Review

A Systematic Review of Supernumerary Robotic Limbs: Design Trade-Offs, Control Strategies, and Application Domains

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Abstract

Supernumerary robotic limbs (SRLs) represent an emerging class of wearable robotic systems designed to augment, rather than replace, human motor capabilities. Unlike prostheses or exoskeletons, SRLs operate as independent kinematic agents that enable users to perform multi-limb tasks, reduce physical workload, and enhance operational efficiency in complex environments. This study presents a systematic review of SRL technologies, focusing on mechanical design configurations, sensing modalities, and control strategies, and their influence on key performance metrics such as payload capacity, positioning accuracy, and human–robot interaction efficiency. A structured literature review methodology was adopted following PRISMA guidelines, covering publications from 2010 to 2025 across major scientific databases. The analysis reveals fundamental trade-offs between degrees of freedom, weight, and payload capacity, where high-dexterity systems often impose increased ergonomic burden. Control strategies have evolved from direct teleoperation toward hybrid and shared-autonomy frameworks integrating vision, bio-signals, and machine learning, although challenges remain in achieving intuitive and low-latency interaction. Application domains span industrial manufacturing, construction, rehabilitation, and assistive daily activities, with growing interest in precision-constrained environments such as healthcare. Despite significant progress, limitations persist in actuator back-drivability, long-term wearability, and robust intention recognition under real-world conditions. This review synthesizes current advancements, identifies critical research gaps, and outlines future directions toward scalable, human-centric SRL systems capable of seamless integration into industrial and clinical workflows.

Keywords: supernumerary robotic limbs; human–robot interaction; actuator back-drivability; smart grasping; weight management; assistive technology

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1. Introduction

Wearable robotics has advanced substantially over the past decade, driven by the need to enhance human physical capability, reduce occupational injury, and enable efficient human–robot collaboration. Within this field, supernumerary robotic limbs (SRLs) have emerged as a distinct paradigm that augments human performance by introducing additional, independently controlled robotic appendages. Unlike prostheses, which aim to restore lost function, or exoskeletons, which amplify existing limb capabilities, SRLs operate as parallel kinematic agents that collaborate with the user to execute multi-limb tasks [1–4].

Early developments in SRLs were motivated by industrial use cases requiring simultaneous manipulation and stabilization, particularly in overhead assembly and confined workspaces. Parietti and Asada [2] demonstrated one of the first wearable supernumerary arms designed to assist with aircraft assembly tasks, highlighting the potential of SRLs to reduce physical strain and enable single-operator task execution. Subsequent systems expanded this concept toward collaborative manipulation, shared autonomy, and assistive support in both industrial and non-industrial environments [5–8].

From a mechanical design perspective, SRLs present a multi-objective optimization problem involving competing requirements such as degrees of freedom (DoF), payload capacity, structural weight, and ergonomic compatibility. High-DoF configurations improve dexterity and workspace coverage but typically increase system mass and control complexity, which can negatively impact wearability and user comfort. Conversely, lightweight and low-DoF designs offer improved portability but are often limited in manipulation capability and load-bearing performance [9–11]. These trade-offs necessitate careful integration of actuation technologies, structural design, and human-centered constraints.

Sensing and control constitute another critical dimension of SRL development. Accurate interpretation of human intent is essential for seamless interaction, particularly in dynamic and unstructured environments. Current approaches integrate multimodal sensing, including inertial measurement units (IMUs), vision systems, and bioelectric interfaces such as electromyography (EMG) and electroencephalography (EEG), to infer user motion and intention [12,13]. Control strategies have evolved from direct teleoperation toward shared and semi-autonomous frameworks that combine model-based control with machine learning techniques, enabling improved responsiveness and reduced cognitive burden on the user [5,6,13,14]. Despite these advances, robust intention recognition and low-latency control remain open challenges, especially under real-world conditions characterized by noise, variability, and occlusion.

The application scope of SRLs has expanded considerably, encompassing industrial manufacturing, construction, rehabilitation, and assistive technologies for daily living. In industrial contexts, SRLs function as collaborative robotic assistants capable of stabilizing tools, supporting heavy components, and enabling concurrent task execution [2,3,5]. In medical and assistive domains, they have been explored for rehabilitation and functional assistance, particularly for individuals with motor impairments, where SRLs can facilitate bimanual activities and improve independence [12,15]. Emerging applications in precision-constrained environments further emphasize the need for compact, safe, and highly controllable systems.

Despite rapid progress, several limitations continue to hinder large-scale adoption of SRLs. These include challenges in achieving high torque-to-weight ratios in actuators, ensuring back-drivability and user safety, maintaining long-term wearability, and developing intuitive control interfaces that minimize cognitive load [9,10,16]. Additionally, the integration of SRLs into real-world workflows requires consideration of ergonomic, economic, and operational factors that extend beyond purely technical performance.

This study presents a systematic review of SRL technologies, focusing on the relationships between mechanical design, sensing modalities, and control strategies, and their impact on system performance and usability. By synthesizing findings across diverse application domains, this work aims to establish a structured understanding of the state of the art, identify critical research gaps, and outline directions for the development of scalable, human-centered SRL systems. The paper contributions can be summarized as:

1. A PRISMA-guided systematic review of supernumerary robotic limbs (SRLs) covering mechanical design, sensing, and control strategies.
2. A unified taxonomy enabling consistent classification and comparison of existing SRL systems.
3. A comparative analysis highlighting key trade-offs between payload capacity, dexterity, and wearability.

4. A critical evaluation of control approaches for human–robot interaction and intention recognition.
5. Identification of major research gaps and future directions for scalable, human-centered SRL systems.

The remainder of this paper is organized as follows. Section 2 presents the systematic review methodology based on the PRISMA framework, including the search strategy, eligibility criteria, and study selection process. Section 3 discusses the mechanical design aspects of supernumerary robotic limbs (SRLs), including kinematic configurations, actuation mechanisms, payload capacity, and ergonomic considerations. Section 4 reviews the sensing modalities, actuation technologies, and system integration architectures employed in SRLs. Section 5 provides a comprehensive analysis of control strategies, covering classical, adaptive, model-based, and learning-based approaches for human–robot interaction and intention recognition. Section 6 examines the major application domains of SRLs, including industrial, assistive, medical, teleoperation, and human augmentation systems. Section 7 highlights the key technical challenges and open research issues related to wearability, safety, energy efficiency, and standardization. Finally, Section 8 concludes the paper and outlines future research directions for the development of intelligent and human-centered SRL systems.

2. Methodology

This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological transparency, reproducibility, and comprehensive coverage of the literature on supernumerary robotic limbs (SRLs).

2.1. Search Strategy

A structured literature search was performed across four major scientific databases: Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The search covered publications from January 2010 to December 2025, corresponding to the period of significant development in SRL technologies [17–22].

The search strategy combined domain-specific keywords using Boolean operators as follows: (“supernumerary robotic limb” OR “supernumerary robotic arm” OR “extra robotic limb” OR “third arm robot” OR “wearable robotic arm”) AND (“control” OR “human–robot interaction” OR “sensing” OR “design” OR “wearable robotics”).

Additional keyword variations were applied to ensure comprehensive coverage across different terminologies used in the literature.

2.2. Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria.

Inclusion criteria:

- Peer-reviewed journal articles and conference papers
- Studies addressing SRL design, control, sensing, or applications
- Experimental validation or detailed system implementation
- Publications in English

Exclusion criteria:

- Studies focused solely on prosthetics or exoskeletons without SRL functionality
- Review articles, editorials, or opinion papers
- Studies lacking sufficient technical detail or validation
- Duplicate records

2.3. Study Selection Process

The study selection process was conducted in three stages: identification, screening, and eligibility assessment. Initially, 368 records were identified through database searching. After removing duplicates, 312 unique records remained. These records were screened based on titles and abstracts, resulting in the exclusion of 214 studies that were not relevant to the scope of SRLs.

The remaining 98 articles were subjected to full-text review to assess their eligibility. During this stage, 57 articles were excluded for the following reasons: lack of direct relevance to SRLs (n = 21), focus on exoskeletons or prosthetic systems (n = 14), absence of experimental validation (n = 12), and insufficient technical detail (n = 10).

Ultimately, 41 studies met all inclusion criteria and were included in the qualitative synthesis [1–41].

The overall study selection procedure is illustrated in the PRISMA 2020 flow diagram (Figure 1), which summarizes the number of records identified, screened, excluded, and included at each stage of the review process.

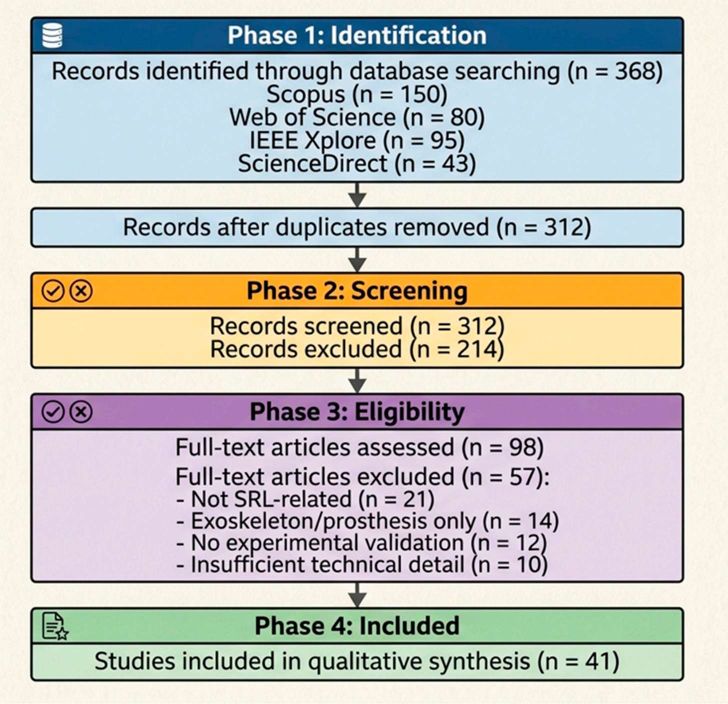

Figure 1. PRISMA 2020 flow diagram illustrating the study selection process, including identification, screening, eligibility assessment, and final inclusion of studies on supernumerary robotic limbs.

