

Soft Robotics- An Analysis on Trends and Technologies

Mitesha Dange¹, Sandip Bidgar²

¹Department of Robotics and Automation, AISSMS College of Engineering

Abstract—Soft robotics has emerged as a groundbreaking technology within the medical sector, providing enhanced flexibility, adaptability, and biocompatibility that surpass the limitations of conventional rigid robots. This report offers an extensive review of the existing applications, technological progress, and future possibilities of soft robotics in healthcare. The primary areas of emphasis include surgical robotics, rehabilitation devices, prosthetics, and diagnostic instruments. By analyzing the latest materials, such as elastomers and shape-memory alloys, alongside advanced technologies like pneumatic actuators, the paper underscores both the benefits and challenges associated with the integration of soft robots into medical practice. While there is significant potential for improved patient care, challenges such as material durability, control accuracy, and regulatory obstacles continue to pose considerable barriers. Additionally, ethical issues related to patient safety and the autonomous operation of soft robotics are examined. The report concludes by outlining prospective developments, including bio-hybrid robots and AI-driven systems, and stresses the necessity for further research to fully realize the transformative potential of soft robotics in healthcare.

Index Terms—Soft robotics, Tecnology, Robot Invasive sergery, Soft Robotics for surgery,rehabilitation, Prosthetics, Endoscopies Soft robots,Assistive edevices, Wearables;

I INTRODUCTION

Background of soft robotics

Soft robotics represents an emerging and dynamic area within the field of robotics, dedicated to the development of robots constructed from pliable and deformable materials. These robots are designed to emulate the movements and flexibility of living organisms more effectively than their traditional rigid counterparts. The inherent ability of soft robots to bend, twist, and stretch enables them to execute intricate tasks in settings that demand sensitivity and adaptability. This discipline takes cues from nature,

particularly from creatures such as octopuses and worms, which adeptly alter their shapes to traverse various environments or handle fragile items.

Soft robots are primarily utilized for the mechanical compliance of machine components, with this compliance influenced by both the material and mechanical structural characteristics. In recent years, the field of soft robotics has experienced significant growth due to its wide-ranging practical applications, leading to the establishment of numerous new journals, research groups, and global open-access resources dedicated to soft robotics. The fundamental distinctions between soft and hard robots are illustrated in Figure 1.1. Young's modulus serves as an important indicator of the tensile properties of materials used in the construction of robotic structures. Rigid robotic structures generally exhibit high Young's modulus values, typically ranging from 10^3 to 10^5 Pa, while soft tissue structures are made from materials with considerably lower tensile strength, resulting in Young's modulus values on the order of 10^0 to 10^2 Pa. When a soft robot encounters an obstacle, its lack of rigidity provides flexibility and geometric adaptability to navigate around each obstacle. The compliance of soft robots is akin to that of soft tissues or skin; however, this characteristic poses challenges in modeling high-order compliance scenarios for soft robots, as there are currently no dynamic models capable of reliably predicting and tracking the position of every specific point on the robot.

Scope of Soft Robotics

The domain of soft robotics encompasses a wide range of applications, significantly impacting various sectors through its innovative characteristics of flexibility and adaptability. In the healthcare sector, soft robotics greatly improves surgical precision via minimally invasive techniques, facilitates patient rehabilitation with the use of soft exoskeletons and prosthetics, and enhances targeted drug delivery in complex biological

environments. In industrial settings, soft robots are increasingly utilized in manufacturing and assembly processes, where their gentle handling is ideal for managing fragile items. Collaborative robots made from soft materials can operate safely alongside human workers, enhance productivity and allow for mutual adaptation to each other's movements, which is crucial for optimizing operations across diverse industries. In agriculture, soft robotics is revolutionizing the methods of crop harvesting and monitoring. These systems are capable of delicately picking fruits and vegetables, thereby minimizing damage and waste.

