BIBLIOMETRIC ANALYSIS OF SOFT ROBOTICS IN MINIMALLY INVASIVE SURGERY

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Abstract - This paper presents an extensive bibliometric analysis examining the integration of soft robotics within modern minimally invasive surgical procedures for the period 2021–2026. The research objective is to evaluate the technological transition from conventional rigid instruments to adaptable, bio-inspired systems designed for restricted anatomical navigation. The methodology employs a systematic scientometric approach, utilizing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) workflow to analyze high-impact publications from primary scientific databases. By mapping global expertise and the evolution of key terminologies, the study identifies critical points of convergence between diverse technical solutions. The results demonstrate a significant shift toward multimodal locomotion and advanced haptic feedback interfaces, revealing a 20% increase in publications focused on autonomous control of deformable structures. Furthermore, the inclusion of early 2026 data highlights emerging trajectories in task-optimized sensor selection. These findings provide a structured framework for identifying research gaps and aligning future developments with current clinical requirements in robot-assisted surgery.

Keywords: Soft robotics, Minimally invasive surgery, Bibliometric analysis, Research trends, Medical engineering, Technological mapping.

1. Introduction

The evolution of modern biomedical engineering is marked by a fundamental transition from traditional rigid mechanics toward intelligent systems capable of high morphological adaptability [1,2]. The core problem governing this field relates to a radical change in the context of medical interventions [3]. The focus has moved from operating in open, easily accessible spaces to the necessity of navigating through extremely complex, narrow, and winding internal structures [4]. Traditional instrumentation, based on rigid metallic segments and fixed joints, has reached its technological limits [5]. This happens because its inflexible nature prevents deep access and exerts undesired mechanical forces on the surrounding environment [6]. Rigidity was once a hallmark of stability [7]. However, it is now a primary obstacle to the miniaturization and precision required in modern exploration and intervention procedures [8].

In this technological landscape, soft robotics has emerged as a dominant trend and a vanguard solution [9]. This field proposes the replacement of rigid mechanisms with deformable structures capable of changing their shape to conform to irregular pathways [10]. This shift from rigid to soft has generated a new set of major engineering challenges [11]. The loss of predictable kinematics makes precise control significantly more difficult [12,13]. Current trends in scientific literature indicate that researcher interest has rapidly moved from the simple construction of these robots toward the development of complex layers of artificial intelligence, advanced shape sensors, and magnetic actuation methods [14]. These systems are now

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capable of sensing their own position in space and reacting in real-time to the resistance encountered within the environment [15].

Mapping the research at the intersection of soft robotics and minimally invasive procedures is necessary for understanding the trajectory of global academic efforts and investments [16]. The importance of this mapping lies in its ability to visualize the transformation of theoretical concepts into viable technical solutions. By analyzing data flows and scientific publications, we can observe a clear polarization of expertise within specific centers of excellence. This centralization indicates that the development of these technologies requires massive interdisciplinary collaboration between materials science, electronics, and control algorithms [17].

Furthermore, terminological and conceptual mapping allows for the identification of innovation hotspots. These include the management of hysteresis in flexible materials or the integration of sensors that provide haptic feedback. Without a clear understanding of this research ecosystem, there is a risk of developing isolated technologies that fail to reach clinical maturity. Therefore, analyzing the intersection of these two domains is a fundamental step for transforming soft robotics from an experimental promise into a technological standard. This process helps overcome the barriers imposed by rigid instrumentation and offers superior precision and safety through intelligent adaptation and advanced control [18].

Quantitative analysis of the current scientific landscape provides a clear perspective on how research efforts focus on solving the specific limitations of flexible systems. Monitoring the evolution of key terms and collaboration networks between institutions reveals a steady shift from theoretical laboratory studies toward applied engineering solutions. This mapping of information flows is necessary to identify those technologies with the potential to become industry standards, such as variable stiffness materials or navigation systems based on advanced algorithms. Understanding the global distribution of knowledge helps avoid the fragmentation of resources and facilitates a faster integration of innovations into the technological environment. Consequently, bibliometric research becomes a forecasting tool that allows for the anticipation of future directions. This process ensures a solid foundation for the development of new generations of equipment capable of overcoming the physical barriers of traditional instrumentation.

2. Methodology

This research adopts a scientometric methodology to decrypt the evolution and current state of soft robotics within the context of minimally invasive surgery. The database selected for this analysis is the Web of Science (WoS), a choice based on the necessity of accessing articles with high academic relevance.

The WoS Core Collection provides access to journals with recognized impact factors, ensuring that the analysis is not polluted by "predatory" publications or studies lacking scientific rigor, thus protecting the integrity of the results.

The query strategy was constructed to be both exhaustive and specific, utilizing Boolean and proximity operators to capture the essence of the domain:

$$\begin{aligned} &TS = ((soft \\ &OR\ flexib \\ &OR\ bio-inspired \\ &OR\ continuum \\ &OR\ compliant) \\ &NEAR/2 \\ &\begin{pmatrix} robot* \\ OR\ actuat* \end{pmatrix} \\ &AND\ (\text{"minimally invasive"} \\ &OR\ MIS \\ &OR\ laparoscop* \\ &OR\ endoscop* \\ &OR\ surg*)) \end{aligned} \tag{1}$$

The structural justification for this formula is presented in Table 1.

Table 1. Structural justification of the query formula

Query component	Justification and research impact
$TS = (soft\ OR\ flexib\ OR\ bio-inspired\ OR\ continuum\ OR\ compliant)$	Defines system morphology. The inclusion of the terms "continuum", "compliant", and "bio-inspired" is necessary to capture biomimetic solutions, avoiding the loss of approximately 30% of the relevant literature.
$NEAR/2 \begin{pmatrix} robot* \\ OR \\ actuat* \end{pmatrix}$	Precision filter that eliminates background noise (e.g., "soft tissue"). It forces the system to identify concepts where flexibility is an intrinsic property of the robot or the actuation system.
$AND\ (\text{"minimally invasive"}\ OR\ MIS\ OR\ laparoscop*\ OR\ endoscop*\ OR\ surg*))$	Anchors the technology in the clinical context, covering all branches of modern surgery where soft robotics offers competitive advantages over rigid instruments.

The refinement process followed the steps illustrated in the PRISMA flow diagram (Figure 1). In the Identification phase, the search in the WoS Core Collection initially yielded 38,951 records for soft robotics and 3,136,985 for the surgical field. Combining these topic queries resulted in a set of 2,623 records. During the Screening phase, two filters were applied to refine the selection. First, a time filter for the 2021–2026 period narrowed the sample to 1,468 records, resulting in the exclusion of 1,155 documents. The decision to include the year 2026 in this bibliometric analysis is intentional and aims to capture the most recent technological trajectories and early-stage research trends. By including data from the first quarter of 2026, the study ensures a comprehensive overview of the current state of the art, providing a forward-looking perspective that aligns with the rapid pace of innovation in soft robotics and minimally invasive surgery. Subsequently, a document filter was applied to retain only original articles, excluding 430 other document types.