2.4. Data Extraction and Synthesis

Data were systematically extracted from the selected studies [1–41], focusing on mechanical design parameters (degrees of freedom, payload, and structural configuration), sensing modalities, control strategies, and application domains. Where available, quantitative performance metrics such as accuracy, response time, and load capacity were recorded.

The extracted data were analyzed using a comparative framework to identify common design patterns, evaluate trade-offs between key system parameters, and highlight trends across different application domains.

2.5. Quality Assessment

A qualitative assessment of the included studies was performed based on methodological clarity, level of experimental validation, and completeness of reported results. Studies with insufficient detail or unclear validation procedures were excluded during the eligibility stage to ensure the reliability of the synthesized findings [17].

3. Mechanical Design

The mechanical design of supernumerary robotic limbs (SRLs) is governed by competing requirements including dexterity, payload capacity, structural weight, and ergonomic compatibility. Unlike conventional robotic manipulators, SRLs operate in direct proximity to the human body, imposing strict constraints on safety, comfort, and motion interference. Consequently, SRL design constitutes a multi-objective optimization problem, where improvements in one parameter often introduce trade-offs in others [23,24].

3.1. Degrees of Freedom and Kinematic Configuration

The number of degrees of freedom (DoF) directly determines the functional capability of SRLs. Low-DoF systems (2–3 DoF) are typically employed for task-specific operations such as stabilization or tool holding, offering reduced weight and simplified control [23]. In contrast, high-DoF systems (6–7 DoF) provide enhanced dexterity and kinematic redundancy, enabling obstacle avoidance and flexible manipulation in cluttered environments [24–26]. However, increasing DoF introduces higher mass, energy consumption, and control complexity. Intermediate configurations (4–5 DoF) are therefore widely adopted as a compromise between performance and wearability [27]. This relationship highlights a fundamental trade-off between dexterity, payload capacity, and system weight, as illustrated in Figure 2.

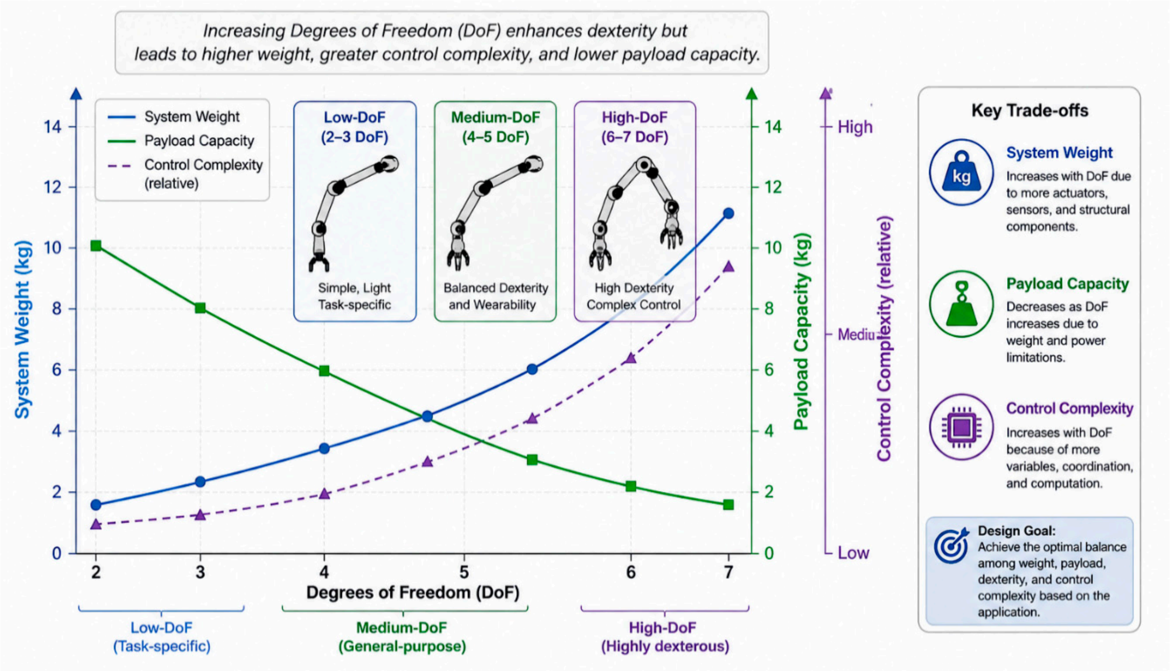

Figure 2. Trade-off relationships in supernumerary robotic limb design, illustrating the influence of increasing degrees of freedom on system weight, payload capacity, and control complexity.

3.2. Transmission, Compliance, and Back-Drivability

The choice of actuation and transmission mechanism significantly influences SRL performance. High-ratio geared actuators provide increased torque but introduce high reflected inertia and friction, reducing back-drivability [28]. In contrast, tendon-driven systems reduce distal mass and improve dynamic response but introduce compliance and transmission losses [29].

Series elastic actuators (SEAs) incorporate compliant elements to enhance safety and enable force estimation, although they reduce control bandwidth and positional accuracy [30]. Back-drivability, a critical requirement for wearable systems, reflects the ability of the user to physically interact with and override the robotic motion. These differences between actuation strategies are summarized in Figure 3.

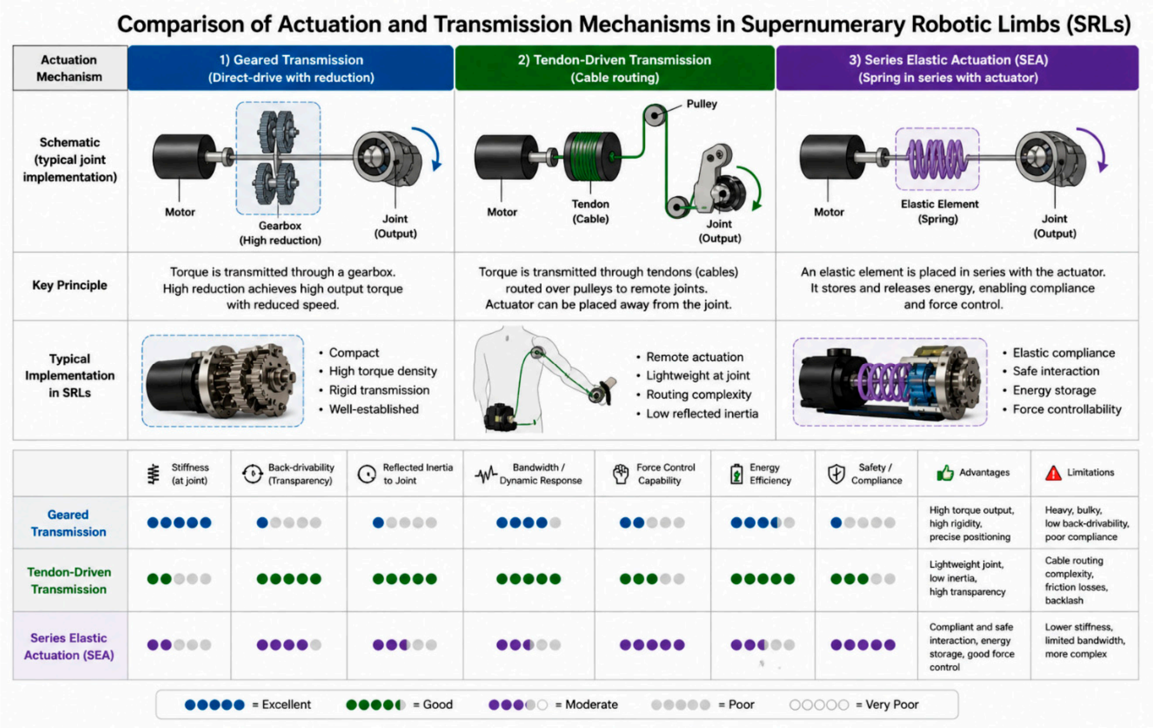

Figure 3. Comparison of actuation and transmission mechanisms in supernumerary robotic limbs (SRLs), including geared, tendon-driven, and series elastic actuation, highlighting differences in stiffness, back-drivability, and dynamic response.

3.3. Accuracy, Stiffness, and Disturbance Rejection

Positioning accuracy in SRLs is influenced by structural stiffness, joint transmission characteristics, and sensor resolution. Rigid-link systems offer higher precision, whereas compliant systems improve safety at the expense of accuracy [31]. Because SRLs are mounted on a moving human base, disturbance rejection is essential for maintaining stable end-effector positioning during dynamic user motion [32].

Human motion introduces dynamic disturbances that propagate through the kinematic chain, affecting end-effector stability. Effective designs integrate mechanical isolation and control compensation techniques to mitigate these effects. A balance between stiffness and compliance is therefore required to achieve both precision and safe interaction.