The marine industry also benefits from soft robotics, particularly through the use of soft autonomous underwater vehicles (AUVs) that can navigate complex underwater landscapes without disrupting marine ecosystems. Robotic fish, designed to mimic natural movements, are employed to study aquatic environments and behaviors, providing valuable insights for environmental research. In search and rescue operations, soft robots can maneuver through debris and confined spaces, proving vital in disaster response scenarios. Their ability to transport supplies and assist individuals in inaccessible areas highlights the practical applications of soft robotics in emergency medical assistance and humanitarian efforts.

II META ANALYSIS OF RESEARCH

A. Comparative Studies: Diverse Research on Applications of Soft Robotics

The applications of soft robotics extend into numerous medical domains, including surgery, rehabilitation, prosthetics, diagnostic tools, and assistive technologies. This comparative examination emphasizes several critical areas.

1. Minimally Invasive Surgery:

- The study titled *Soft Robotic Grippers for Minimally Invasive Surgery* examines the use of soft robotic grippers designed for the careful handling of delicate tissues during surgical procedures. The integration of silicone elastomers and pneumatic actuation provides the necessary flexibility while reducing tissue damage.
- The research *Soft Continuum Robots for Endoscopy: Design and Evaluation* (Wang et al., 2021) investigates the creation of soft continuum robots intended for endoscopic applications,

where their enhanced dexterity and flexibility facilitate navigation through intricate anatomical structures, presenting a significant advantage over traditional rigid instruments.

Comparison: Liu et al. (2020) centers on the manipulation of tissues during surgical interventions, highlighting the importance of gentle contact and grip control, whereas Wang et al. (2021) emphasizes the precision and dexterity essential for maneuvering within restricted anatomical environments during endoscopic procedures.

2. Rehabilitation:

- *Soft Exo suits for Stroke Rehabilitation: Assistance of Ankle Motion* (aPark et al., 2019) examines the development of soft exo suits aimed at facilitating stroke rehabilitation, offering support to help individuals recover motor functions with minimal discomfort.
- *Inflatable Soft Robots for Wearable Muscle Assistance* (Yap et al., 2018) investigates inflatable soft robots that can be worn, designed to improve muscle strength and deliver adjustable support during movement, which proves to be highly advantageous in rehabilitation contexts.

In comparison, Park et al. (2019) highlights the importance of comfort and adaptability, particularly for stroke survivors working to regain motor control, whereas Yap et al. (2018) concentrates on the flexibility and customization of muscle assistance to address diverse rehabilitation requirements.

3. Prosthetics

- *Tendon-Driven Soft Robotic Prosthetic Hands for Dexterous Manipulation* [1] examines soft robotic prosthetic hands equipped with tendon-driven actuators that replicate fine motor control and a natural range of motion, thereby enhancing dexterity.
- *Soft Robotic Lower Limb Prosthetics: Pneumatic Actuation for Gait Restoration* (Clemens et al., 2020) explores soft robotic lower limb prosthetics that employ pneumatic actuators to more effectively mimic natural gait patterns in comparison to traditional rigid prosthetics.

In summary, Della Santina et al. (2019) emphasizes the restoration of fine motor skills in the hands, enhancing dexterity and natural movement, whereas Clemens et al. (2020) focuses on full-limb prosthetics

aimed at restoring gait with a more natural walking pattern.

4. Diagnostics Devices

- Soft Robotics for Tumour Palpation and Tissue Stiffness Measurement (Kim et al., 2021) presents a soft robotic apparatus aimed at tumour detection through tissue palpation and stiffness assessment, thereby providing non-invasive diagnostic options.
- Bio-inspired Soft Robots for Endovascular Navigation (Nelson et al., 2020) investigates a bio-inspired soft robotic system capable of manoeuvring within blood vessels to facilitate the diagnosis and treatment of vascular conditions, ensuring accurate navigation through intricate vascular networks.

In comparison, Kim et al. (2021) emphasizes the measurement of tissue stiffness as a non-invasive approach for tumor detection, whereas Nelson et al. (2020) concentrates on vascular diagnostics, highlighting the ability to navigate confined spaces within the circulatory system for both diagnostic and therapeutic applications.

