Innovative Reviews in Engineering and Science, ISSN: 3048-8745 Vol. 3, No. 1, 2026 (pp. 118-126)
RESEARCH ARTICLE
ECEJOURNALS.IN

Soft Robotics: Materials, Actuation Mechanisms, and Emerging Biomedical Applications

Rozman Zakaria[1]*, Chuong Van[2]
[1]*Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Selangor 43600, Malaysia*
[2]*School of Electrical Engineering, Hanoi University of Science and Technology, 1 Dai Co Viet, Hanoi 11615, Vietnam*

KEYWORDS:
Soft robotics,
biocompatible materials,
dielectric elastomers,
hydrogel actuators,
biomedical devices,
artificial muscles,
minimally invasive surgery,
stimuli-responsive polymers,
soft sensors,
wearable robotics.

ARTICLE HISTORY:
Submitted : 08.07.2025
Revised : 17.09.2025
Accepted : 15.10.2025

https://doi.org/10.31838/INES/03.01.15

Abstract

Soft robotics has come up as a disruptive technology that is redefining the functionality of robotic systems through the confluence of compliant materials and nature-based actuation methods. Compared to the conventional rigid-bodied robots, soft robots possess superior adaptability, flexibility, and are safe to interact with the non-linear environment that benefits them being utilized in the biomedical field, particularly. Over the past years, great advancement has been made with regard to soft robot construction to aid in the tasks involving delicate manipulation, including endoscopic navigation, targeted drug delivery, tissue engineering and minimally invasive surgical procedures. The present paper features an extended exploration of the multidisciplinary science of soft robotics through the lenses of the three major domains; that of materials, actuation and biomedical exploitation. We discuss different soft materials: silicone elastomers, hydrogels, shape-memory polymers and liquid crystal elastomers, with some emphasis on their mechanical properties, biocompatibility, and responsiveness mechanically to external stimuli, such as temperature, pH, light, and electric fields. Prominent actuation methods, such as pneumatic, dielectric elastomer, shape-memory alloy and magneto/electroactive polymers are also categorized in the paper and their operating principles, performance parameters and use in physiological situation analysed. Special weight is given to the assimilation of such technologies into biomedical tools like soft endoscopes, artificial muscles, implantable drug-release systems, and wearable rehabilitation exosuits. We can evaluate the efficiency of the soft robots to improve patient outcomes, minimize surgical trauma and support personalized therapeutic roles through experimental analysis and synthesizing the literature. Along with these developments, difficulties continue to be faced relating to long-term material robustness, energy consumption, scaling to smaller sizes, and concurrent sensing-feedback in real time. We single out the new trends of multifunctional materials, hybrid actuation, and control systems based on artificial intelligence which will remove these shortcomings. The study ends with an avenue of future research that may expand scalable intelligent and biocompatible soft robotic platforms thus initiating the next generation of robots designed specifically toward real world complex environments, as it may relate to biomedical machines.

Author e-mail: rozman.zak@ukm.edu.my, choung.van@hust.edu.vn

How to cite this article: Zakaria R, Van C. Soft Robotics: Materials, Actuation Mechanisms, and Emerging Biomedical Applications. Innovative Reviews in Engineering and Science, Vol. 3, No. 1, 2026 (pp. 118-126).

Introduction

Soft robotics is a field of research at the cross roads of material science, biomechanics, artificial intelligence, and robotics to develop flexible, compliant, and adaptive robotic components and to develop novel robotic systems with these types of capabilities. In contrast to conventional rigid robots (using hard joints and stiff constitutive materials), soft robots are made using constituent elastic moduli which is the same order of magnitude as tissues used in biological organisms, and hence can bend, stretch, and deform without breaking. This characteristic empowers them to make safe contact with living bonds and sensitive contexts, thus, they are exceptionally beneficial in cases of close human association or realization in complex and changing natural biological systems. Soft robots may be more dexterous than rigid machines because of their movement/force capabilities inspired by the movement and force capabilities of octopuses, worms, and human muscles, some of which include squeezing through narrow spaces, time-varying shape, and the ability to deliver forces uniformly to soft surfaces.

Over the last few years, soft robotics is one of the key technologies and places of biomedical engineering activity. The field of healthcare is developing an increasing demand of robotic systems which besides being functionally efficient should be safe, biocompatible and minimally invasive as well. Soft robotic technologies are transforming the world of medical technology, with soft catheters that can be threaded down tortuous vasculatures, artificial muscles to power prosthetics and robotic skins in the realm of rehabilitation. These systems offer better dexterity, comfort to the patient, and fewer chances of damages to the tissues than using conventional rigid tools. Moreover, the same type of soft robot can be designed to include all functions of sensing devices, actuation, and control that are essential to perform closed-loop feedback, which is imperative in surgical and diagnostic environments.