3.4. Reachability and Workspace Design

Workspace characteristics depend on link dimensions, joint configuration, and mounting location. SRLs are designed to extend beyond the natural reach of the user while minimizing interference with biological limbs. Compact designs offer portability but limited workspace, whereas extended-link designs increase reach at the cost of inertia and stability.

Reconfigurable mechanisms, such as telescopic or scissor-based structures, enable adaptive workspace extension [33]. The influence of mounting location on reachable workspace is illustrated in Figure 4.

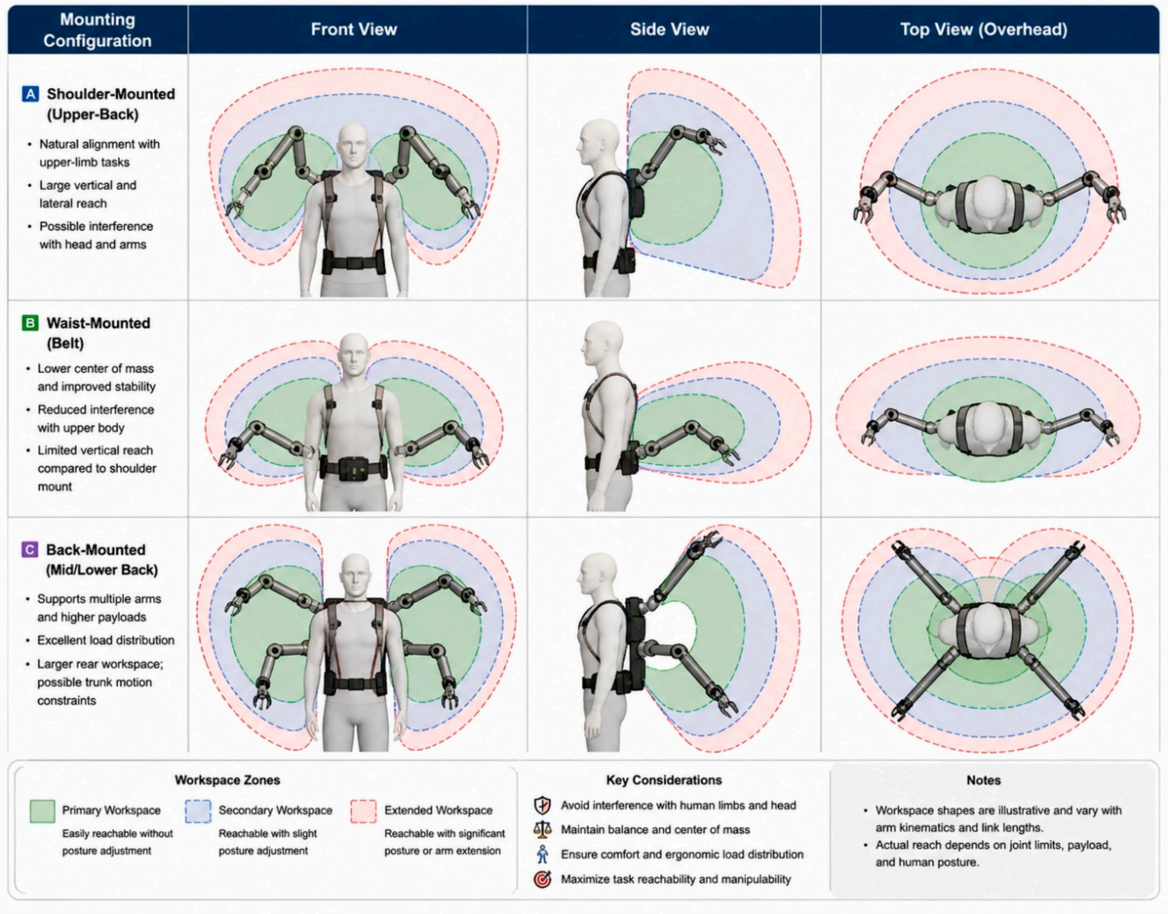

Figure 4. Supernumerary robotic limb configurations and corresponding workspace characteristics based on mounting location, illustrating primary, secondary, and extended reachable regions for shoulder-, waist-, and back-mounted systems.

3.5. Payload Capacity and Load Distribution

Payload capacity defines the operational scope of SRLs across different applications. Industrial systems typically support higher loads, enabling material handling and tool stabilization, whereas assistive systems prioritize lightweight design and operate under lower payload constraints [34].

Load distribution is a key factor affecting user comfort and fatigue. Shoulder-mounted systems transfer forces through the torso, while Shoulder-mounted systems transfer forces through the torso, while waist-mounted systems align with the body’s center of mass to improve stability and ergonomic load distribution [35]. The relationship between payload and system weight across different applications is illustrated in Figure 5.

Table 1 summarizes the statistical ranges of system weight and payload capacity for assistive and industrial supernumerary robotic limbs (SRLs). Assistive systems are characterized by low weight and limited payload, reflecting design priorities related to wearability and user comfort. In contrast, industrial systems exhibit significantly higher weight and payload ranges, emphasizing load-bearing capability and structural robustness. The reported mean values highlight the distinct performance profiles of the two categories and support the distribution trends observed in Figure 5.

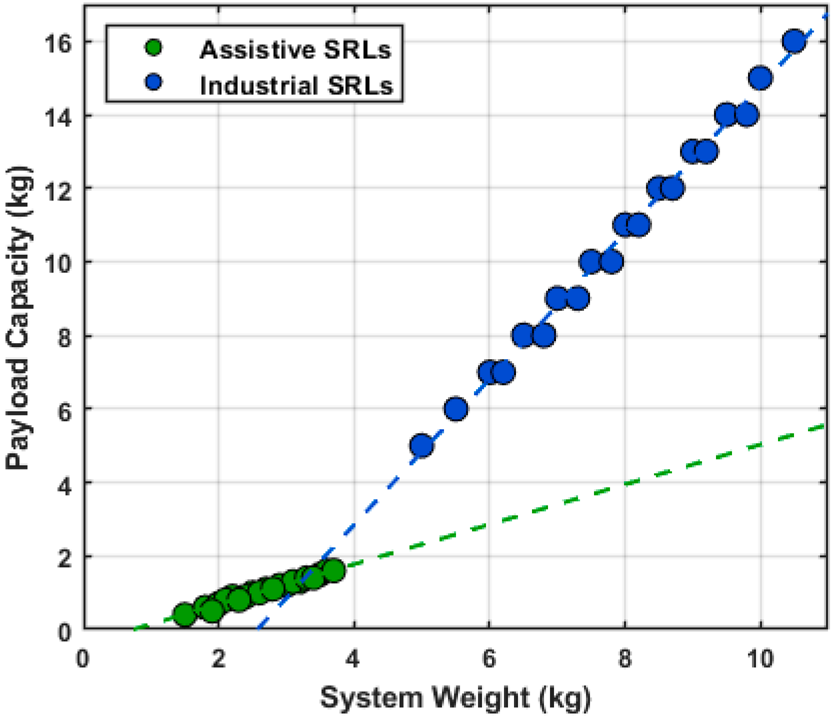

Figure 5. Payload capacity versus system weight in supernumerary robotic limbs (SRLs), showing the distribution of assistive and industrial systems with corresponding trend lines.

Table 1. Summary of payload capacity and system weight ranges for supernumerary robotic limbs (SRLs).

Category	No. of Systems	Weight Range (kg)	Payload Range (kg)	Mean Weight (kg)	Mean Payload (kg)
Assistive SRLs	21	1.5 – 3.7	0.4 – 1.6	2.6	1.0
Industrial SRLs	20	5.0 – 10.5	5 – 16	7.8	10.5

3.6. Mounting Strategies and Ergonomic Integration

Mounting configuration strongly influences usability and system effectiveness. Shoulder-mounted designs provide direct alignment with upper-limb tasks, while waist-mounted systems improve stability and load handling. Back-mounted configurations enable multi-limb integration and better load distribution.

Ergonomic considerations include harness design, weight distribution, and user comfort. Systems must minimize interference with natural motion and avoid excessive strain on specific body regions to ensure long-term usability [36].

3.7. Design Trade-Offs and Optimization

SRL design involves balancing multiple conflicting objectives, including payload, weight, dexterity, and safety. Increasing payload requires stronger actuators and structures, which increases system weight and reduces wearability. Similarly, increasing DoF improves dexterity but introduces higher control complexity.

Optimal designs are therefore application-specific. Industrial systems prioritize robustness and load capacity, whereas assistive systems emphasize lightweight construction and ease of use [37]. A multi-objective trade-off representation of SRL design parameters is shown in Figure 6. The data presented in Figure 5 represent typical values derived from reported ranges across the reviewed studies, due to variability in available quantitative specifications. The performance metrics are normalized to enable comparative visualization across different SRL design criteria.