5. Assistive Device

- The study titled Soft Robotics for Wearable Assistive Devices: Enhancing Mobility for Elderly Patients (Chen et al., 2019) explores the application of soft wearable robotics aimed at improving mobility among elderly individuals, with an emphasis on lightweight and flexible support systems.
- In contrast, the research Soft Robotic Glove for Hand Assistance in Daily Tasks (Bouter et al., 2021) examines a soft robotic glove designed to aid individuals with diminished hand strength, facilitating their ability to perform everyday tasks such as grasping objects and opening containers.

While Chen et al. (2019) concentrates on enhancing overall mobility for elderly patients through general physical support, Bouter et al. (2021) specifically addresses hand assistance in daily activities, providing fine motor support for those with compromised grip strength.

B. Metrics: Common Metrics in soft robotics

In the realm of soft robotics, various applications employ a set of standard metrics for assessment:

- Efficiency: This metric is generally evaluated by comparing the power consumption of actuators to the task at hand. For instance, research conducted

by Wang et al. (2021) investigates the energy requirements for endoscopic navigation.

- Biocompatibility: Particularly vital in medical contexts, biocompatibility guarantees that soft robots can be safely utilized within the human body over extended periods. Investigations by Nelson et al. (2020) and Patel et al. (2021) utilize materials such as hydrogels and elastomers to facilitate safe interactions with biological tissues.
- Cost-effectiveness: The economic feasibility of soft robots is crucial for their broader application in medical settings. Research by Chen et al. (2019) and Bouter et al. (2021) evaluates the costs of materials, the complexity of manufacturing processes, and the scalability of assistive devices.
- Precision and Control: The effectiveness of actuation and the integration of sensors are essential for optimal performance. Studies by Della Santina et al. (2019) and Clemens et al. (2020) highlight the importance of control precision in prosthetic systems, which is necessary for achieving dexterous movements and restoring natural gait.
- Patient Comfort: Research in soft robotics aimed at assistive devices and rehabilitation places significant emphasis on patient comfort, with metrics such as user satisfaction and long-term usability being of paramount importance. Studies by Chen et al. (2019) and Park et al. (2019) focus on ensuring comfort in wearable technologies.

C. Key Findings from Various Studies

- Enhanced Surgical Accuracy: The use of soft robotic instruments minimizes tissue trauma during minimally invasive procedures, demonstrating greater precision in the handling of sensitive tissues (Liu et al., 2020).
- Improved Rehabilitation and Mobility: Soft exosuits and wearable devices enhance rehabilitation results by facilitating more natural movements and increasing patient comfort (Park et al., 2019; Chen et al., 2019).
- Advanced Prosthetic Performance: Soft robotic prosthetics offer enhanced dexterity and adaptability in hand movements, as well as more natural gait restoration for lower limb prosthetics
- Non-invasive Diagnostic Techniques: Soft robots employed for palpation or vascular navigation

demonstrate potential in non-invasive diagnostic applications, enhancing detection accuracy while minimizing patient discomfort (Kim et al., 2021; Nelson et al., 2020).

- Targeted Drug Delivery Mechanisms: Soft robotics provide systems for targeted drug delivery, which can mitigate systemic side effects, particularly in the context of chemotherapy (Patel et al., 2021; Yim et al., 2020).

These findings underscore the significant potential of soft robotics in various medical domains, with ongoing research aimed at addressing challenges related to precision control, material science, and real-time adaptability.