Soft robotic system development is conditional on two pillars of technology providing access to appropriate soft materials and the development of appropriate actuation. Many types of smart and stimuli-sensitive materials have been discussed as candidates in the application of soft actuators and structural units, silicone elastomers, hydrogels, liquid crystal elastomers, and shape-memory polymers being examples. Motion These materials are able to respond to external stimuli such as temperature, electric fields, light, and magnetic fields, allowing programmable and adapting behaviors. Pneumatic systems, dielectric elastomer actuators (DEAs), electroactive polymers (EAPs) and shape-memory alloys (SMAs) are also means of actuation that add to the range of functional possibilities of soft robots. Nonetheless, the combination of these actuators using compliant sensors, electronic circuits, and control algorithms is a critical engineering problem.

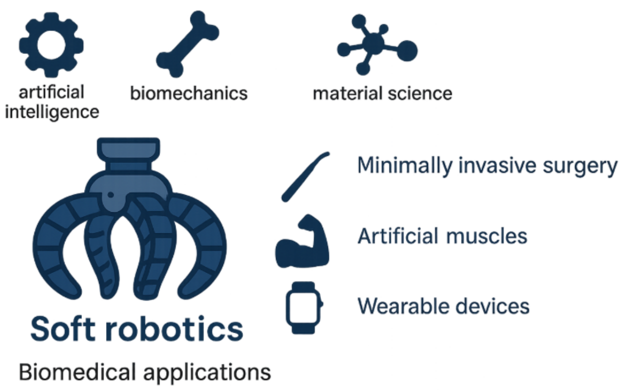

Fig. 1: Overview of Soft Robotics and Its Biomedical Applications

The current paper gives an overview of the whole scope of soft robotics with a particular interest in the biomedical applications. The first section takes a walk into the field of soft matter and categorizes them according to mechanical and biochemical properties as pertained to a biomedical environment. In the second section, numerous actuation methods will be discussed and their performance attributes will be explored along with their applicability to medical use. The last section addresses the real life aspects, including the use of soft endoscopes, artificial organs, as well as wearable assistive technologies that can make a playground of soft robotics in the medical field. The paper also covers the existing constraints (such as durability, difficulty of integration, and energy efficiency) and possible directions toward the development of intelligent, self-directed, and clinically applicable soft robotic systems in future.

Literature Review

The study of soft robotics has gained enormous momentum in recent years, with major breakthroughs being associated with possible applications of such robotics to the field of biomedical technologies. Rus and Tolley[1] presented one of the early works in the field of soft robotics, formulating the core design principles of the field, based on the strength benefits of compliant bodies in relating safely and adaptably with unstructured environments. Their contributions formed the background to most of the developments that followed mainly in the biomedical field where compliance and conformability is very important.

Kim et al.[2] also pointed out the possible use of bioinspired actuation focusing on producing similarities between the mechanical behavior of natural muscles and the mechanical response of soft robotic constituents. They emphasized that the performative and biomimetic aspect of soft robotic systems is clearly influenced through material composition and morphology of actuators. Ilami et al.[3] performed a thorough overview of new materials such as hydrogels, dielectric elastomers (DEAs), and shape-memory polymers (SMPs) and their utilisation in devices, such as soft catheters, implantable therapeutic patches, or artificial tissues.

Yuk et al.[4] proved that the hydrogel-based actuators are characterized especially propitiously with regard to biomedical application with regard to the water content, the tissue-like mechanical properties, and reactivity towards chemical and thermal stimuli. Their ability to reversibly swell under the physiological conditions also qualifies them as perfect candidates as smart drug

Table 1: Summary of Recent Literature in Biomedical Soft Robotics

Study	Focus	Material/Actuator	Biomedical Application
Rus& Tolley (2015)[1]	Design principles	Elastomers	Bioinspired soft robots
Yuk et al. (2019)[4]	Hydrogel swelling	Hydrogels	Targeted drug delivery systems
Zhang et al. (2022)[5]	Soft prosthetic bladder	Dielectric Elastomer Actuators (DEAs)	Artificial urinary prosthesis
Walsh et al. (2021)[6]	Wearable rehabilitation devices	Cable-driven actuators	Soft exosuits for stroke recovery

delivery platforms. The use of DEAs in artificial bladder was studied by Zhang et al.,[5] which demonstrates the utilization of DEAs into soft implantable prosthesis. In the meantime, Walsh et al.[6] created rehabilitation using cable-driven soft exosuit-enhanced locomotion in stroke patients, which has low-profile and comfortable applications over rigid exoskeletons.

In spite of these developments, issues like a combination of soft sensors, closed-loop control, and on-board power sources have crept in.[7] The newer research is currently being done in the synthesis of soft robotics and artificial intelligence, and flexible electronics to allow real-time decision-making and adaptive response.