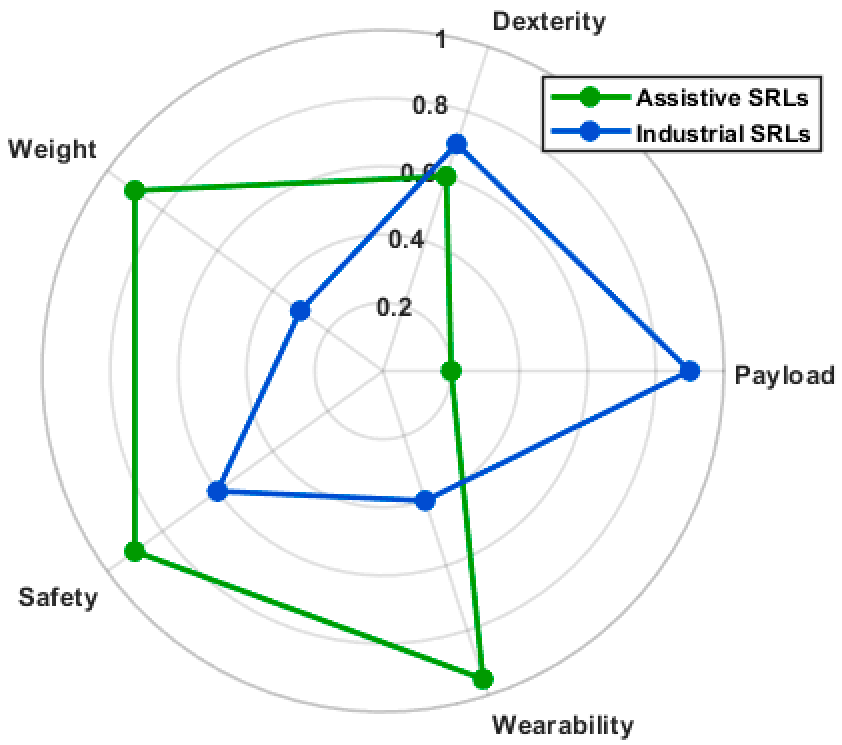

Figure 6. Multi-objective trade-off representation of supernumerary robotic limb (SRL) design parameters, comparing assistive and industrial systems across payload, dexterity, weight, safety, and wearability.

4. Components: Sensors and Actuators

The performance of supernumerary robotic limbs (SRLs) is determined by the coordinated design of sensing and actuation subsystems. Sensors enable perception of user intent and environmental context, while actuators provide the mechanical output required for task execution. The effectiveness of SRLs therefore depends on achieving a balance between responsiveness, accuracy, safety, and ergonomic constraints [38].

4.1. Sensing Modalities for Human–Robot Interaction

Sensing in SRLs can be broadly categorized into motion-based, vision-based, and bio-signal-based approaches. Motion-based sensing relies on inertial measurement units (IMUs), encoders, and force/torque sensors to capture user movement and interaction forces [39]. These sensors provide reliable, low-latency measurements but primarily reflect executed motion rather than intended action.

Vision-based systems utilize cameras and depth sensors to interpret environmental context and object interactions [40]. They enable higher levels of autonomy but are sensitive to occlusion, lighting variations, and computational latency. Bio-signal interfaces, such as electromyography (EMG) and electroencephalography (EEG), directly capture physiological signals associated with user intent. EMG-based control offers relatively high responsiveness but is affected by signal noise and muscle fatigue [41]. EEG-based control enables hands-free interaction but suffers from low signal reliability and limited resolution. In practice, hybrid sensing approaches are increasingly adopted to combine complementary modalities, improving robustness and reducing ambiguity in intention recognition.

4.2. Actuation Technologies

Actuation systems define the mechanical capabilities of SRLs in terms of torque generation, speed, and compliance. Electric motors are widely used due to their compactness, controllability, and efficiency [28,30]. However, achieving high torque typically requires gear reduction, which increases inertia and reduces back-drivability.

Pneumatic actuators offer high power-to-weight ratios and inherent compliance, making them suitable for applications requiring safe human interaction [22]. Their dependence on external air supply and limited precision restrict their use in portable systems.

Series elastic actuators (SEAs) incorporate elastic elements to enhance safety and enable force control through deformation measurement. While they improve interaction safety and shock absorption, they introduce compliance that can reduce positioning accuracy and control bandwidth [30].

The selection of actuation technology is therefore application-dependent, with industrial systems prioritizing load capacity and robustness, while assistive systems emphasize lightweight design and intrinsic safety.

4.3. System Integration Architecture

The effectiveness of supernumerary robotic limbs (SRLs) relies on the seamless integration of sensing, control, and actuation subsystems within a closed-loop framework. Unlike conventional robotic systems, SRLs operate in continuous interaction with the human body, requiring real-time responsiveness, adaptive behavior, and intrinsic safety. Consequently, the system architecture must support low-latency data processing, robust feedback mechanisms, and reliable execution of control commands.

A generalized SRL architecture is illustrated in Figure 7. The system is organized into three primary layers: sensing modules, control unit, and actuation modules, interconnected through bidirectional data and feedback pathways.

The sensing layer collects multimodal data from motion sensors (e.g., IMUs, encoders), bio-signals (e.g., EMG, EEG), and environmental sensors (e.g., vision and proximity). These inputs provide complementary information regarding user motion, intention, and task context. Due to the inherent noise and uncertainty in individual sensing modalities, sensor fusion techniques are typically employed to improve reliability and accuracy [5,13,41].

The control unit processes the acquired data through a hierarchical pipeline. At the upper level, signal processing and feature extraction are performed to filter noise and identify relevant patterns. This is followed by intention recognition, where machine learning or rule-based methods infer user intent. Subsequently, decision-making and trajectory planning modules generate desired motion commands while considering task constraints and safety requirements. At the lower level, control algorithms such as proportional–integral–derivative (PID), impedance control, or force control are implemented to ensure stable and precise actuation [10,21] Achieving intuitive and safe human–robot interaction remains a key challenge.

The actuation layer executes the control commands using appropriate actuators, including electric motors, pneumatic systems, or series elastic actuators. The choice of actuation technology directly affects system responsiveness, compliance, and load capacity. Importantly, actuator outputs must be continuously adjusted based on feedback to maintain stability and safe interaction.

A key feature of the architecture is the feedback and monitoring loop, which provides real-time information on system states such as position, velocity, and force. This loop enables state estimation, performance monitoring, and safety supervision, including collision detection and constraint enforcement. Additionally, power management and safety mechanisms are integrated to ensure reliable operation, particularly in portable SRL systems where energy efficiency and thermal constraints are critical.

Overall, the architecture depicted in Figure 7 highlights the tightly coupled nature of sensing, control, and actuation in SRLs. Effective system integration requires coordinated design across these layers, with particular emphasis on minimizing latency, enhancing robustness, and ensuring safe human–robot interaction.

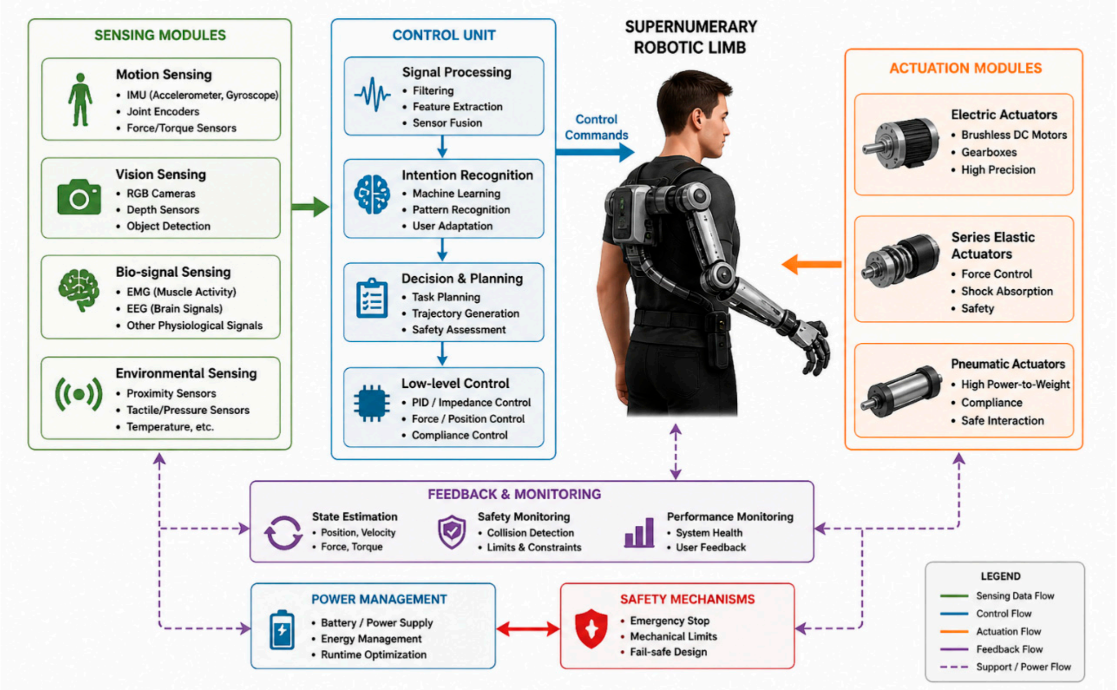

Figure 7. General architecture of supernumerary robotic limb systems, illustrating the interaction between sensing modalities, control algorithms, and actuation mechanisms.

4.4. Comparative Analysis of Components

The performance of sensing and actuation technologies can be evaluated based on their advantages, limitations, and suitability for different applications. Table 2 summarizes the key characteristics of commonly used components in SRLs.

Table 2. Comparison of sensing modalities and actuation technologies used in supernumerary robotic limbs (SRLs).

Category	Type	Advantages	Limitations	Typical Use
Sensing	IMU	Real-time, low cost	Drift, indirect intent	Motion tracking
Sensing	Vision	Environmental awareness	Latency, occlusion	Object interaction
Sensing	EMG	Direct intention	Noise, fatigue	Assistive control
Sensing	EEG	Hands-free control	Low reliability	Rehabilitation
Actuation	Electric	High precision, compact	Low back-drivability	General SRLs
Actuation	Pneumatic	High power, compliant	Bulky, complex	Industrial tasks
Actuation	SEA	Safe, force control	Lower bandwidth	Human interaction

The comparison indicates that no single sensing or actuation approach is universally optimal. Instead, system design requires selecting and integrating components based on application-specific requirements and performance constraints.

