems which demonstrated effective operation. Such materials achieve controlled physical displacement from various physical stimuli to make the development of rehabilitation robots possible with unmatched levels of compliance and adaptability and biomimetic functionality.

The base components of pneumatic artificial muscle actuators consist of elastic elastomeric polymers and pneumatic fiber braids which achieve their functionality through the McKibben muscle design. The actuators contain rubber tubes wrapped in braided fabric where one tubing end operates pressure control through proportional electromagnetic valves and the opposite end stays sealed. Bending forces result from opposing sides with different elasticity when subjected to pressure(8). The principle enabled Polygerinos and colleagues to create silicone-based soft rehabilitation gloves which exhibited more than 320° bending along with sufficient force for passive finger closing actions. Rectangular actuators developed from original designs enhanced both precision of grip function and performance in tasks where clinical testing revealed that patients showed a 40% boost in their block-picking capability.

Three alternative pneumatic actuation methods exist including Zhang's hyperelastic soft fingers and Al-Fahaam's linearly extending artificial muscles with fixed unilateral sleeve length and Jiang's fishbone-inspired design. A particular breakthrough has happened through the adoption of lost-wax-inverse-flow-injection manufacturing that produces multi-degree-of-freedom actuators with one pneumatic chamber to achieve complex movements. Each finger in the rehabilitation glove gets two freedom degrees from single-chamber pneumatic actuation which delivers necessary movement directions to perform multiple local rehabilitation tasks.

Soft actuators successfully power various rehabilitation devices which support shoulder rehabilitation through O'Neill's neoprene vest with fabric actuators as well as elbow rehabilitation using Zhang's two-degree-of-freedom robot and lower limb support through Huang's exoskeleton and special oral applications through Yi's silicone-based actuator.

Various soft intelligent materials help achieve specialized rehabilitation functions when used together. Even though shape memory alloys (SMAs) have temperature dependence issues they can make possible the production of lightweight rehabilitation exoskeletons such as Copaci's elbow joint system together with Villoslada's wrist exoskeleton. Firouzeh introduced SMPs into her facial rehabilitation robot to achieve appropriate resistance levels during therapy by controlling joint stiffness through temperature adjustment methods. Dielectric elastomers represent a promising candidate within electroactive polymers (EAPs) for developing new soft actuators destined for hand and wrist rehabilitation challenges stemming from insufficient force output. The area of hydrogels holds promise as an emerging technology in medical rehabilitation because Banerjee and Yuk showed early indications of developing flexible biocompatible actuators through their research.

The seamless blending of multiple actuation technologies needs innovative process development for their structural union. Production methods like soft lithography combined with 3D printing of flexible materials followed by lost-wax processing and multi-material fabrication have allowed the development of complex advanced soft rehabilitation robots(9). The combination of modern manufacturing approaches with material development improvements keeps increasing the functionality of soft rehabilitation robots and simplifying production which are essential elements for future clinical adoption and home use.

3. Modeling Methods and Control Strategies for Soft Rehabilitation Robots

The advancement of soft rehabilitation robotics depends heavily on the success of developing efficient modeling approaches with control strategies. Soft rehabilitation devices present mechanical behaviors which are complex nonlinear time-varying and defy traditional modeling frameworks because they differ substantially from conventional rigid robots. The inherent system complex nature develops through three elements: the nature of soft material characteristics in addition to operational mechanical intricacies and variable human-robot interface operations. Researchers continue to advance theoretical understanding and practical implementation methods which control such complex therapeutic devices.

Tendon-Driven System Modeling and Control

The modeling of tendon-driven soft rehabilitation robots becomes difficult because of complex mechanical interactions which occur between flexible cables and human anatomy and compliant structures. Multiple efficient modeling and control methods have developed to deliver precise safe rehabilitation procedures in the face of those challenges.

Kinematic and Dynamic Modeling

Control systems benefit from simplified kinematic models that serve as practical foundations for the design of control systems which apply to numerous tendon-based systems. Scientific studies conducted by Nycz and othershasil in building planar three-link kinematic chain models that reasonably represent finger joints to build tractable control systems. The simplified models offer enough precision for rehabilitation purposes which depend on effective assistance over precise movements.