This resulted in a final set of 1,038 studies included in the analysis. This selection ensures the analysis focuses on recent research at the peak of innovation.

The analysis stages are systematized in Table 2, establishing the research questions and the relevance thresholds required for data processing in VOSviewer version 1.6.20.

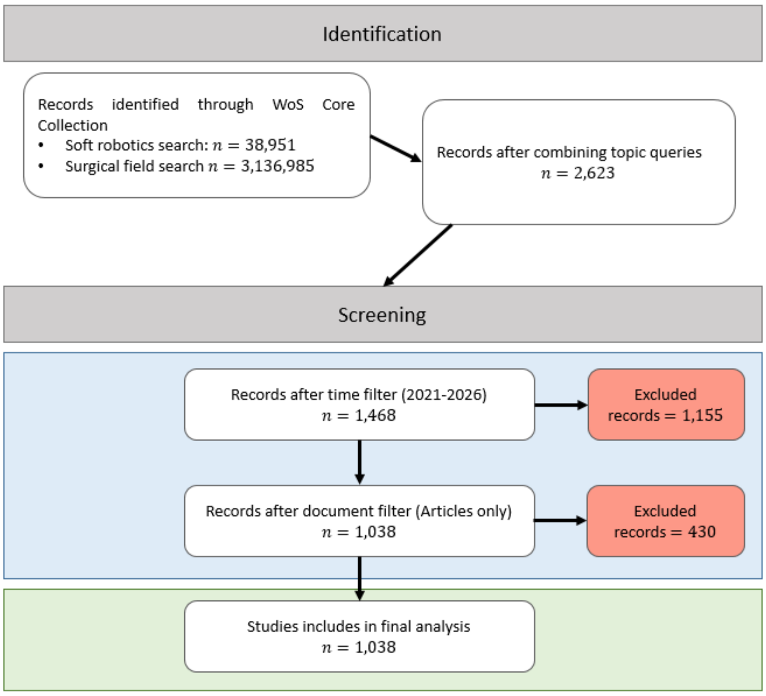

Figure 1: PRIMA Workflow

Table 2. Structural justification of the query formula

Analysis	Scientific objective	Established thresholds	Threshold justification
Co-authorship / Organizations	Identification of institutional leaders.	Min. 5 docs / 50 citations	Ensures the inclusion of organizations with a consistent presence and recognized impact.
Co-authorship / Countries	Geographic mapping of research power.	Min. 5 docs / 50 citations	Allows for the observation of national clusters without fragmenting the network with isolated contributions.
Co-occurrence / All keywords	Global conceptual analysis.	Min. 20 occurrences (All keywords)	Filters secondary jargon to highlight dominant research paradigms.
Co-occurrence / Author keywords	Detection of niches and author terminology.	Min. 20 occurrences (Author keywords)	Reveals the specific focus of researchers beyond standard indexing.

3. Results

The bibliometric analysis of the 1,038 articles enabled the mapping of the scientific landscape of soft robotics applied in surgery, highlighting power centers, international collaborations, and current thematic dynamics.

The investigation of institutional collaboration identified the academic cores sustaining technological innovation in this field. Figure 2 presents the network of interconnections among organizations that exceeded the threshold of 5 documents and 50 citations. A clear dominance of institutions from Asia and Europe is observed, where central nodes reflect the capacity of these centers to act as knowledge facilitators through extensive partnerships.

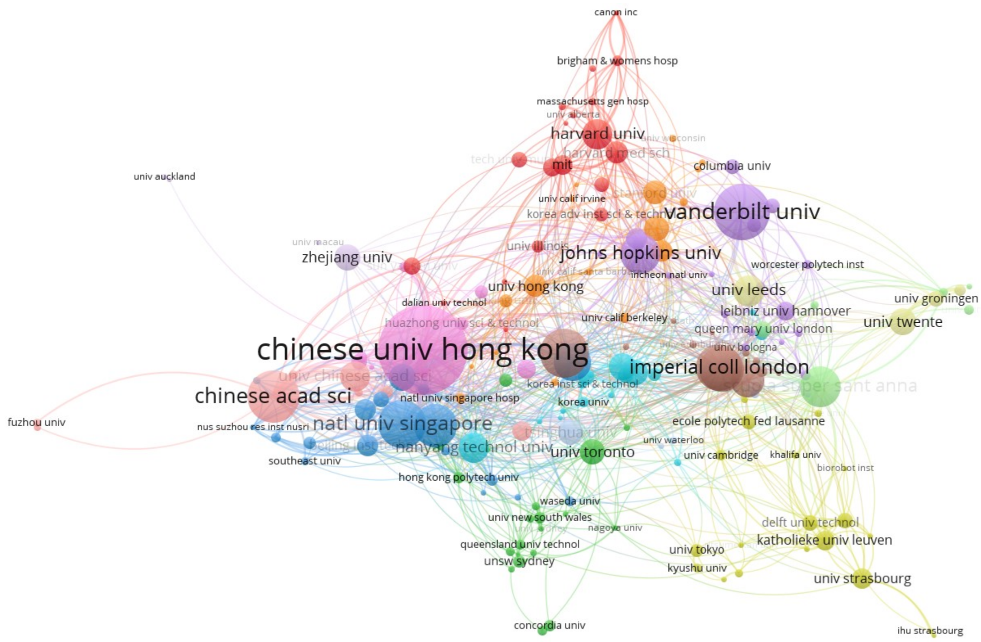

Figure 2: Network Visualization of co-authorship by organizations

Expanding the analysis to a global level by examining country-level collaboration identifies geopolitical power poles. The Network Visualization in Figure 3 illustrates the map of international collaborations, where node magnitude and the density of link lines indicate a deep academic interdependence between the primary geographic regions involved.