4.5. Design Trade-Offs and Challenges

The integration of sensing and actuation components introduces several design trade-offs. High-accuracy sensing often requires increased computational resources, leading to latency. Similarly, high-torque actuators improve performance but increase system weight and reduce wearability.

Power consumption and thermal management are critical concerns, particularly for portable SRLs. Battery limitations constrain operating time, while heat generation affects user comfort and system reliability.

Achieving intuitive and safe human–robot interaction remains a key challenge, particularly in wearable and assistive SRL platforms operating under dynamic environmental conditions [5,12,13]. This requires seamless integration of sensing, control, and actuation, supported by adaptive algorithms capable of handling uncertainty and variability in real-world environments.

Overall, advances in sensor fusion, lightweight actuation, and intelligent control are expected to play a central role in improving the performance and usability of future SRL systems.

5. Control Methods

Control strategies are fundamental to the operation of supernumerary robotic limbs (SRLs), as they define how user intent is interpreted and translated into coordinated robotic motion. Unlike conventional robotic systems, SRLs must operate in continuous physical interaction with the human body, requiring control frameworks that are not only accurate and responsive but also adaptive and inherently safe [5,10,13]. Consequently, modern SRL control systems are typically hierarchical, integrating multiple layers of control to manage perception, decision-making, and actuation.

5.1. Hierarchical Control Architecture

SRL control systems are commonly organized into hierarchical structures, as illustrated in Figure 8. At the highest level, intention recognition modules interpret user inputs derived from sensing modalities such as EMG, IMU, or vision systems [5,6,13,41]. These signals are processed through feature extraction and classification algorithms to infer user intent [13,24,25].

The intermediate layer performs decision-making and trajectory planning, generating desired motion commands based on task requirements and environmental constraints. At the lowest level, control algorithms such as PID or impedance control regulate actuator outputs to ensure stable and precise execution [10,21]. This layered architecture enables modular design and facilitates the integration of advanced algorithms while maintaining system stability.

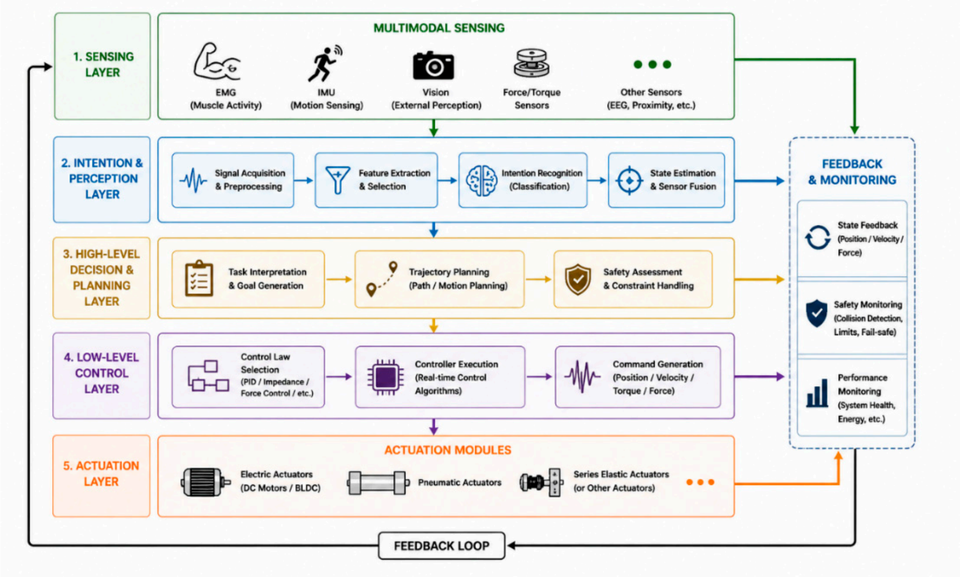

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Figure 8. Hierarchical control architecture of SRLs, illustrating the integration of sensing, intention recognition, high-level planning, and low-level control with feedback loops.

5.2. Classical and Interaction-Based Control

Classical control approaches remain widely adopted in supernumerary robotic limbs (SRLs) due to their simplicity, robustness, and suitability for real-time implementation. These methods are primarily employed at the low-level control layer to regulate actuator dynamics, joint motion, and interaction forces. Among them, proportional–integral–derivative (PID) control is the most commonly used strategy because of its straightforward implementation and stable performance under relatively predictable operating conditions [10,18].

PID controllers are particularly effective for position and velocity regulation in SRLs with limited dynamic uncertainty. Their low computational complexity makes them suitable for wearable robotic systems with constrained processing resources and power availability. However, SRLs operate in highly dynamic environments involving continuous human interaction, variable payloads, and uncertain motion patterns. Under such conditions, fixed-parameter PID controllers may experience overshoot, degraded tracking performance, and limited adaptability.

To address these limitations and improve interaction safety, impedance and admittance control strategies are widely integrated into SRL systems. Unlike purely position-based control approaches, these methods explicitly regulate the relationship between force and motion, enabling compliant and adaptive interaction between the robotic limb and the user [21,27].

Impedance control defines the desired dynamic behavior of the SRL by controlling its response to external forces through adjustable stiffness and damping characteristics. This approach enables smooth and compliant interaction while reducing excessive contact forces, making it particularly suitable for assistive and rehabilitation-oriented applications where user comfort and safety are critical.

Admittance control operates inversely by modifying the motion response according to measured interaction forces. This strategy is commonly employed in systems equipped with rigid actuation and high-precision force sensing. Admittance-based control can improve motion transparency and facilitate cooperative manipulation tasks; however, its performance depends heavily on accurate force estimation and sensor reliability [27]. The comparison between classical and interaction-based control strategies is summarized in Table 3.

Table 3. Comparison of classical and interaction-based control strategies in SRLs.

Control Strategy	**Main Objective**	**Advantages**	**Limitations**	**Typical Application**
PID Control	Position/velocity regulation	Simple, stable, low computational cost	Limited adaptability	Low-level actuator control
Impedance Control	Force–motion interaction	Safe and compliant behavior	Sensitive parameter tuning	Assistive and rehabilitation SRLs
Admittance Control	Motion adaptation based on force input	Smooth cooperative interaction	Requires accurate force sensing	Human–robot collaboration

The comparison highlights that no single interaction-based strategy is universally optimal. PID control offers stability and simplicity but lacks adaptability under uncertain conditions. In contrast, impedance and admittance control improve safety and interaction quality at the cost of increased tuning complexity and sensing requirements.

The interaction mechanisms enabled by these approaches are conceptually integrated within the hierarchical architecture shown in Figure 8, where low-level controllers continuously regulate actuator outputs using sensory feedback and interaction-force measurements. Such closed-loop frameworks allow SRLs to dynamically adapt to user motion and environmental disturbances while maintaining stable operation.

Despite their effectiveness, interaction-based control methods still face several challenges. Accurate tuning of stiffness, damping, and force-response parameters is essential for achieving intuitive and stable behavior. Excessive stiffness may compromise safety, whereas overly compliant behavior can reduce positioning accuracy and responsiveness. This trade-off becomes particularly significant in applications requiring both precision and safe physical interaction.

5.3. Model-Based and Adaptive Control

Model-based and adaptive control strategies have been increasingly adopted in supernumerary robotic limbs (SRLs) to address the nonlinear dynamics, parameter uncertainties, and varying interaction conditions associated with human–robot collaboration. Unlike classical controllers that rely primarily on fixed control parameters, these approaches incorporate system dynamics and real-time adaptation mechanisms to improve accuracy, robustness, and responsiveness.

Model-based control approaches utilize mathematical representations of SRL dynamics to predict and regulate system behavior. Among these methods, computed torque control and model predictive control (MPC) are the most commonly employed techniques [10,14]. Computed torque control compensates for nonlinear dynamic effects, including inertia, Coriolis forces, and gravity, thereby improving trajectory tracking performance and motion precision.

Model predictive control extends this concept by optimizing control inputs over a prediction horizon while explicitly considering system constraints such as actuator limits, interaction forces, and trajectory boundaries. This capability makes MPC particularly suitable for complex SRL applications involving multi-degree-of-freedom motion and dynamic environments. Additionally, MPC enables smoother trajectory generation and enhanced disturbance rejection compared with conventional feedback control methods.

Despite these advantages, model-based approaches depend heavily on the accuracy of the underlying dynamic model. Human–robot interaction introduces uncertainties related to changing payloads, user motion variability, and biomechanical coupling, which may reduce model accuracy and degrade controller performance. Furthermore, advanced optimization-based controllers such as MPC require substantial computational resources, making real-time implementation challenging in portable wearable systems.

To overcome these limitations, adaptive control techniques have been introduced to enable online adjustment of controller parameters according to changing operating conditions. Adaptive controllers continuously estimate system uncertainties and modify control gains in real time, improving robustness against dynamic disturbances and user variability.

Adaptive impedance control is one of the most widely investigated approaches in SRLs because it combines compliant interaction behavior with real-time adaptability [12]. By adjusting stiffness and damping parameters dynamically, the controller can maintain stable and safe interaction while accommodating variations in task conditions and user behavior.

Similarly, model reference adaptive control (MRAC) has been explored for SRL applications to ensure that system behavior follows a desired reference model despite parameter uncertainties [24]. Such approaches are particularly beneficial in wearable systems where mechanical properties and interaction dynamics vary continuously during operation. The comparative characteristics of model-based and adaptive control strategies are summarized in Table 4.

Table 4. Comparison of model-based and adaptive control strategies in SRLs.