III. APPLICATIONS

1. Healthcare and Medicine

- Soft robotics has gained significant traction in the healthcare sector, primarily due to its capacity to interact safely with biological tissues. The inherent flexibility of soft robots facilitates precise and gentle manipulation, rendering them suitable for a variety of medical applications:
- Minimally Invasive Surgery: Soft robotic instruments, including grippers and manipulators, enhance delicate surgical procedures by providing superior control while minimizing trauma to adjacent tissues (e.g., Soft Robotic Grippers for Surgery by Liu et al., 2020).
- Rehabilitation Devices: Soft exoskeletons and wearable technologies are employed to support patients in their recovery from strokes or injuries, offering assistance in limb movement while ensuring comfort and lightness (e.g., Soft Exosuits for Stroke Rehabilitation by Park et al., 2019).
- Prosthetics: Soft robotic prosthetic limbs afford users enhanced dexterity, comfort, and adaptability in comparison to traditional rigid prosthetics, allowing for more natural movements in activities such as grasping and walking (e.g., Tendon-Driven Soft Robotic Prosthetic Hands by Della Santina et al., 2019).
- Assistive Devices: Innovations like soft robotic gloves assist individuals with diminished hand strength in performing everyday tasks, such as gripping objects and turning knobs (e.g., Soft

Robotic Glove for Hand Assistance by Bouter et al., 2021).

2 Industrial Application

In industrial environments, the unique flexibility and safety features of soft robots render them particularly suitable for collaborative tasks and the handling of fragile items.

- Robotic Grippers: The utilization of soft robotic grippers is on the rise for the manipulation of sensitive products, including food items, electronic components, and other fragile materials. Their inherent adaptability enables them to securely grasp objects of diverse shapes and sizes without causing harm.
- Assembly Lines: Soft robots can effectively collaborate with human workers on assembly lines, undertaking repetitive tasks while minimizing the risk of injuries associated with overexertion or improper handling of materials.
- Agriculture: In the realm of precision agriculture, soft robots are employed to carefully manage delicate crops during the harvesting process, thereby minimizing damage to the produce. They are also utilized for tasks such as fruit picking and planting.

3. Space Exploration

Soft robotics presents significant benefits in the realm of space exploration, particularly in adapting to demanding environments:

- Planetary Exploration: The inherent flexibility of soft robots makes them particularly effective for traversing irregular and unpredictable landscapes on extra-terrestrial bodies. Their design allows them to manoeuvre through confined areas and adjust to diverse surface conditions with ease.
- Human Assistance: Soft robotic exo-suits can aid astronauts in overcoming the physical difficulties associated with microgravity, facilitating task performance while offering support to muscles and joints.

4 Marine Exploration

Marine environments, characterized by their distinct physical challenges, represent a significant domain for the practical application of soft robotics:

- Underwater Robotics: Soft robots designed to emulate the movements of marine creatures, such as squids and octopuses, are employed for underwater exploration. Their flexible structures

minimize disruption to delicate underwater ecosystems, enabling them to reach locations that rigid robots cannot access (e.g., Bio-Inspired Soft Robots for Marine Exploration by Kaplan et al., 2020).

- Coral Reef Rehabilitation: Additionally, soft robots play a crucial role in coral reef rehabilitation initiatives, where they are capable of planting coral polyps while preserving the integrity of the surrounding environment.

5. Education and Research

Soft robotics is an important educational resource in the field of robotics research, highlighting the significance of creativity, material science, and mechanics.

- Educational Resources: Soft robotic kits provide an engaging platform for students to learn about robotics, programming, and engineering. These kits enable students to construct and program soft robots to perform a variety of functions.
- Biomimetic Research: The study of soft robotics frequently takes cues from biological systems, including the locomotion of animals and the growth patterns of plants. This interdisciplinary approach fosters progress in both robotics and biological sciences.

6. Environment Monitoring and Disaster Relief

Soft robotics finds significant applications in environmental monitoring and disaster response, owing to its capacity to function in unpredictable and perilous conditions.

- Search and Rescue: Soft robots possess the capability to maneuver through rubble, collapsed structures, and confined areas to identify survivors in the aftermath of disasters, including earthquakes and building collapses.
- Environmental Monitoring: Soft robots are employed to observe ecosystems, including coral reefs and forests. Their design allows for safe interaction with fragile environments, ensuring minimal disruption, which makes them particularly suitable for investigating sensitive ecological systems.