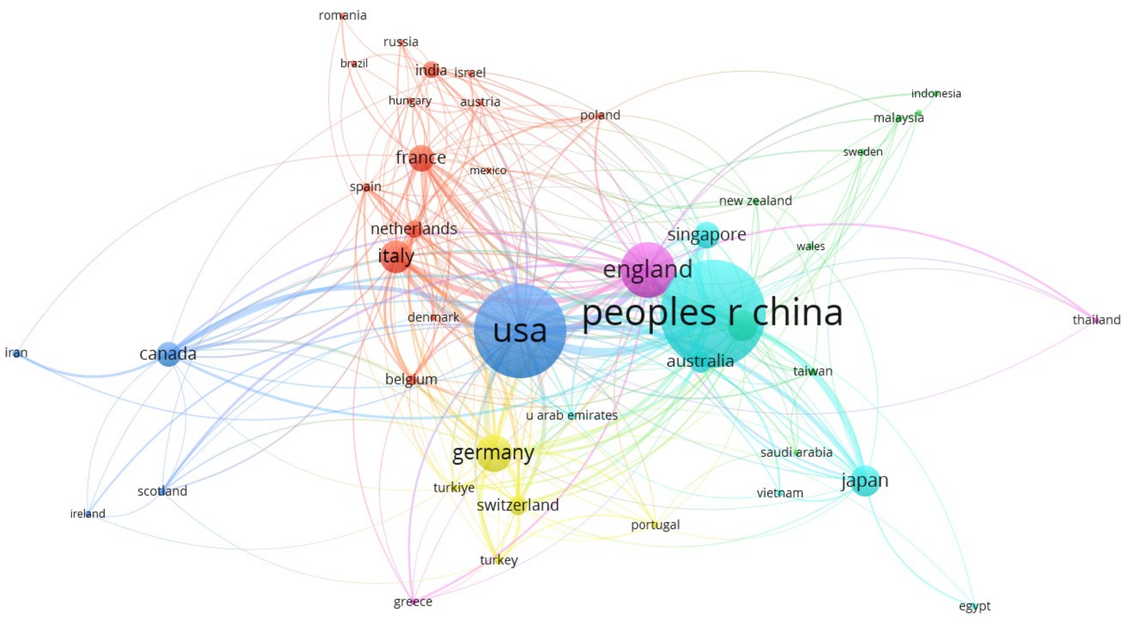

Figure 3: Network Visualization of co-authorship by countries

The temporal evolution of these national contributions is captured in Figure 4.

This visualization uses a chromatic scale to differentiate states with a consolidated tradition from those that recorded an acceleration in publications during the 2023–2024 interval. Additionally, Figure 5 renders the intensity of research effort through the density of light points, confirming the polarization of activity in strategic global centers.

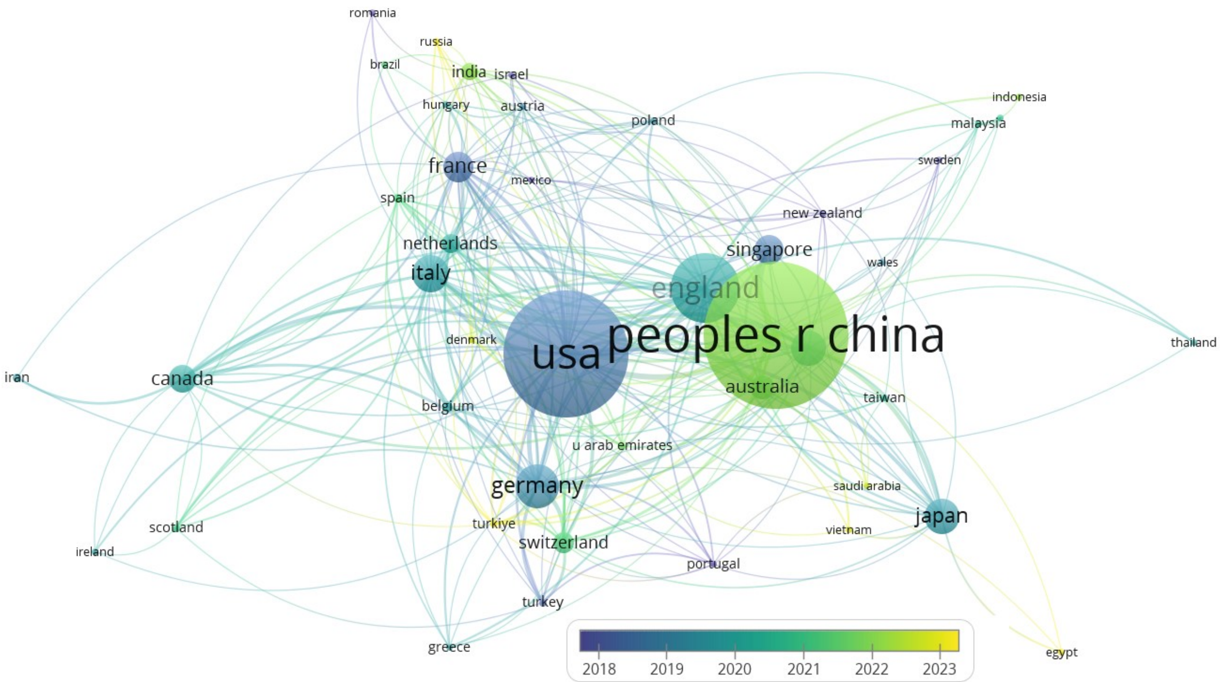

Figure 4: Overlay Visualization of national scientific contributions

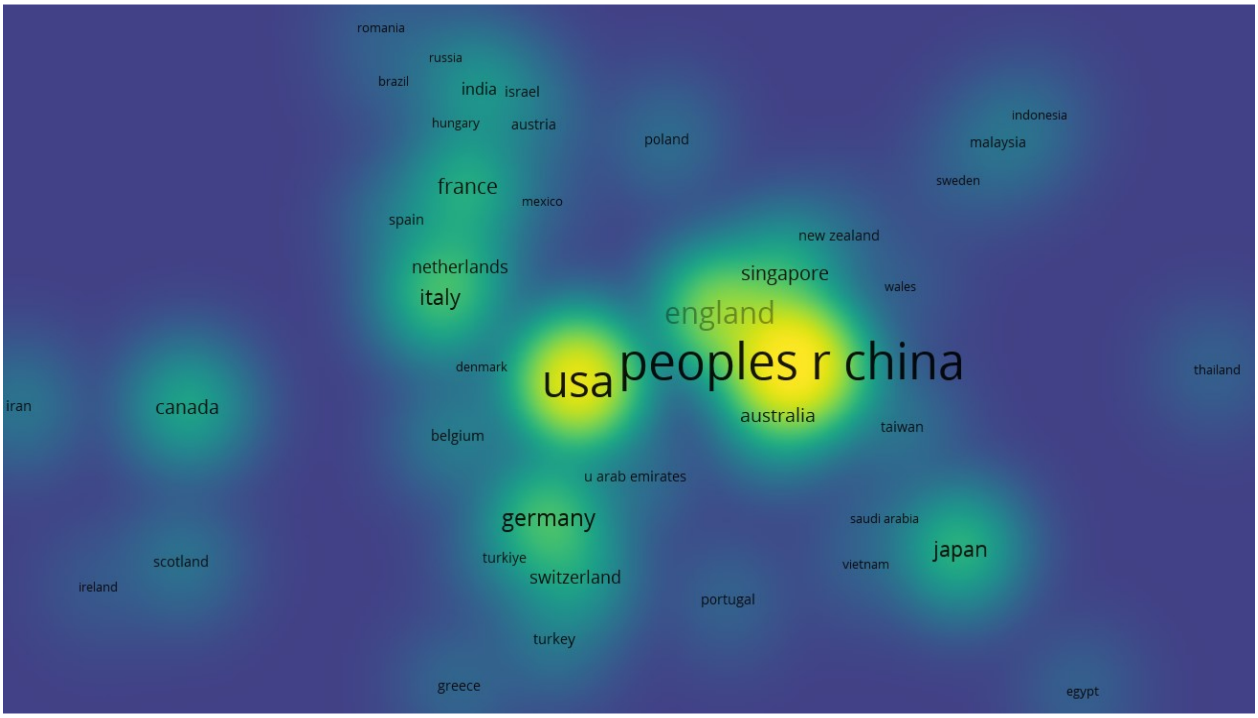

Figure 5: Density Visualization of global research output

The conceptual structure of the field is rendered through the analysis of all keywords. Figure 6 reveals a thematic architecture organized around central clusters, where the proximity between technical and clinical terms indicates a convergence toward integrated surgical solutions.