Control Strategy	Main Objective	Advantages	Limitations	Typical Application

Computed Torque Control	Nonlinear dynamic compensation	High trajectory accuracy	Requires accurate dynamic model	Precision motion control
Model Predictive Control (MPC)	Constraint-aware optimization	Predictive behavior, disturbance rejection	High computational cost	Industrial and multi-DoF SRLs
Adaptive Control	Real-time parameter adjustment	Robustness to uncertainty	Stability and convergence challenges	Dynamic environments
Adaptive Impedance Control	Adaptive compliant interaction	Improved safety and flexibility	Complex tuning	Assistive SRLs
MRAC	Reference-model tracking	Handles parameter variations	Sensitive adaptation design	Wearable robotic systems

The comparison indicates that model-based controllers generally provide higher motion precision and dynamic performance, whereas adaptive approaches offer improved robustness under uncertain and time-varying conditions. Consequently, many modern SRLs combine both paradigms within hybrid control frameworks to balance accuracy, adaptability, and computational efficiency.

The integration of model-based and adaptive controllers within the hierarchical architecture shown in Figure 8 enables SRLs to achieve stable operation while responding dynamically to user motion and environmental disturbances. In such architectures, high-level planners generate optimized motion trajectories, whereas adaptive low-level controllers compensate for uncertainties and interaction variability in real time.

Nevertheless, several challenges remain. The computational complexity associated with optimization-based control and online parameter estimation may limit portability and real-time implementation. In addition, ensuring stability during rapid adaptation remains a critical concern, particularly in safety-critical human–robot interaction scenarios.

5.4. Learning-Based and Intelligent Control

Learning-based and intelligent control strategies have emerged as a major research direction in supernumerary robotic limbs (SRLs) due to their ability to handle nonlinear dynamics, uncertain environments, and user-specific interaction patterns. Unlike conventional controllers that rely on predefined mathematical models, intelligent control approaches utilize data-driven methods to learn system behavior, adapt to changing conditions, and improve performance over time.

Machine learning techniques are primarily employed in SRLs for intention recognition, motion prediction, trajectory planning, and adaptive decision-making [5,13,24]. By analyzing multimodal sensory data, including electromyography (EMG), electroencephalography (EEG), inertial measurements, and vision-based information, learning-based frameworks can infer user intent and generate more intuitive robotic responses.

Artificial neural networks (ANNs) are among the most widely adopted approaches due to their capability to approximate complex nonlinear relationships between sensory inputs and control outputs [24]. Neural-network-based controllers can improve motion estimation accuracy and compensate for uncertainties that are difficult to model analytically. However, their effectiveness depends heavily on training quality, dataset diversity, and computational resources.

Deep learning methods further enhance feature extraction and pattern recognition capabilities by automatically learning hierarchical representations from large datasets. Convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have demonstrated promising performance in bio-signal classification and sequential motion prediction tasks [25]. Nevertheless, deep learning frameworks typically require extensive training data and high computational power, limiting their deployment in lightweight wearable systems.

Reinforcement learning (RL) has also gained increasing attention in SRLs because it enables autonomous learning through interaction with the environment. In RL-based control, the system learns optimal actions by maximizing a reward function associated with task performance, interaction quality, or energy efficiency. Such approaches are particularly attractive for adaptive and personalized SRL control, where user behavior and environmental conditions may continuously change [24].

Despite their advantages, reinforcement learning methods face challenges related to convergence stability, exploration safety, and training efficiency. Direct online learning in wearable robotic systems may introduce safety risks during unstable exploration phases. Consequently, many studies employ simulated training environments or hybrid frameworks that combine reinforcement learning with conventional safety-oriented controllers.

Brain–computer interfaces (BCIs) and EMG-driven intelligent control systems represent another important research direction [13,25,41]. These interfaces enable direct interpretation of user physiological signals, allowing SRLs to respond more naturally to user intention. Machine learning algorithms are commonly integrated into these frameworks to improve classification accuracy and reduce signal ambiguity. However, physiological signals are highly sensitive to noise, electrode placement, muscle fatigue, and inter-user variability, which limits long-term robustness. The major characteristics of learning-based and intelligent control approaches are summarized in Table 5.

Table 5. Comparison of learning-based and intelligent control strategies in SRLs.

Control Strategy	**Main Objective**	**Advantages**	**Limitations**	**Typical Application**
Artificial Neural Networks (ANNs)	Nonlinear mapping and prediction	Handles complex dynamics	Data-dependent training	Motion estimation
Deep Learning	Feature extraction and classification	High recognition accuracy	High computational demand	Bio-signal analysis
Reinforcement Learning (RL)	Autonomous adaptive learning	Personalized control	Training instability and safety concerns	Adaptive interaction
EMG-Based Intelligent Control	User intention recognition	Intuitive interaction	Signal variability and noise	Assistive SRLs
BCI-Based Control	Direct neural interaction	Hands-free operation	Low signal reliability	Rehabilitation systems

The comparison demonstrates that intelligent control methods significantly improve adaptability and personalization compared with conventional control approaches. However, these benefits are accompanied by increased computational complexity, data dependency, and implementation challenges.

The integration of learning-based approaches within the hierarchical architecture shown in Figure 8 enables SRLs to combine high-level cognitive decision-making with low-level stable control. In many modern systems, intelligent algorithms are employed for intention recognition and motion planning, while classical or adaptive controllers maintain stability and safety at the actuator level.

A major trend in current SRL research is the development of hybrid intelligent control frameworks that combine machine learning, adaptive control, and sensor fusion techniques. Such systems aim to balance robustness, safety, responsiveness, and computational efficiency while improving long-term user adaptation.

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Despite rapid progress, several challenges remain unresolved. Real-time implementation of computationally intensive algorithms in wearable platforms remains difficult due to limited onboard processing power and battery capacity. Additionally, ensuring explainability, reliability, and safe adaptation in AI-driven systems remains a critical requirement for practical deployment.

5.5. Comparative Analysis of Control Strategies

The selection of an appropriate control strategy for supernumerary robotic limbs (SRLs) is fundamentally a multi-criteria decision problem involving trade-offs between stability, adaptability, computational complexity, and interaction safety. As summarized in Table 6, each control paradigm offers distinct advantages and limitations, and no single approach is universally optimal across all applications.

Classical control methods, particularly PID-based controllers, remain the foundation of low-level control due to their simplicity, robustness, and ease of implementation. These methods are well-suited for regulating actuator dynamics and ensuring system stability under nominal operating conditions. However, their reliance on fixed parameters limits their ability to cope with nonlinearities and uncertainties inherent in human–robot interaction.

Impedance and admittance control strategies address this limitation by explicitly modeling the dynamic interaction between the SRL and the user. By defining a desired relationship between force and motion, these approaches enable compliant behavior and enhance safety during physical interaction. Nevertheless, their performance is highly dependent on accurate parameter tuning, and improper configuration may lead to instability or reduced responsiveness.

Model-based control approaches, such as model predictive control (MPC), offer improved accuracy and constraint handling by incorporating system dynamics into the control formulation. These methods are particularly advantageous in industrial SRLs, where precision and repeatability are critical. However, their effectiveness depends on the availability of accurate system models and sufficient computational resources, which may limit their applicability in portable or real-time systems.

Adaptive control techniques provide a mechanism to handle system uncertainties and variations in user behavior by continuously updating controller parameters based on feedback. This adaptability enhances robustness in dynamic environments but introduces additional computational complexity and potential convergence issues. Furthermore, the stability of adaptive systems must be carefully ensured, particularly in safety-critical applications.

Learning-based control methods, including neural networks and reinforcement learning, represent a significant advancement in SRL control. These approaches enable the system to learn user-specific patterns and improve performance over time, particularly in intention recognition and high-level decision-making. Despite their advantages, learning-based methods face challenges related to data requirements, training time, generalization, and real-time implementation.

Hybrid control architectures have emerged as a practical solution to combine the strengths of different approaches [5,13,24]. Typically, classical or impedance controllers are used at the low-level to guarantee stability and safety, while adaptive or learning-based methods operate at higher levels to enhance flexibility and user adaptation. This hierarchical integration enables SRLs to achieve both robust performance and intuitive interaction.

From an application perspective, assistive SRLs tend to prioritize safety, compliance, and user adaptability, favoring impedance-based and learning-enhanced control strategies [12,13]. In contrast, industrial SRLs emphasize precision, load capacity, and repeatability, making model-based and classical control approaches more suitable [3,14,28]. This distinction reflects the fundamentally different performance requirements of the two domains.

Overall, the comparative analysis highlights that future SRL systems will likely rely on hybrid and hierarchical control frameworks that integrate classical stability with adaptive and intelligent capabilities. Such approaches are essential for addressing the complex and dynamic nature of human–robot interaction while maintaining reliability and safety.

Table 6. Comparative analysis of control strategies for supernumerary robotic limbs (SRLs).

Control Type	Advantages	Limitations	Typical Use
PID / Classical	Simple, stable	Limited adaptability	Low-level control
Impedance / Admittance	Safe interaction	Requires tuning	Human interaction
Model-Based (MPC)	High accuracy	High complexity	Industrial tasks
Adaptive Control	Handles uncertainty	Computational cost	Dynamic environments
Learning-Based (AI)	Personalized control	Data-dependent	Intention recognition
Hybrid Control	Balanced performance	Complex design	Modern SRLs

5.6. Control Trade-Offs and Design Considerations

The selection of control strategies involves trade-offs between stability, adaptability, computational complexity, and responsiveness. Classical methods provide high stability but limited flexibility, while learning-based approaches offer adaptability at the expense of computational overhead. Figure 9 illustrates that assistive SRLs typically prioritize safety and adaptability, whereas industrial systems emphasize stability and precision. Consequently, hybrid control architectures that combine classical, adaptive, and learning-based methods are increasingly adopted [5,13,24].