Complex hand movement models are developed through cable-guided positioning systems which integrate palm force measurement methods. The research conducted by Kang and colleagues established a metacarpophalangeal (MCP) joint flexion model for force and direction prediction through wire actuation length and tension measurements. Experimental tests confirmed the model's accuracy resulting in minimal differences between measured and predicted wire lengths across various joint position measurements which made development of controllers possible.

Position and Admittance Control

Restorative systems rely on position control through traditional methods in their operation such as Rose's hybrid rigid-soft hand exoskeleton together with Guo's soft hand sheath. These controllers create treatment-based reference paths that direct the actuators to keep the robot at pre-defined positions during exercise sessions. The admittance control system allows robots to adjust their operations based on detected user intentions which leads to improved patient-robot cohabitation. The In's Exo-Glove utilizes wrist movement to provide intuitive control input since this movement remains functional even when patients have major hand disabilities.

Adaptive and Model-Free Approaches

The combination of difficult tendon operations alongside individual patient requirements has fueled adaptive control system development as well as approaches which do not require models. Vikas established a control system for soft robots through specific contact points that operates without exact system requirements and Kwon developed feedforward control which adjusts soft robotic ankle-foot orthosis function to changing patient ability levels(10). Bae has introduced adaptive real-time detection algorithms which represent the most advanced approach for stroke rehabilitation exosuit control. Various control systems split the gait cycle into distinct phases by using detection algorithms to update the actuator signals for delivering individualized support that matches patient-specific movement characteristics.

Soft Intelligent Material System Modeling and Control

The implementation of rehabilitation robots using soft intelligent materials remains a complex task because these systems demonstrate non-linear material behavior, complex deformations and substantial delay responses. The challenges are being tackled with model-based and model-free solution approaches.

Finite Element Modeling and Quasi-Static Analysis

Finite element modeling (FEM) serves today as an excellent method to simulate soft actuators mechanical characteristics. Polygerinos, Zhang and their coauthors Guo and Rosalia developed FEM analytical approaches which created prediction models to estimate soft pneumatic actuators' actuation responses along with deformation patterns and force output caps. Soft pneumatic actuation behavior gets accurately predicted through modeling approaches which include material hyperelasticity elements and combined with geometric nonlinearity and contact constraint components911). The research by Polygerinos and others uses quasi-static analysis together with FEM to analyze the intermediate states of actuator deformation so that dynamic behavior predictions become more precise.

According to Ru and colleagues pneumatic muscle actuators can be modeled by second-order differential equations that were identified by parameters measured during high-speed camera visual recognition experiments. This method achieved accurate representation of the nonlinear movements within fiber-reinforced pneumatic muscles suitable for controller development tasks.

PID and Extended PID Control

The combination of proportional-integral-derivative (PID) controllers shows unexpected success when used to control soft material systems which demonstrate high complexity. PID control by Wei and Delph along with other researchers enables control of pneumatic soft actuators resulting in adequate response characteristics and positioning accuracy. PID controllers stand out as excellent choices for clinical uses because they provide both simplicity and reliable system operation even when theoretical ideal solutions remain unattainable.

The performance of PID systems increases with supplementary elements that handle the nonlinear behavior observed in soft systems. Al-Fahaam uses Bang-bang closed-loop controllers in their soft rehabilitation gloves to alter control states according to position feedback and achieve effective position control by overcoming system nonlinearities. Al-Fahaam uses direct control algorithms to redesign standard PID frameworks in order to enhance the operation of soft actuators.

Advanced Nonlinear Control Approaches

Research studies implemented advanced nonlinear control methods in order to overcome soft actuators' basic nonlinear characteristics. Sliding mode control (SMC) provides excellent system trajectory maintenance through specified sliding surfaces while ignoring uncertainties and disturbances in system performance. The implementation of proxy-based sliding mode control as a control method improves performance when compared to PID control methods for soft bending actuators by delivering enhanced tracking accuracy and better disturbance response. Additional robotic systems with underactuated characteristics received attention from Huang who introduced advanced disturbance observers of higher order to optimize control robustness.