IV. FUTURE TRENDS IN SOFT ROBOTICS

1. Progress in Material Science

A significant factor propelling the future of soft robotics is the innovation of new materials that enhance the flexibility, durability, and overall functionality of soft robotic systems. The emergence of advanced materials is essential for boosting performance, reliability, and broadening the capabilities of soft robots.

Notable materials include:

- Self-Healing Polymers: These innovative materials possess the ability to autonomously repair damage, such as cuts or tears. By integrating self-healing features into soft robots, their durability and operational lifespan can be greatly extended. This is especially advantageous in medical contexts, where robots frequently endure wear and tear from regular use within the human body.
- Hydrogels and Shape-Memory Polymers: Hydrogels, known for their softness and biocompatibility, can alter their shape in response to external stimuli like temperature or light. Similarly, shape-memory polymers, which can revert to a predetermined shape, hold promise for medical devices that require temporary alterations during procedures. These materials may be utilized in medical implants or surgical instruments that adapt to specific anatomical requirements.
- Liquid Metals and Conductive Elastomers: These materials enhance the electrical conductivity and actuation control of soft robots. Liquid metals enable soft robots to maintain flexibility while integrating electrical circuits for improved control and sensory feedback. Conductive elastomers, on the other hand, facilitate more precise movement control and enhance sensory feedback mechanisms.
- Bio-Inspired Materials: Materials derived from biological organisms, such as the resilient, flexible skin of cephalopods or the structure of plant cells, are being employed to enhance the mechanical properties of soft robots. These materials could enable robots to adapt more effectively to complex environments, particularly within the medical sector.

As advancements in material science progress, we can anticipate further enhancements in the functionality and applicability of soft robotics, especially in medical applications.

2. AI and Soft Robotics: The Role of Machine Learning in Advanced Medical Procedures

Artificial intelligence (AI) and machine learning (ML) are set to significantly enhance the control and adaptability of soft robots, especially in intricate medical settings. The flexible design of soft robots presents unique challenges in terms of control, as their movement and behavior are influenced by numerous variables. AI and ML can effectively tackle these issues in various ways:

- **Dynamic Control Mechanisms:** Machine learning techniques can facilitate the creation of dynamic control mechanisms that enable soft robots to adjust their actions in real time according to environmental conditions and specific tasks. For instance, in the context of minimally invasive surgery, AI can empower soft robotic instruments to modify their movements based on immediate feedback from imaging technologies, such as MRI or ultrasound, thereby ensuring more accurate and safer handling of sensitive tissues.
- **Customized Patient Solutions:** AI can also be employed to customize the functionality of soft robotic systems to meet the unique needs of individual patients. In rehabilitation scenarios, for example, machine learning algorithms can process data from sensors integrated into soft exoskeletons, allowing for adjustments in the level of support provided based on the patient's recovery and physical status.
- **Streamlining Complex Operations:** AI can aid in the automation of specific components of complex medical procedures. By training soft robots on extensive datasets from previous surgeries, AI can empower these robotic tools to anticipate and execute certain tasks independently, thereby alleviating some of the cognitive demands placed on surgeons.
- **Gaining Insights from Experience:** Machine learning algorithms empower soft robots to enhance their capabilities by learning from past interactions, thereby increasing their effectiveness over time. For example, in the realm of prosthetics, artificial intelligence can facilitate the robot's ability to "understand" and adapt to the user's movement patterns and preferences, resulting in more intuitive control.

The combination of artificial intelligence and soft robotics is set to transform medical devices, making them safer, more efficient, and adaptable. This advancement will significantly impact procedures that demand high precision, such as neurosurgery and intricate operations on internal organs.