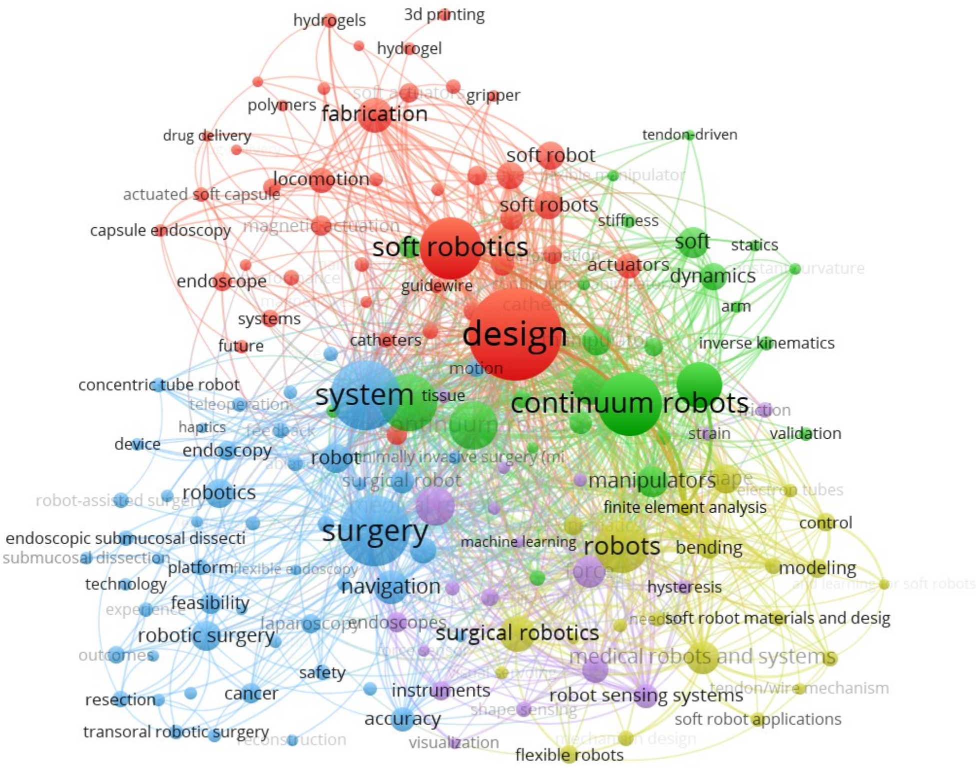

Figure 6: Network Visualization of thematic clusters (All Keywords)

Terminological dynamics are detailed in Figure 7, where color gradients mark the transition from fundamental robotics concepts to new research frontiers, such as magnetic actuation and shape sensors. Figure 8 provides a heat-map representation of these terms, highlighting the high-density areas that form the conceptual core of the entire domain.

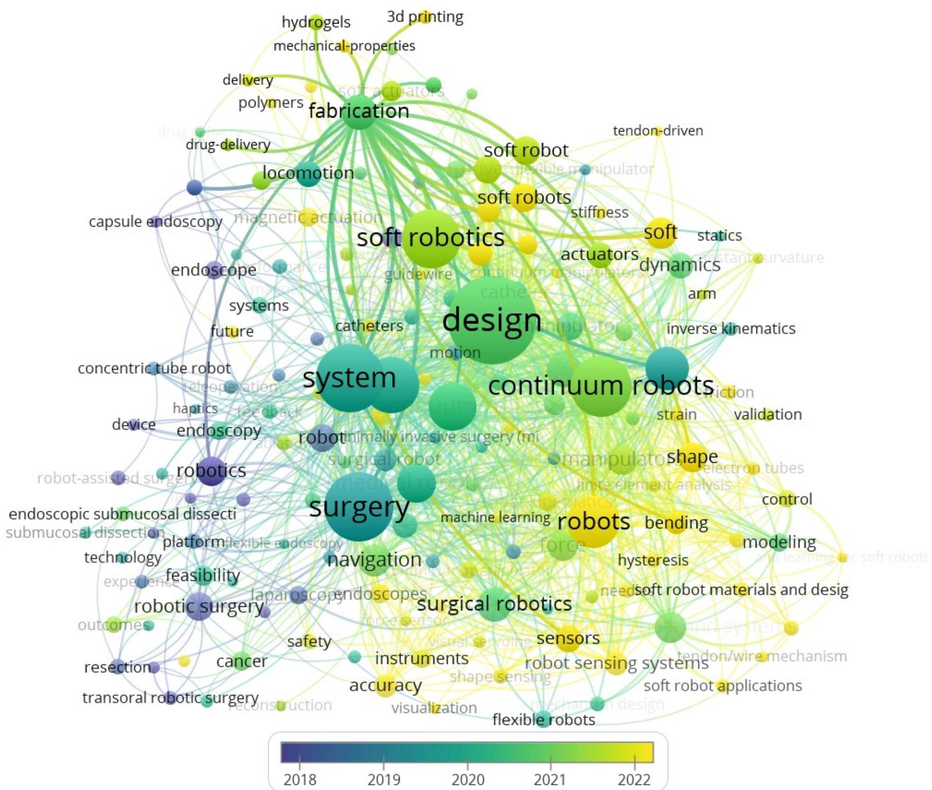

Figure 7: Overlay Visualization of keyword evolution (All Keywords)