Through his proposal of the switch-mode firefly algorithm Huang developed a global parameter optimization method which selects appropriate control parameters for obtaining favorable performance outcomes with pneumatic muscle exoskeletons. The control strategy needs fewer complex nonlinear parameter settings through automatic tuning methods thus advancing clinical deployability of advanced control concepts.

Model Predictive and Impedance Control

Model predictive control (MPC) brings key benefits to soft rehabilitation robots through its ability to incorporate predicted future actions when making present control choices. Huang produced advanced pneumatic muscle actuator control through his innovative approach which brought together particle swarm optimization with neural networks to achieve superior effectiveness by decreasing tracking errors more than traditional approaches. ESGP-NMPC presented another method that enhanced tracking error dynamics stability through the ESGP-NMPC (Echo State Gaussian Process-based Nonlinear Model Predictive Control) system to deliver remarkable results for precise tracking goals.

Rehabilitation applications benefit most from impedance control strategies that manage the force-position dynamic connection rather than operating these elements independently. The research presented by Wei developed an ankle rehabilitation control method based on impedance modeling which controls the assistance level through parameter alterations. The system gains flexibility through this technique because it allows users to adjust stiffness to match patient needs during various rehabilitation phases.

Machine Learning and Iterative Learning Control

The implementing of machine learning techniques emerges as the most promising control system development for soft rehabilitation robots to handle their core nonlinearities and uncertainties. The repetitive nature of rehabilitation exercises allows iterative learning control (ILC) to improve control actions during multiple iterations thereby achieving outstanding results. The NIFT method developed by Wei enabled ankle rehabilitation through flexible structures by performing parameter adjustment continuously to reach up to 95.6% improved performance over traditional Ziegler-Nichols regulated mechanisms.

Scientists continue to investigate diverse machine learning methods for developing both modeling and controlling mechanisms of soft rehabilitation robots. Neural network models exhibit the ability to describe complex nonlinear systems through learning without requiring mathematical equations and reinforcement learning allows systems to develop better control policies from collected experience. Soft rehabilitation systems benefit most from control strategies that handle their high-dimensional nonlinear uncertain operation characteristics well.

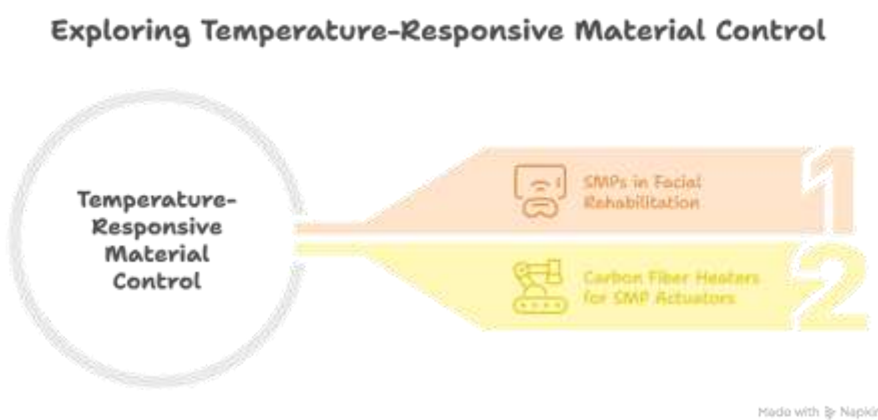

FIGURE 1 Exploring Temperature-Responsive Material Control

Special Considerations for Emerging Soft Materials

Specialized engineering solutions need to be developed for each soft intelligent material since these substances show particular modeling constraints along with control restrictions related to their specific characteristics.

Shape Memory Alloy Control

SMAs need specialized nonlinear control techniques to manage their major thermal hysteresis nonlinear behavior. The bilinear controller created by Villoslada called BPID linked PID control with bilinear compensation to deliver reference step tracking results through minimal control overshooting and ultimate positioning errors less than 0.1% displacement range. The SMA-based wrist exoskeletons received precise position control through the quadrinomial bilinear PID controller which Serrano implemented beyond Serrano's initial approach.