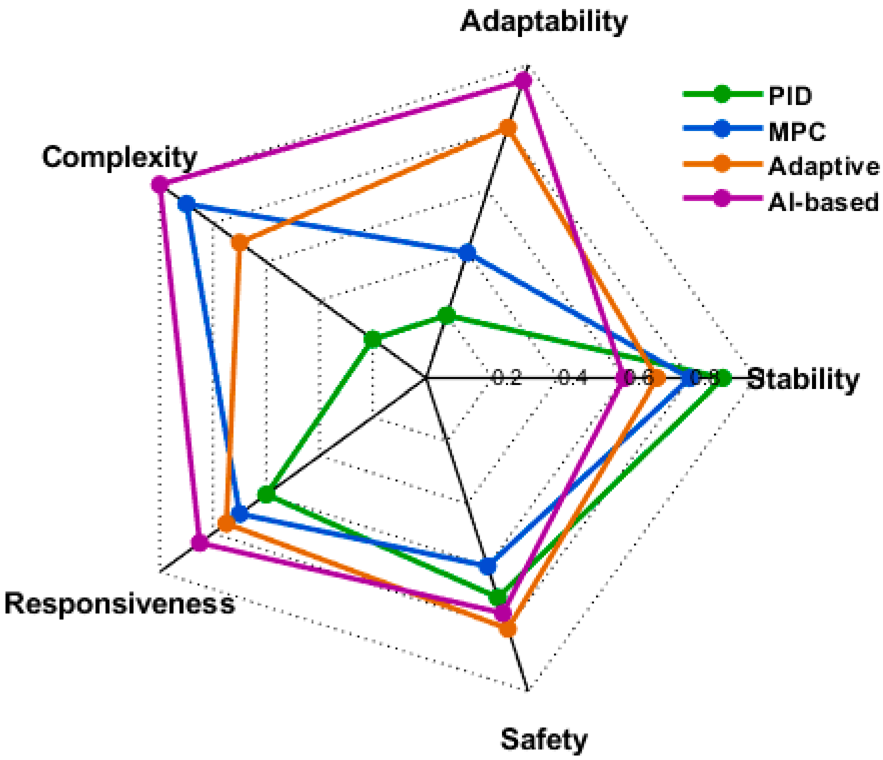

Figure 9. Trade-off comparison of SRL control strategies in terms of stability, adaptability, computational complexity, and responsiveness.

6. Applications and Future Directions

Supernumerary robotic limbs (SRLs) have emerged as a promising technology for augmenting human physical capabilities across a wide range of application domains. Their ability to provide additional manipulation capacity, reduce physical workload, and support human–robot collaboration has driven increasing interest in industrial, assistive, medical, and augmentation-oriented environments [3,5,12,15,28]. However, the requirements of these domains differ significantly, leading to distinct design priorities in terms of sensing, actuation, control, and ergonomic integration.

The major application domains of SRLs and their associated technical requirements are summarized in Figure 10.

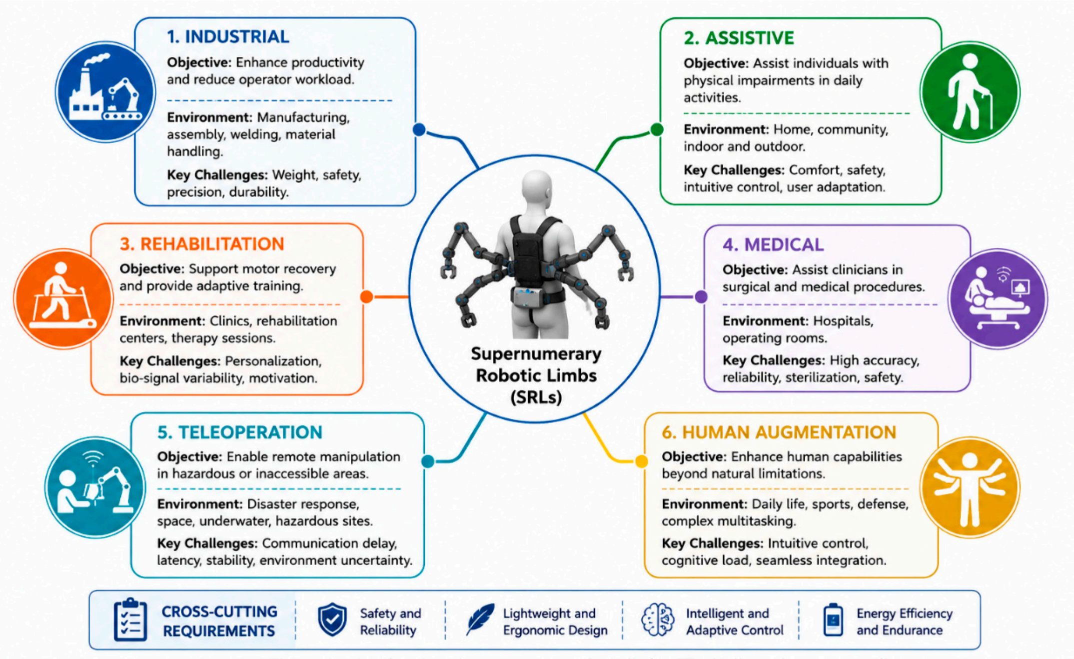

Figure 10. Major application domains of supernumerary robotic limbs (SRLs), illustrating corresponding objectives, operational environments, and key technical challenges.

6.1. Industrial Applications

Industrial environments represent one of the most mature application areas for SRLs. These systems are commonly used to support physically demanding tasks such as assembly, welding, drilling, material handling, and tool stabilization [2,3,7,28]. By redistributing loads and providing additional manipulation capability, SRLs can reduce operator fatigue while improving productivity and task efficiency.

Industrial SRLs typically emphasize high payload capacity, structural robustness, and motion precision. Consequently, these systems frequently employ rigid mechanical architectures, high-torque actuators, and model-based control strategies. However, increasing payload capability often results in higher system weight, which introduces ergonomic and safety challenges during prolonged operation [2,26,28].

6.2. Assistive and Rehabilitation Applications

Assistive SRLs are designed to support individuals with reduced mobility or physical impairments. These systems can assist users in performing activities of daily living, compensating for lost motor functionality, and enhancing independence. In rehabilitation scenarios, SRLs are additionally used to provide repetitive therapeutic motion and adaptive training for motor recovery [12,31].

Compared with industrial systems, assistive SRLs prioritize lightweight construction, compliance, and user comfort. Bio-signal interfaces such as electromyography (EMG) and electroencephalography (EEG) are frequently integrated to enable intuitive intention-driven control. However, variability in physiological signals and user adaptation remain significant challenges affecting long-term reliability [13,25,41].

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6.3. Medical and Surgical Applications

Recent studies have explored the use of SRLs in medical and surgical environments, where additional robotic limbs can assist clinicians during complex procedures. Examples include instrument positioning, camera stabilization, and cooperative manipulation during minimally invasive surgery.

These applications impose strict requirements on positioning accuracy, low latency, and interaction safety. Consequently, medical SRLs typically integrate high-resolution sensing systems, force-feedback mechanisms, and advanced control algorithms to ensure reliable operation in safety-critical environments [10,21].

6.4. Teleoperation and Human Augmentation

Teleoperation-oriented SRLs enable remote manipulation in hazardous or inaccessible environments, including disaster response, space operations, and hazardous material handling. In such systems, the SRL acts as an extension of the human operator, combining robotic precision with human decision-making [32,33].

Human augmentation applications aim to enhance natural human capabilities rather than compensate for impairments. Examples include multitasking support, extended reach, and cooperative object manipulation. These systems require highly intuitive and low-latency control strategies to minimize cognitive load and ensure seamless integration with natural body motion [3,4,15].

6.5. Comparative Analysis of SRL Applications

The requirements and design priorities of SRLs vary substantially across application domains. Industrial systems emphasize payload capacity, robustness, and repeatability, whereas assistive and rehabilitation systems focus on ergonomic integration, safety, and adaptability [8,12,14]. Medical applications prioritize precision and reliability, while augmentation-oriented systems require intuitive interaction and low cognitive burden. The comparative characteristics of major SRL application domains are summarized in Table 7.

Table 7. Comparative overview of major SRL application domains.

Domain	Objective	Key Requirement	Main Challenge
Industrial	Load support	Precision, payload	Safety
Assistive	User assistance	Comfort, compliance	Adaptation
Rehabilitation	Motor recovery	Bio-feedback	Personalization
Medical	Surgical support	Accuracy	Reliability
Teleoperation	Remote interaction	Low latency	Communication delay
Augmentation	Human enhancement	Intuitive control	Cognitive load

The comparison highlights the absence of a universally optimal SRL architecture. Instead, system design is strongly application-dependent, requiring different combinations of sensing, actuation, and control strategies to satisfy domain-specific constraints [5,12,14,27].

7. Challenges and Open Research Issues

Despite significant progress in supernumerary robotic limbs (SRLs), several technical and practical limitations continue to restrict their widespread deployment in real-world environments. These challenges involve mechanical design, sensing reliability, control robustness, energy efficiency, computational requirements, and ergonomic integration. Addressing these issues is essential for achieving safe, adaptive, and human-centered SRL systems [5,12,14,36]. The major research challenges and their interrelationships are summarized in Figure 11.