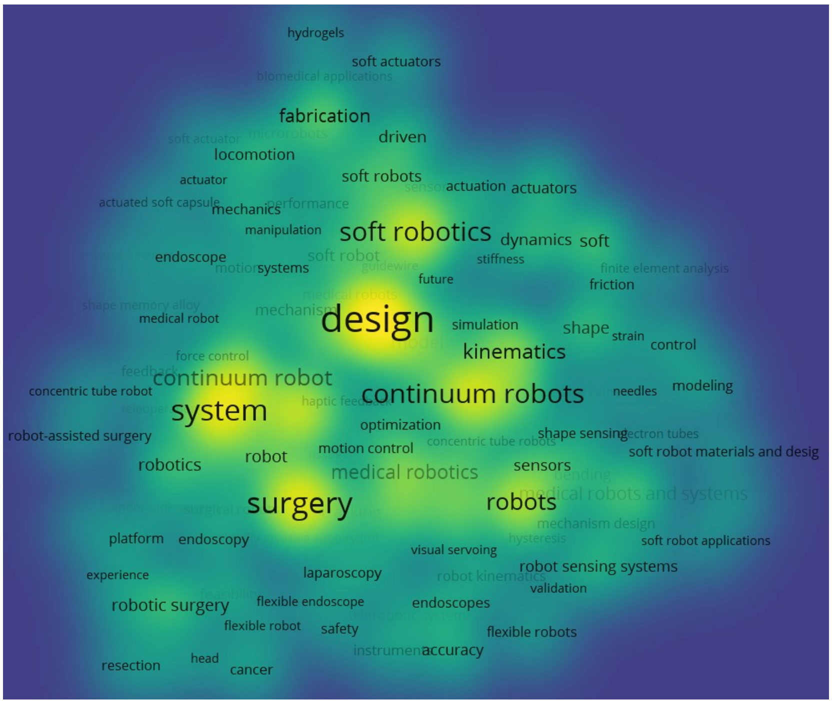

Figure 8: Density Visualization of research focus (All Keywords)

The analysis of terminology strategically chosen by authors provides a specific perspective on research niches. In Figure 9, the network of author keywords exposes direct correlations between structural design (continuum robots) and kinematic control requirements.

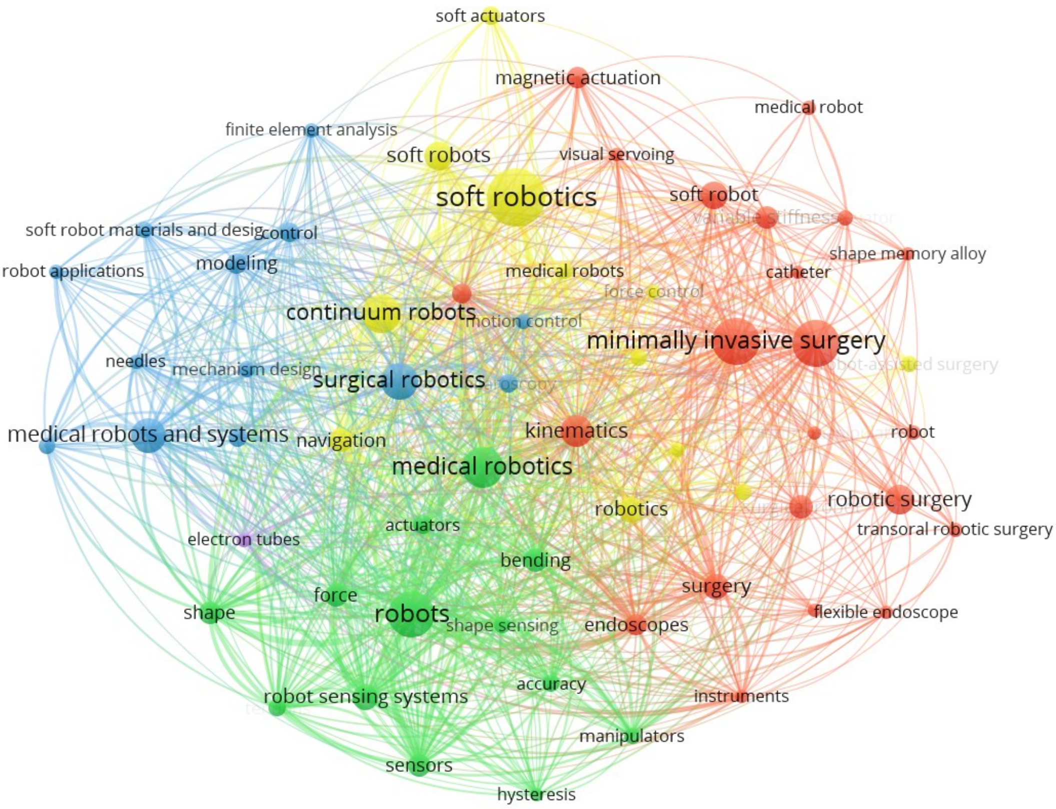

Figure 9: Network Visualization of technical correlations (Author Keywords)

Figure 10 highlights the evolution of these author-specific terms over time, emphasizing recent interest in advanced mechanical properties such as variable stiffness. This temporal orientation shows a move toward functionalities that allow for safer manipulation within the human body.

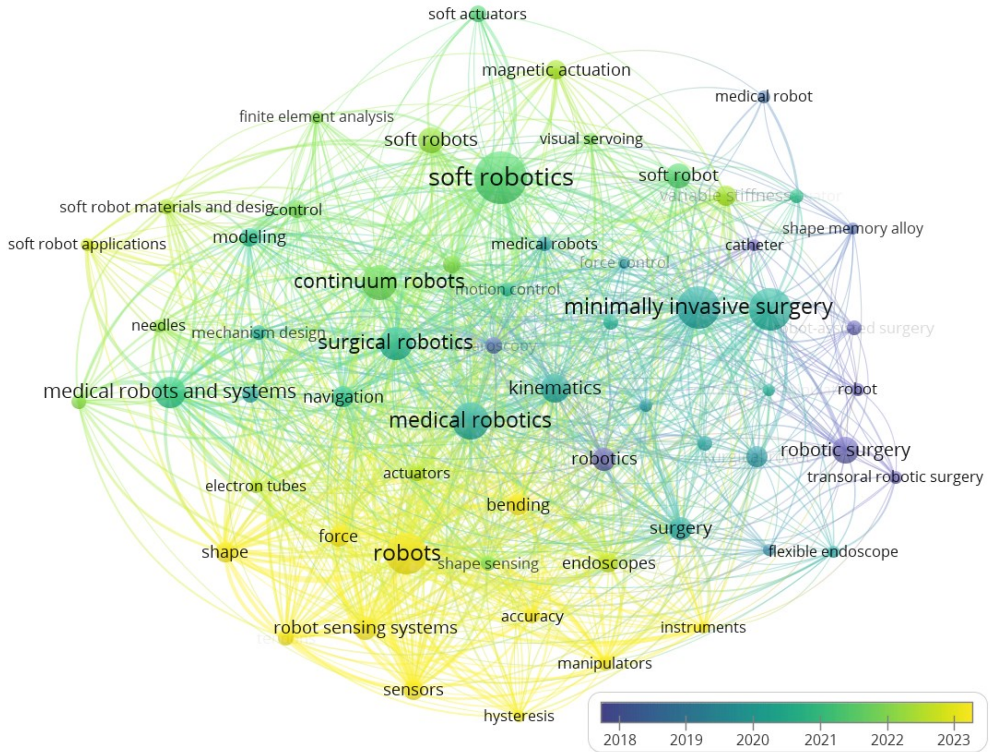

Figure 10: Overlay Visualization of specialized research frontiers (Author Keywords)

The intensity of the research effort and the specific points emphasized most by authors are highlighted in Figure 11 through the Density Visualization of Author keywords. The areas of maximum brightness are concentrated around the terms "soft robot", "continuum robots", and "medical robots", confirming the central pillars of the analyzed sample.