Temperature-Dependent Material Control

The use of variable stiffness control techniques represents an effective method for shape memory polymers (SMPs) together with comparable temperature-responsive materials. Using SMP layers Firouzeh built a facial rehabilitation robot containing retractable heaters which control stiffness by managing temperatures accurately. The structure includes adjustable stiffness layers (ASLs) which demonstrate stiffness adjustments of up to 40 times from 30°C to 110°C to control facial rehabilitation exercise resistance levels. Pathan used carbon fiber based soft heaters to implement temperature control for SMP actuators in his design for artificial joints.

Electroactive Polymer Control

Specialized electromechanical modeling techniques must be developed to analyze EAPs because these materials link electrical signals directly to their deformative behavior. Mutlu created a multi-tiered mathematical system which treats EAP actuators as a soft robotic system of multiple rigid elements suitable for developing control mechanisms. The model serves as a foundation to create unique controllers for dielectric elastomer actuators used in hand therapy but current hardware force production remains a barrier to practical implementation.

Integrated Sensing and Control Architectures

The development of complex control systems for rehabilitation robots now depends on advanced sensor technology which functions as feedback for automatic control loops and the detection of human intentions. The soft orthosis design by Zhao includes integrated strain sensors that measure curvature while operating and assists state machine controller-based control loops for precise operation. The force estimation algorithm developed by Yu using masseter muscle electromyography signals allows users to control oral rehabilitation robots through intuitive methods.

Several types of sensing devices (position sensors along with force sensors and both EMG signals and EEG inputs) create advanced control structures for rehabilitation interventions that recognize patient capacity evolution and intention changes. The intersection of sensing techniques with control algorithms creates an important scientific boundary for soft rehabilitation robotics systems which leads to more effective therapeutic approaches customized for individual patients.

4. Current Limitations and Future Perspectives in Soft Rehabilitation Robotics

Soft rehabilitation and nursing-care robotic development achieved major progress during the previous decade yet many obstacles exist before reaching both clinical use and commercial market success. The implementation of promising technologies faces barriers across technical, clinical, economic and practical domains which should be overcome through innovative solutions before achieving their therapeutic potential. Research on next-generation soft robotic systems now focuses on creating promising innovations which will reshape rehabilitation medicine in the coming years. The current section reviews existing barriers in the field and explores future directions which promote its advancement.

Technical Challenges and Limitations

Mechanical Design Constraints

The necessary trade-off between adaptability and mechanical stability creates a basic conceptual trouble for designers of soft treatment robots. Completely flexible systems demonstrate their best safety and comfort features yet they lack the required mechanical resilience for dependable therapeutic practices. Employing rigid components in designs can decrease the essential compliant benefits obtained from soft robotics technology. The search for proper equilibrium between these oppositional needs stays a continuous problem especially among products that need strong force transmission.

Material durability serves as a major limitation that industry faces. Flexible components tend to show reduced resistance against fatigue compared to rigid structures because they lead to questions about extended reliability in medical facilities. Rehabilitation exercises that use cyclic loading patterns increase wear in soft components thus leading to increased maintenance costs due to component replacements. Case and Yap argue that improving soft material durability alongside maintenance of desirable mechanical properties needs urgent research attention.

Weight limitations together with portability constraints restrict the clinical use and home applications of present systems. Pneumatically operated rehabilitation robots need external compressors or pumps which add excessive weight together with system complexity. The use of compact actuators remains feasible in tendon-driven systems but the mechanical transmission systems tend to introduce substantial system bulk. Additional weight caused by these constraints creates problems for wearable rehabilitation devices by rendering them uncomfortable while simultaneously limiting their ability to achieve therapeutic goals.

Control and Modeling Limitations

Multiple challenges exist in precise control because soft materials operate with nonlinear time-varying characteristics. Latest developments in modeling techniques have not solved the problem of obtaining precise dynamic models for soft rehabilitation robots and especially such models with multiple materials need more attention. Alternative robust control strategies became necessary because theoretical models show a substantial mismatch with real system operation while needing to maintain effective therapeutic outcomes.