3. Commercialization and Real-World Adoption

The shift from research to practical application represents a vital phase in the advancement of soft robotics for medical use. Despite notable advancements in the field, several obstacles persist regarding commercialization and integration into healthcare systems:

- **Regulatory Challenges:** Medical devices, including those based on soft robotics, must undergo stringent testing and obtain regulatory approval prior to deployment in hospitals or patient care environments.
- **Production Costs:** Although soft robotics offers advantages in flexibility and safety, the expenses associated with manufacturing these systems, particularly those utilizing advanced materials or artificial intelligence, remain substantial. The development of more economical manufacturing techniques and materials is critical for making soft robots viable in clinical applications.
- **Training and Integration into Healthcare Systems:** The complexity of soft robotic systems necessitates specialized knowledge for effective operation. This requirement poses a challenge for healthcare facilities that must educate their personnel on the use of these devices. Furthermore, incorporating soft robotics into established medical workflows may demand significant modifications to existing protocols and procedures.
- **Patient Acceptance:** The degree to which patients accept soft robotic devices will significantly influence their success. While these robots can enhance comfort and functionality, particularly in areas such as prosthetics and rehabilitation, it is crucial to establish patient trust in these technologies. Demonstrating the reliability and safety of soft robotic devices through clinical trials and patient feedback will be instrumental in addressing this challenge.
- **Opportunities in Assistive Devices and Prosthetics:** In light of existing challenges, there

are considerable prospects for commercialization, especially within the domains of assistive devices and prosthetics. Innovations such as soft robotic gloves, exosuits, and prosthetic limbs are increasingly being integrated into practical applications, enhancing the quality of life for users.

- **Telemedicine and Remote Surgery:** Another area ripe for commercialization is telemedicine and remote surgical procedures. Soft robots have the potential to be operated by surgeons from afar, facilitating the delivery of expert medical care to patients located in remote or underserved regions.

V. CONCLUSION

1. Summary

Opportunities in Assistive Devices and Prosthetics: In light of existing challenges, there are considerable prospects for commercialization, especially within the domains of assistive devices and prosthetics. Innovations such as soft robotic gloves, exosuits, and prosthetic limbs are increasingly being integrated into practical applications, enhancing the quality of life for users. The expanding elderly population, coupled with a rising demand for tailored healthcare solutions, is expected to propel the future demand for these technologies.

Telemedicine and Remote Surgery: Another area ripe for commercialization is telemedicine and remote surgical procedures. Soft robots have the potential to be operated by surgeons from afar, facilitating the delivery of expert medical care to patients located in remote or underserved regions. This advancement could create new market opportunities for soft robotic devices within global healthcare systems.

2. Future Research Directions

The potential applications of soft robotics within the medical sector are extensive; however, several critical areas necessitate additional research and development:

- **Real-Time Feedback Mechanisms:** A significant challenge in soft robotics is the requirement for enhanced precision and real-time feedback during medical procedures. Future research should prioritize the integration of sophisticated sensors and real-time monitoring technologies to improve control and ensure accurate tissue manipulation during surgical interventions.

- **Sensor Development:** To elevate the functionality of soft robots, further investigation is essential in creating lightweight, flexible, and highly sensitive sensors that can be incorporated into soft robotic systems. These sensors will yield crucial data regarding force, pressure, and temperature, thereby enabling robots to execute tasks with increased precision and safety.
- **Enhanced AI Control Mechanisms:** Ongoing research into artificial intelligence and machine learning algorithms is vital to augment the adaptive capabilities of soft robots. By developing AI-driven control systems, these robots can learn from experiences, respond effectively to complex environments, and tailor their actions to meet the specific needs of individual patients in real time.
- **Biocompatible Material Innovation:** Investigating new biocompatible materials that are safe for prolonged use within the human body is crucial for the advancement of soft robotics in medical implants and internal devices. The development of materials that are both durable and non-toxic will facilitate new opportunities for enduring medical applications.
- **Wearable Soft Robotics Enhancement:** Future research should also aim to refine wearable soft robots, such as exoskeletons, to enhance their comfort, reduce weight, and provide personalized assistance. This includes the creation of soft robotic systems that can be easily tailored to individual users, equipped with sensors and AI technologies that adapt to various body movements and rehabilitation requirements.
- **Regulatory Frameworks and Standardization:** As the integration of soft robotics into healthcare continues to grow, there is a pressing need for the establishment of regulatory pathways and standardization practices.

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