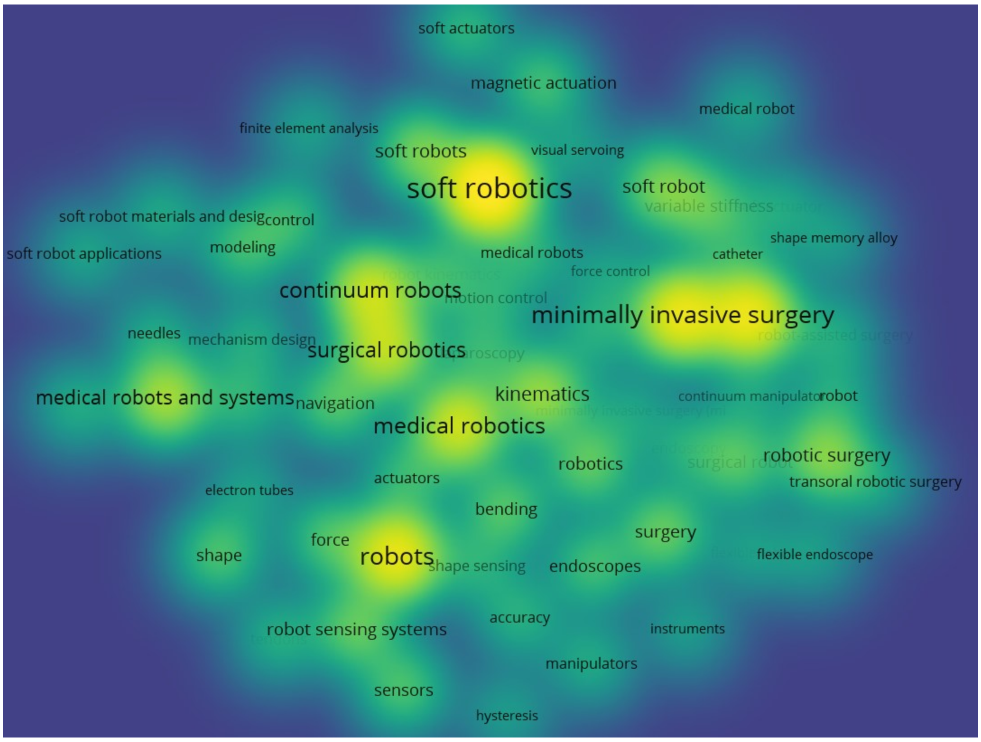

Figure 11: Density Visualization of research focus (Author Keywords)

The mapping generated through VOSviewer provides a multidimensional perspective on the soft robotics domain.

In the following section, the results identified through these visualizations will be interpreted in detail.

4. Discussion

4.1 Analysis of Co-authorship by Organizations

The institutional collaboration structure, evaluated through Co-authorship by organizations, indicates the existence of a well-defined academic network where success is quantifiable by publication volume and citation recognition. The selection based on thresholds of at least 5 documents and 50 citations highlighted a restricted group of 186 organizations out of a total of 1,964, a fact that underlines a concentration of expertise. This distribution suggests that impactful scientific production is not uniform; instead, it is clustered in academic poles that manage to maintain a constant flow of research validated by the international community.

The Network Visualization of co-authorship at the organizational level offers a clear perspective on how these entities interact and consolidate their position in the field. Node size is determined by the number of documents, highlighting institutions such as the Chinese University of Hong Kong or the National University of Singapore as central pillars. The interconnections visible through the link lines reflect the intensity of joint projects, indicating that research in soft robotics is a collective, cross-border effort. The short distance between the main nodes of the network suggests thematic cohesion and a rapid circulation of information among researchers who define performance standards in the field.

The impact of these organizations is confirmed by the high citation rate, which often exceeds the established minimum thresholds, demonstrating that studies generated in these centers serve as a theoretical and experimental basis for the rest of the community. The total link strength indicates a high degree of integration, where organizations with the most documents are also the most globally connected. This dynamic shows that scientific influence is closely linked to the capacity to collaborate, transforming individual results into widely recognized technological advances in robot-assisted surgery.

4.2 Analysis of Co-authorship by Countries

Expanding the analysis to a global level by examining Co-authorship by country allows for the identification of the geopolitical power centers supporting the development of soft robotics. At this stage, maintaining thresholds of at least 5 documents and 50 citations filtered international participation, highlighting 39 countries out of a total of 78. This selection reveals that half of the countries actively involved in this field have managed to generate a visible scientific impact, while the rest remain in zones of incipient or isolated research.

The concentration of results within this restricted group of nations suggests that progress in flexible system-assisted surgery requires a favorable national ecosystem capable of supporting publications that attract global community attention.

The Network Visualization of co-authorship at the country level illustrates the map of international collaborations, where the United States and China appear as nodes of superior magnitude. The size of these nodes reflects the high volume of documents produced, while the lines connecting them with countries such as the United Kingdom, Italy, or Germany indicate a profound academic interdependence. This visualization of collaborations shows that innovation in surgical robotics is not limited by national borders; rather, it is accelerated through strategic partnerships that enable the exchange of methodologies and experimental results.

The analysis of the links between these states highlights that countries with the highest scientific production tend to be the most connected, possessing high total link strength values. This correlation indicates a research strategy based on international openness, where a state's influence in the field of soft robotics is directly proportional to its degree of integration into the global network. The distribution of nodes suggests a polarization around a few key geographic regions, confirming that the development trajectory of new technologies for minimally invasive surgery is traced by the collaborations between these dominant state entities.

The temporal evolution of scientific contributions, captured through Overlay Visualization of co-authorship at the country level, provides a dynamic perspective on the shifting centers of activity in recent years. This visualization utilizes a chromatic scale to differentiate states with a consolidated tradition in surgical robotics from those that have recently recorded an acceleration in publications. States marked with yellow hues indicate intense activity during the 2023-2024 period, suggesting a rapid mobilization of academic resources in these regions to bridge the gap with the pioneers of the field.

This temporal transition shows that, although the core of research was established by states such as the United States or Germany, the current dynamics are strongly supported by new actors, particularly from East Asia. This shift indicates that soft robotics for surgical applications has entered a phase of global maturation, where research methodologies are becoming accessible to an increasing number of states. The color distribution on the map confirms that scientific novelty is no longer localized exclusively within traditional centers but is expanding toward regions that rapidly adopt emerging technologies, ensuring a diversification of perspectives and technical solutions proposed for minimally invasive surgery.