The ability to produce quick responses constitutes a major obstacle for effective control. The slow response times in pneumatic systems exceed those of conventional rigid actuators due to fluid dynamics limitations and thermal response constraints of shape memory alloys and polymers exist independently of each other. The delay from physical dynamics hinders efficient execution of speed-sensitive recovery procedures that need quick time-sensitive methods including walking assistance programs.

Using several different body sensors for detecting robot status while controlling state information proves difficult as an integrated system. Soft systems resist rigid-body sensor tools thus demanding dedicated flexible sensors to work properly through major shape changes. Research advancement in optical strain sensing together with soft pressure sensing and flexible electronic technologies continues but the construction of complete reliable sensor systems for soft rehabilitation robotics keeps moving forward as an ongoing research initiative.

Human-Robot Interaction Challenges

Modern robotic systems lack proper development of user-friendly interfaces which enable control and adjustment functions. The simple control methods of rehabilitation robots fail to interpret patient intentions properly thus reducing both patient engagement and therapeutic effectiveness. Acquiring robot-based actions that match patient needs turns problematic specifically for medically challenged individuals who lack the ability to directly control robots.

Another drawback that emerges from rehabilitation robots stems from their inability to adapt to different patient populations. Most contemporary rehabilitation robots provide small adjustment scopes that do not effectively accommodate the wide range of human anatomical structures and functional characteristics found in patients. Medical robots require further development to accomplish easy adjustments matching patients' specific physical features and unique abilities together with their evolving rehabilitation requirements.

Clinical and Practical Limitations

Limited Clinical Validation

Very few soft rehabilitation robots gain clinical acceptance because their designs lack sufficient clinical data validation. Several laboratory tests have generated promising results yet only limited systems have completed substantial trials on large patient populations throughout lengthy periods of time. The insufficient availability of research evidence regarding therapeutic success and ideal treatment approaches and extended-term results prevents both medical organizations and regulatory bodies from accepting these treatments.

Standardized assessment methodologies are absent in the process of clinical validation. Standard evaluation procedures exist for pharmaceutical treatment but rehabilitation robotics lacks established frameworks to measure technical performances coupled with therapeutic effectiveness together with patient results. Different evaluation methods used for rehabilitation robotics systems make it hard to compare systems and hinder the interpretation of clinical data findings.

Accessibility and Cost Barriers

Several potential users lack access to rehabilitation robotics because of its expensive production costs and material expenses. Modern soft rehabilitation robots exhibit high manufacturing expenses through their use of special materials with complicated fabrication methods. Products that utilize these expensive resources become unaffordably expensive thereby blocking end-users from obtaining these promising solutions most notably in areas with limited resources and home settings.

The complications arising from operational complexity make it harder for practical deployment to proceed. Operation of numerous systems requires technical expertise to set them up and calibrate them before users can effectively use them requiring trained personnel for proper management. The complex setup requirements restrict the possible deployment areas to rehabilitation centers while preventing basic home usage because technical support is generally absent.

Reliability issues together with maintenance requirements create obstacles for widespread adoption of such systems. Soft components need more frequent replacements than rigid components do which leads to lasting maintenance costs and possible treatment interruptions. The unreliable nature of these technologies causes difficulties for medical practitioners since they need to determine whether therapeutic tools will permanently affect common therapeutic standards.

Emerging Research Directions and Future Perspectives

Advanced Materials and Manufacturing

The development of next-generation soft rehabilitation robots depends heavily on multi-functional materials as a leading scientific advancement. Actuation capabilities and structural support together with sensing features are essential research areas because they make possible better integrated and efficient designs. The combination of conductive elastomers which mix electrical conductivity with mechanical flexibility together with self-healing polymers which automatically repair minor damage along with stimulus-responsive composites which alter properties in response to environmental conditions indicates promising potential for future systems.

The development of soft robots benefits continuously from additive manufacturing technologies. Advanced 3D printing methods allow designers to create elaborate structures made from various materials with exact control of their mechanical attributes. The capabilities enable medical professionals to build rehabilitative devices that match specific patient anatomy and necessary functional needs. Embedded 3D printing technology represents an upcoming method that allows researchers to include functional elements directly during component production which leads to improved systems integration of actuation components alongside structural and sensing components.