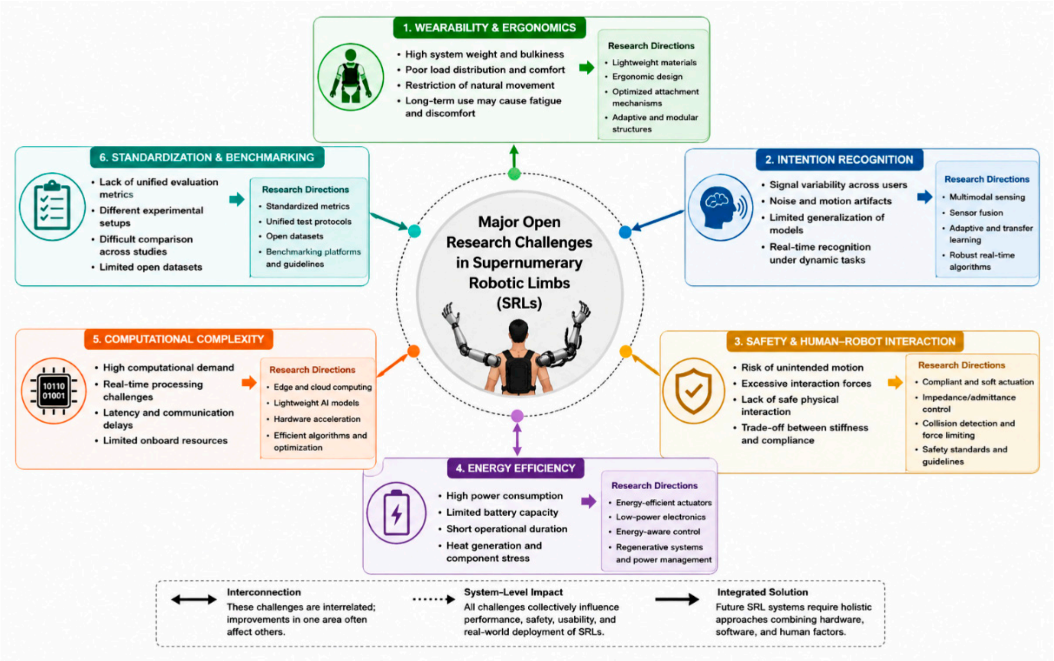

Figure 11. Major open research challenges in supernumerary robotic limbs (SRLs), illustrating the interconnection between ergonomics, sensing, control, energy management, and safety requirements.

7.1. Wearability and Ergonomic Constraints

One of the most critical challenges in SRL development is balancing payload capacity with user comfort and mobility. Increasing actuator power and structural rigidity improves task performance but also increases system mass and inertia, negatively affecting wearability and long-term usability [8,16,35].

Additionally, improper load distribution may lead to muscle fatigue, discomfort, and restricted natural movement. Future research should therefore focus on lightweight materials, optimized mounting mechanisms, and adaptive ergonomic structures capable of reducing biomechanical stress during prolonged operation [35,36].

7.2. Reliable Intention Recognition

Accurate intention recognition remains a key requirement for intuitive human–robot interaction. Existing approaches based on EMG, EEG, IMUs, and vision systems are frequently affected by signal variability, noise, environmental disturbances, and user-specific differences [5,6,13,25,41].

Although machine learning methods have improved classification accuracy, maintaining robust real-time performance under dynamic conditions remains difficult. Consequently, multimodal sensor fusion and adaptive learning strategies are expected to become increasingly important in future SRL systems.

7.3. Safety and Human–Robot Interaction

Safety is particularly critical because SRLs operate in direct physical interaction with the human body. Unexpected motion, excessive force, or controller instability may result in discomfort or injury.

Current solutions rely on impedance control, compliant actuators, force-limiting strategies, and collision detection mechanisms. However, maintaining high responsiveness while ensuring safe interaction remains challenging due to the trade-off between stiffness and compliance [10,21,27].

7.4. Energy Efficiency and Computational Complexity

Portable SRLs are constrained by limited battery capacity and high power consumption, especially in systems employing multiple actuators and computationally intensive algorithms. Increasing control sophistication often leads to higher processing requirements and reduced operational duration [9,22,24].

Real-time processing of multimodal sensing, sensor fusion, and adaptive control further increases computational complexity and latency. Emerging solutions include edge computing, lightweight AI models, energy-aware control strategies, and hardware acceleration techniques [24,25].

7.5. Standardization and Benchmarking

The absence of standardized evaluation methodologies remains a major limitation in SRL research. Existing studies often use different experimental setups, performance metrics, and testing protocols, making direct comparison difficult [39].

Establishing unified benchmarking frameworks for payload capacity, response time, ergonomic impact, safety, and energy efficiency would significantly improve reproducibility and facilitate technological progress.

7.6. Comparative Summary of Research Challenges

The major open challenges and corresponding future research directions are summarized in Table 8. The comparison demonstrates that SRL development is constrained by multiple interconnected factors spanning mechanical design, sensing reliability, control robustness, computational efficiency, and ergonomic integration [5,12,24,36].

Table 8. Key challenges and future research directions in SRLs.

Challenge	Impact on SRLs	Potential Research Direction
Wearability	Reduced comfort and mobility	Lightweight materials and ergonomic design
Intention Recognition	Unreliable user interaction	Multimodal sensor fusion and adaptive AI
Safety	Risk of injury or instability	Compliant actuation and adaptive control
Energy Efficiency	Limited operational duration	Low-power electronics and optimized control
Computational Complexity	Latency and reduced responsiveness	Edge computing and lightweight AI
Lack of Standardization	Difficult system comparison	Unified benchmarking protocols

The table highlights that wearability remains one of the most influential constraints in SRL design because increases in payload capacity and actuator power are typically accompanied by higher system weight and structural complexity. This trade-off directly affects user comfort, mobility, and long-term usability, particularly in assistive and wearable applications.

Similarly, intention-recognition reliability continues to represent a major challenge due to the variability and uncertainty associated with physiological and motion-based signals. Although machine learning approaches have improved adaptability, robust real-time performance under practical operating conditions remains limited. Consequently, future systems are expected to increasingly rely on multimodal sensing and adaptive learning frameworks to improve robustness and reduce user dependency [13,24,25].

The comparison further indicates that safety and control stability are strongly interconnected. Enhancing system responsiveness often requires increased stiffness and higher control bandwidth, which may negatively affect compliant interaction and user safety. This conflict highlights the importance of adaptive impedance control, compliant actuation, and real-time monitoring mechanisms capable of balancing performance and safety requirements [12,21,30].

Energy efficiency and computational complexity also emerge as closely related challenges. Advanced sensing, adaptive control, and AI-based frameworks significantly increase processing requirements and power consumption, limiting portability and operational endurance. Therefore, future SRLs will likely require lightweight embedded AI models, edge-computing architectures, and energy-aware control strategies to maintain real-time performance without compromising battery life [24,25].

Finally, the lack of standardized benchmarking methodologies remains a critical obstacle for fair comparison across studies. Existing research often employs inconsistent performance metrics and experimental setups, making objective evaluation difficult. Establishing unified benchmarking protocols and open datasets would significantly improve reproducibility, accelerate technological progress, and facilitate the transition of SRLs from laboratory prototypes to real-world deployment [39].

8. Conclusion

This paper presented a comprehensive PRISMA-based systematic review of supernumerary robotic limbs (SRLs), covering recent developments in mechanical design, sensing technologies, actuation systems, control strategies, application domains, and emerging research challenges. The review demonstrated that SRLs have evolved from experimental wearable prototypes into increasingly intelligent and application-oriented robotic systems capable of augmenting human physical capabilities across industrial, assistive, medical, and rehabilitation environments.

The analysis revealed that SRL development is fundamentally governed by complex trade-offs involving payload capacity, wearability, safety, adaptability, energy efficiency, and control complexity. Industrial systems primarily emphasize robustness, precision, and high load-bearing capability, whereas assistive and rehabilitation-oriented systems prioritize lightweight structures, ergonomic integration, compliance, and intuitive interaction. Consequently, SRL architectures are strongly application-dependent, requiring different combinations of sensing, actuation, and control technologies.

This review further highlighted that no single sensing modality, actuator configuration, or control strategy can independently satisfy all operational requirements. Classical and interaction-based controllers provide stability and safe physical interaction, model-based and adaptive approaches improve robustness and precision, while learning-based frameworks enable intelligent and personalized behavior. As a result, modern SRLs increasingly rely on hybrid hierarchical architectures integrating sensor fusion, adaptive control, and artificial intelligence to balance performance, responsiveness, and safety.

The comparative evaluation also identified several critical open challenges that continue to limit large-scale deployment. These include ergonomic constraints, unreliable intention recognition, computational complexity, limited energy efficiency, and the absence of standardized benchmarking methodologies. Addressing these limitations requires integrated system-level optimization rather than isolated improvements in individual subsystems.

Future SRL systems are expected to evolve toward lightweight, context-aware, and human-centered robotic platforms capable of seamless interaction with users and dynamic environments. Emerging technologies such as soft robotics, variable-stiffness actuation, multimodal sensor fusion, digital twins, and cloud-assisted learning frameworks are likely to play a central role in improving adaptability, safety, personalization, and long-term usability.

Overall, this review provides a structured and analytical overview of the current state of SRL research while identifying major technological gaps and future opportunities. The presented findings and comparative analyses can support researchers and developers in designing next-generation SRLs that achieve improved functionality, safety, and intelligent human–robot collaboration across diverse real-world applications.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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Conflicts of Interest: The authors declare no conflicts of interest.

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