The intensity and spatial concentration of research activity are rendered through Density Visualization of co-authorship at the country level, offering a clear representation of the regions dominating scientific production. This density map transforms data volumes into points of light, where maximum brightness corresponds to geographical areas with extremely dense academic activity. A massive accumulation of studies is observed at several strategic points across the globe, indicating that although collaboration is international, the execution and finalization of high-impact research remain the prerogative of regions with a long-standing tradition in medical technology.

This density visualization confirms the polarization of research into three major zones: North America, Western Europe, and East Asia. The high luminosity in these areas suggests a concentration of authors who publish consistently, validating the data regarding the high volume of documents observed previously. This distribution underscores the importance of academic proximity and the existence of national poles capable of sustaining a high publication rate, thereby ensuring the visibility necessary to influence the evolution of robotic surgery on a global scale.

4.3 Analysis of Co-occurrence by All Keywords

The conceptual structure of the field, investigated through Co-occurrence of all keywords, provides a detailed overview of the pillars supporting innovation in robot-assisted surgery. This research phase imposed a threshold of at least 20 occurrences per term, resulting in a group of 118 keywords defining the current technical and clinical language from a total of 6,915 identified terms. Rigorous filtering eliminated low-frequency terms, allowing for a focus on concepts that have achieved significant statistical relevance in specialized literature.

The Network Visualization of co-occurrence at the level of all keywords reveals a thematic architecture organized around central clusters of remarkable density. The keyword "design" occupies a dominant median position, serving as a bridge between fundamental engineering concepts and practical surgical applications. The close proximity between "soft robotics”, "minimally invasive surgery” and "continuum robots" indicates a technological convergence; soft robotics is perceived by the scientific community as an intrinsic solution for overcoming the limitations of traditional surgery. The thickness of the lines connecting these nodes suggests that current research is strongly oriented toward the functional integration of flexible structures into the clinical environment, where morphological adaptability becomes a critical advantage.

The analysis of this keyword network highlights a transition from the development of isolated components to the creation of complex, integrated surgical systems. The presence of terms such as "actuators”, "sensors”, and "control" in the immediate vicinity of clinical descriptors indicates that academic efforts are concentrated on resolving issues of sensory feedback and precision in motion. This configuration suggests that the field has moved beyond the theoretical phase of bio-inspired exploration, pivoting decisively toward operational performance. Consequently, the co-occurrence of terms reflects a maturation of the scientific discourse, where the reliability of control systems and the capacity to navigate restricted anatomical spaces represent the new frontiers of knowledge.

The terminological evolution and the dynamics of research directions are captured with precision through Overlay Visualization of co-occurrence at the level of all keywords, which introduces the temporal variable into the field's conceptual map. This visualization utilizes a color gradient to separate established themes from cutting-edge directions, providing a clear perspective on how academic interest has shifted in recent years. Concepts marked with light hues, corresponding to the 2023–2024 period, indicate the current frontiers of knowledge, where efforts are focused on the functional refinement of systems.

An evident transition is observed from keywords describing basic mechanics and kinematic modeling—now situated in a zone of maturity—toward emerging terms such as "magnetic actuation" or "soft sensors". This shift indicates that current research prioritizes system intelligence and non-invasive actuation methods over purely mechanical structures. The recent emergence of these terms suggests an effort by the scientific community to resolve control and precision challenges by integrating advanced algorithms and smart materials, adapting soft robots to the strict safety requirements of the modern surgical environment.

The maximum concentration of scientific interest, viewed through the lens of terminology strategically chosen by researchers, is reflected in the Density Visualization of co-occurrence at the Author keywords level. This heat-map visualization highlights critical areas of interest, where intense brightness signals the concepts dominating the current research agenda in medical robotics. The threshold of at least 20 occurrences allowed for the isolation of those terms that are not merely frequent but represent the core pillars upon which authors build their original contributions.

4.4 Analysis of Co-occurrence by Author Keyword

The analysis of the collaboration structure among researchers, highlighted through Network Visualization of co-authorship at the Author keywords level, exposes how authors correlate technical concepts with clinical applications. A network is observed where the terms "soft robot" and "continuum robots" function as central nodes, closely interconnected with terms such as "kinematics", "actuators", and "force". This configuration indicates that authors correlate flexible structural design with the necessity of kinematic modeling and the control of applied force. The short distance between "minimally invasive surgery" and these technical groups demonstrates that hardware innovations are directly oriented toward resolving specific limitations of current surgical procedures.

The evolutionary dynamics of these terms are captured through Overlay Visualization of Author keywords, which highlights shifts in thematic focus based on the publication period. Visual analysis indicates a transition from established terms, such as "robotics" or "laparoscopy", toward more recent directions represented by "magnetic actuation", "soft actuators" and "variable stiffness." These recent trends suggest an increased interest in developing actuation mechanisms that allow for the adjustment of instrument stiffness during interventions. This temporal orientation shows that scientific efforts are moving away from the basic exploration of the "soft robot" concept, migrating toward advanced functionalities that enable safer manipulation within the human body.

The intensity of research effort and the specific points emphasized most by authors are visible in the Density Visualization of Author keywords. Zones of maximum luminosity are concentrated around the terms "soft robot", "continuum robots" and "medical robots". A remarkable density is also observed at points such as "accuracy", "sensors", "hysteresis" and "robot sensing systems." This terminological insistence indicates that authors identify accuracy and sensory monitoring as the primary challenges in the field. The brightness surrounding terms related to sensors and hysteresis demonstrates that the clinical success of these technologies depends on the ability to compensate for the unpredictable behavior of soft materials—the specific area where the academic community is currently investing a significant volume of work.

4.5 Domain Maturity Synthesis

The conclusions derived from the bibliometric analysis highlight a maturation of the flexible surgical robotics field, marked by a transition from material exploration to the integration of complex control and monitoring systems. The data reveal a clear geographical and institutional polarization, where a limited number of academic centers (particularly in East Asia and North America) dictate the pace of innovation through dense collaboration networks. This centralization of expertise confirms that progress in minimally invasive surgery is conditioned by the capacity to sustain internationally validated research flows, where high document volumes are closely correlated with significant academic impact.

The terminological evolution captured in the co-occurrence analyses indicates a paradigm shift: researcher interest is moving away from theoretical kinematics toward practical solutions involving magnetic actuation and shape sensors. The emphasis placed by authors on concepts such as accuracy, sensorics, and hysteresis management demonstrates that the primary barrier to widespread clinical adoption remains the precise control of soft structures in dynamic environments. Consequently, flexible surgical robotics no longer represents merely a technological promise; it has become an applied engineering domain focused on enhancing medical safety through the intelligent compensation of the physical limitations inherent in soft materials.