New rehabilitation techniques become possible because of materials which degrade naturally and also work well with human tissue. Adequate degradation capabilities in materials would create temporary assistive devices that help patients recover without forcing them to undergo complex removal operations. Medical-grade materials with minimal inflammatory effects would lead to implantable devices which can sustain their therapeutic applications permanently.

Enhanced Sensing and Control Technologies

Distributed embedded sensing systems offer complete real-time monitoring capabilities which track robot systems as well as patient bodily responses. Soft structures equipped with distributed flexible sensors will identify complex patterns in their deformation along with force patterns to improve control capabilities. Adapted interventions will emerge from the combination of physical movement and body physiology detection through skin conductance along with heart rate and muscle activity measurements.

The modeling along with control challenges of soft systems get addressed by rising numbers of machine learning solutions. Through repetitive interactions reinforcement learning methods without mathematical models enable the creation of complicated control policies having discovered optimal assistance methods. Transfer learning methodologies make it possible to transfer simulated environment learning to real world applications which speeds up controller development processes. Natural language processing as well as computer vision research improves interface methods between people and robots to enable systems that listen to verbal command input or detect visual signals.

Brain-computer interfaces (BCIs) stand as the most advanced technology for achieving simple functionality control over rehabilitation robots. Non-invasive electroencephalography (EEG) devices have become progressively capable of spotting movement plans in neurological systems before real movements happen which provides a possible pathway for neural device control through brain signals. The research conducted by Nithya along with her colleagues demonstrated the potential of commercial EEG headsets for controlling mechanical gloves as they worked toward developing robots that follow neural patterns indicating planned movements.

Expanded Application Domains

Pediatric rehabilitation serves as a discretionary field of application which holds vast untapped possibilities for healthcare improvements. Extensive rehabilitation therapy becomes necessary for children who have developmental disorders and cerebral palsy or who have suffered from traumatic injuries in crucial developmental times. Soft robotic devices provide the most advantage to pediatric use thanks to safety needs coupled with their ability to support anatomical growth in children. The upcoming generation of pediatric rehabilitation robots will integrate therapeutic functions with interactive features to attain better results from younger patients.

The combination of telerehabilitation technology makes it possible to deliver rehabilitation robotics to patients beyond traditional clinical environments. A cloud-based connection between soft rehabilitation robots allows clinical staff to track patient performance data alongside parameter adjustments through distant locations thereby expanding access to specialized rehabilitation services in underserved areas. Data collection from these sessions creates valuable information to optimize care immediately and develop extensive databases for scientific development.

The developmental path of preventive applications extends further than established rehabilitation fields. Soft robotic systems have the potential to stop occupational overuse injuries through their dedicated support of repetitive work activities. The use of similar approaches during aged populations could provide assisting capabilities before major functional impairments occur which might stop or avoid disability onset.

Integrated Rehabilitation Ecosystems

Therapeutic devices that move multiple body joints deliver complete rehabilitation solutions better than mechanical devices that operate on a single joint. Future soft exoskeletons will develop ability to provide supportive functions that span across entire limbs or provide whole body support which will lead to more natural rehabilitation movements. Such combined systems would effectively handle the compensatory techniques which patients with movement disabilities develop thus advancing their recovery throughout different joints and muscle groups.

Hybrid rigid-soft systems serve as a logical solution for integrating strong points between rigid and soft robotics systems. Strategic position of rigid components for force transmission along with soft components intended for human-robot interfaces enables optimal results from both mechanical performance and safety considerations. The implementation of hybrid systems would deliver maximum benefit to weight-bearing lower-limb applications that need stronger mechanical support structures.

The combination of virtual and augmented reality systems demonstrates great potential to improve patient involvement for motor learning processes. When rehabilitation robots integrate soft components they become able to provide patients with educational therapeutic activities within virtual environments that drive intensive training sessions and instant performance monitoring. Virtual interfaces throughout augmented reality would assist patients in executing complicated movement patterns by simultaneously displaying progress markers and movement excellence indicators so patients can possibly learn faster.

5.Conclusion and Future work

Soft rehabilitation and nursing-care robots experienced an important technological revolution in medical rehabilitation technology.The investigation has revealed that soft robotics delivers apparent advantages to rehabilitation applications through its improved safety features while providing enhanced comfort and functional resemblance which conventional rigid devices lack.

Improvements in technology have evolved into two major directions. Instead of traditional robotics the Exo-Glove along with AirexGlove and multiple soft exosuits have proven their ability to rehabilitate the upper and lower limbs by using tendon-driven cable-operated systems to recreate human muscle mechanics. To achieve this improvement rehabilitation robots utilizing soft intelligent materials including pneumatic actuators and shape memory alloys and electroactive polymers and hydrogels provide new opportunities in therapy beyond traditional rigid system capability.

Excessive complexity in modeling together with control system difficulties prevent the widespread use of developed mechanical designs in clinical practice. Soft materials present fundamental nonlinear and time-dependent properties which challenge traditional control systems but model-free methods and machine learning as well as iterative learning control bring improvements to effective solutions. Continuous developments in control innovation methods alongside improvements in embedded sensing along with human-robot interface design minimize the lack of practical implementation from existing theoretical possibilities.

The implementation of advanced robotic control systems faces technical as well as clinical and practical hurdles at present. Different barriers such as material deterioration risks and weight restrictions along with insufficient clinical research results and accessibility barriers prevent widespread implementation of promising robotic technology. Contrary to earlier challenges several new research fields demonstrate significant progress that can help address existing barriers through advanced materials development and additive manufacturing innovations and enhanced sensing and control technologies and expanded application areas. Healthcare ecosystems will benefit from strategic priorities that establish standardized evaluation frameworks, focus on user-centered design and create integration patterns with broader healthcare ecosystems to turn laboratory innovations into clinical impact.

The future of rehabilitation medicine promises complete transformation through soft robotics which provides better protective yet efficient treatment opportunities accessible to all patients. These developing technologies demonstrate potential to enhance recovery effectiveness for motor-impaired patients and make rehabilitation services more widely available and improve life quality through therapeutic applications that assist users in various ways. The path of innovation indicates soft rehabilitation robots will become essential components of complete rehabilitation programs that team up with human therapists to achieve the best possible patient recovery results and independent function benefits for worldwide populations of diverse patients.

Acknowledgement: Nil

Conflicts of interest

The authors have no conflicts of interest to declare

References

1. Laschi C, Cianchetti M. Soft robotics: new perspectives for robot bodyware and control. Front Bioeng Biotechnol. 2014;2:3.
2. Rus D, Tolley MT. Design, fabrication and control of soft robots. Nature. 2015;521(7553):467–475.
3. Majidi C. Soft robotics: a perspective—current trends and prospects for the future. Soft Robot. 2014;1(1):5–11.
4. Kim S, Laschi C, Trimmer B. Soft robotics: a bioinspired evolution in robotics. Trends Biotechnol. 2013;31(5):287–294.
5. Galloway KC, Becker KP, Phillips B, et al. Soft robotic grippers for biological sampling on deep reefs. Soft Robot. 2016;3(1):23–33.
6. Mathewson KE, Holcombe AO, Stokes MG. Dynamic prioritization of visual memory resources underlies efficient cognitive function. Trends Cogn Sci. 2017;21(2):149–160.
7. Guizzo E, Goldstein H. The rise of the robot worker. IEEE Spectr. 2005;42(12):34–39.
8. Shintake J, Rosset S, Schubert B, et al. Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. Adv Mater. 2016;28(2):231–238.
9. Godage IS, Branson DT, Guglielmino E, et al. Shape function-based kinematics and dynamics for variable length continuum robotic arms. IEEE Trans Robot. 2015;31(3):798–806.
10. Lee Y, Kim S, Kim H. Recent advances in soft robots for healthcare. Micromachines. 2021;12(4):412.
11. Cianchetti M, Laschi C, Menciassi A, et al. Biomedical applications of soft robotics. Nat Rev Mater. 2018;3(6):143–153.