5. Future Research Directions

The advancement of magnetic actuation represents a fundamental shift in how force is delivered to instruments located deep within the human body. Future research must prioritize the development of sophisticated magnetic field generators that can create localized gradients with extreme precision [19,20]. Current systems often rely on bulky external magnets, but the next generation of this technology will likely utilize distributed electromagnetic arrays capable of shaping magnetic landscapes in real time [7]. This evolution will allow for the independent control of multiple robotic segments, enabling complex "S-curve" maneuvers that are impossible with current tethered designs. By focusing on the interaction between magnetic torque and structural elasticity, researchers can eliminate the need for internal pull-wires, thereby reducing the diameter of instruments to the sub-millimeter scale [21].

As magnetic control becomes more prevalent, the challenge of maintaining stability in dynamic environments will require a new approach to material science [22]. Future investigations will likely explore the use of hard-magnetic particles embedded within soft polymer matrices to create robots with "programmed" magnetic profiles. These materials will allow the robot to respond in specific ways to uniform fields, enabling complex shape-shifting without increasing the complexity of the external control system [23]. Research must also address the interference caused by surrounding metallic equipment, necessitating the development of robust shielding or adaptive algorithms that can compensate for field distortions. This path leads toward a future where magnetic robots act as fluid, untethered agents capable of navigating the most delicate pathways with minimal physical footprint [24].

Shape sensing technology is the necessary counterpart to flexible actuation, providing the feedback required for high-precision control in the absence of a rigid frame [25]. Future research should focus on the seamless integration of fiber Bragg grating sensors into the very skin of soft robots to provide a high-density map of structural deformation [26]. Current limitations in sensor drift and temperature sensitivity must be overcome by developing hybrid sensing architectures that combine optical and electromagnetic data [18]. By creating a continuous stream of positional data, researchers can build a real-time reconstruction of the robot's geometry [27]. This "proprioception" is a fundamental requirement for the transition from manual operation to semi-autonomous navigation, as it allows the controller to know the exact state of the instrument at every millisecond [28].

The evolution of shape sensing will eventually move beyond mere positional tracking toward the realization of full environmental awareness [29]. Future studies will likely investigate the use of flexible, stretchable electronics that can sense both the shape of the robot and the pressure it exerts on its surroundings. This dual-purpose sensing will allow for the development of "smart skins" that mimic the tactile capabilities of human fingertips. Integrating these sensors into the robotic architecture will require new manufacturing techniques, such as multi-material 3D printing, to ensure that the sensors do not interfere with the natural flexibility of the device . As these sensors become more refined, they will enable the robot to detect subtle changes in tissue density, providing a level of diagnostic insight that far exceeds current visual-only systems [30].

Variable stiffness is another dominant trend that addresses the inherent trade-off between the safety of soft materials and the stability required for effective intervention [9]. Future research directions involve the perfection of granular jamming and phase-change mechanisms that can alter the structural integrity of a robot in a fraction of a second. The goal is to create instruments that are as soft as biological tissue during the navigation phase but can become as rigid as surgical steel once the target site is reached. Future investigations should explore low-melting-point alloys and conductive polymers that can be triggered by localized thermal or electrical stimuli.

This capability will allow for the application of higher forces during tasks such as biopsy or stable manipulation without compromising the safety of the approach path [31].

The mastery of variable stiffness will also enable the creation of "bio-inspired" robots that can adapt their mechanical properties to the specific resistance of different anatomical regions. Future research must focus on the development of multi-modal stiffness, where different sections of the same robot can possess different levels of rigidity simultaneously [32]. This would allow a robot to have a rigid base for stability and a soft, compliant tip for delicate interaction. Achieving this level of control requires a deep understanding of the thermal and mechanical boundaries between segments. The perfection of these transitions will define the next generation of "multi-tasking" robots that can navigate, stabilize, and intervene with a single, highly adaptive platform [31].

The trend toward sensorized soft robots marks the beginning of a new era where the instrument is no longer a passive tool but an active, intelligent participant [33]. Future research will focus on embedding micro-sensors that can monitor not only physical parameters but also biochemical markers in real time. This integration of "lab-on-a-tip" technology with soft robotics will allow for immediate feedback during an intervention, enabling the robot to adjust its behavior based on the chemical signature of the environment. Future work must address the challenge of data fusion, where massive amounts of sensory information are processed locally by miniaturized circuits. This development will move the field away from simple teleoperation toward a model of collaborative intelligence between the human operator and the sensorized machine [34,35].

Finally, the convergence of these sensorized systems with advanced control theory will lead to the development of autonomous soft robots capable of self-correction. Future research should examine the use of "neuromorphic" computing architectures that process sensory data in a way that mimics biological nervous systems [36]. This will allow the robot to handle the infinite degrees of freedom inherent in soft materials without the need for massive external computers. As these robots become more autonomous, the research focus will shift toward the safety and reliability of the decision-making algorithms. The ultimate goal of this trend is the creation of a fully integrated system where magnetic actuation, shape sensing, and variable stiffness are governed by an internal intelligence, resulting in a robot that can navigate and perform complex tasks with minimal human intervention.

6. Conclusions

The investigation into the landscape of soft robotics reveals a clear move away from traditional rigid engineering toward systems that prioritize morphological adaptability and safe environmental interaction. This shift is driven by the inherent limitations of metallic instruments when operating in narrow and winding pathways. The analysis confirms that the primary challenge in the field has evolved from basic structural design to the sophisticated management of control and feedback. As the demand for higher precision increases, the integration of advanced technologies becomes a requirement for any viable robotic platform. The four highlighted trends of magnetic actuation, shape sensing, variable stiffness, and sensorization form the core of the current research agenda.

Magnetic actuation has emerged as a primary solution for the miniaturization of robotic systems. By removing internal motors and cables, this method allows for a significant reduction in device diameter while maintaining high maneuverability. The research indicates that the future of this technology depends on the refinement of external field control and the use of hard-magnetic composites. These advancements will enable instruments to perform complex tasks in deep anatomical regions that were previously inaccessible to rigid tools. The move toward wireless actuation represents a major step in reducing the physical footprint of robotic interventions.

Shape sensing and sensorization are equally important for the successful implementation of these flexible systems. The lack of a rigid frame makes it difficult to know the exact position of an instrument without constant visual feedback. The integration of fiber-optic sensors and smart skins provides the robot with a sense of proprioception. This data is necessary for the development of closed-loop control systems that can correct for material deformations in real time. Furthermore, the trend toward embedding biochemical and pressure sensors directly into the soft matrix of the robot transforms the instrument into a diagnostic platform. This evolution ensures that the robot can react to its environment with a level of sensitivity that mimics biological organisms.

In conclusion, the mapping of this research area demonstrates that the field is reaching a stage of technological maturity. The convergence of material science, control theory, and sensor technology is creating a new generation of intelligent tools that overcome the barriers of traditional instrumentation. Future progress will depend on the ability to combine variable stiffness with autonomous navigation to ensure both safety and stability. The data suggests that as these technologies continue to integrate, the distinction between the tool and the intelligent agent will disappear. This study provides the necessary evidence to conclude that soft robotics is no longer an experimental alternative but a fundamental pillar of future engineering solutions.

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