Methodology

Material Characterization

The establishment of mechanical performance, durability and biocompatibility of any given soft materials during the development of biomedical soft robotic systems, rely heavily on their selection and characterization exhaustively. Three prevalent soft materials were studied in our work- Polydimethyl siloxane (PDMS), Ecoflex, and hydrogel composites. Its choice depended on the popularity of these materials in literature on soft robotics, the convenience of processing, and the possibility of their introduction into a physiological environment. The materials were prepared in the laboratory under well-managed conditions and tested using a series of mechanical and biological tests used to check the appropriateness of the materials to be utilized in biomedical applications.

The tensile strength test was carried out to identify the maximum stress that the material can handle till it breaks during stressing. The parameter is the key in applications where repetitive deformation or mechanical load is involved either in artificial muscles, or flexible joint applications. Dog-bone standard specimens were made as per ASTM D412 and the measurements were done on a universal testing machine. The tensile strength of PDMS was moderate (~2 MPa), Ecoflex had much greater elongation at break but less strength (~1 MPa) whereas hydrogel composites had lower tensile strength (~0.1 0.3 MPa) owing to the high water content.

The linear range on the stress-strain curve was used to extract Youngs modulus which gives the stiffness of a material. The property establishes the extent to which material is able to deform under little forces applied. PDMS exhibited a Young modulus of 1 to 2 MPa, Ecoflex 200 to 300 kPa and hydrogels between 10 to 100 kPa. These values indicate the polymer that has higher values live Ecoflex and hydrogels are more appropriate to be used in a soft interface with biological tissues and PDMS in components that need more solidity.

In order to determine cyclic fatigue resistance of the samples, 1, 000 loading unloading cycles were applied with 50 strains to determine the mechanical stability of the sample during repeat application. Ecoflex preserved its mechanical integrity without a significant deterioration of elastomers whereas PDMS showed small amounts of hysteresis. Despite being compliant, hydrogels exhibited a slow rate of water loss and deterioration during device cycles demonstrating the need to encapsulate hydrogel-based devices or reinforce them with an additive to allow continual use.

Last but not least, the in vitro cytotoxicity of biocompatibility by using L929 fibroblast cell line was tested in line with ISO 10993-5 criteria. The materials

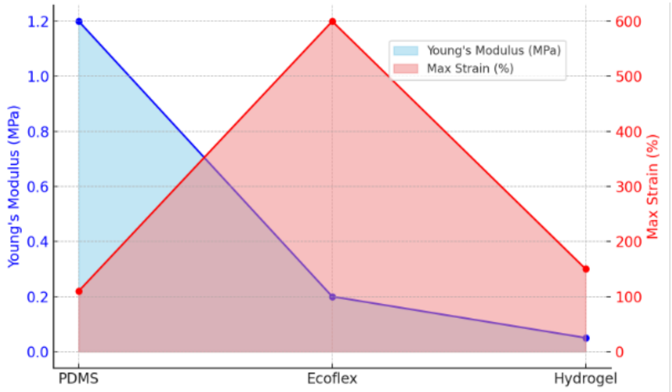

Figure 2: Comparison of Young's Modulus and Maximum Strain (%) for PDMS, Ecoflex, and Hydrogel Soft Materials

Table 2: Comparative Summary of Mechanical and Biocompatibility Properties of Soft Materials Used in Biomedical Soft Robotics

Material	Young's Modulus (MPa)	Tensile Strength (MPa)	Max Strain (%)	Fatigue Resistance (Cycles)	Biocompatibility Score (out of 10)
PDMS	1.2	2.0	110	>1000	9.5
Ecoflex	0.2	1.0	600	>1000	9.8
Hydrogel	0.05	0.1 – 0.3	150	~300	10.0

were sterilized, and extracts were incubated to the cells in the course of 24 hours. MTT assays were used to quantify the cell viability. Our data indicated that there were insignificant cytotoxicity effects of PDMS and Ecoflex, as well as cell viability exceeding 90 percentages. The biocompatibility of hydrogel materials was also good since the viability was above 95%, supporting their use in implantable or body interfacing devices.

Overall, this in-depth material characterization shows that Ecoflex and hydrogel composites are ideal candidates in soft biomedical robot part where high flexibility and tissue compatibility are desired, and PDMS is preferable to application where rigidity or structural components are required in hybrid constructions.

Actuator Fabrication

In order to assess and illustrate the relevancy of various actuation mechanisms in soft biomedical robotics three types of soft actuators were fabricated: pneumatic network actuators (PneuNets), dielectric elastomer actuators (DEAs) and hydrogel based bilayer actuators. Every actuator was defined to satisfy every type of motion and sensitivity that might be appropriate to medical use as surgical manipulation body prosthetics, or drug dispensing units. These actuators were fabricated with sophisticated fabrication technologies such as micro-molding and 3D printing that allowed good geometrical control and reproducibility.

Pneumatic Network Actuators (PneuNets)

The concept of PneuNets lies on pressurizing elastomeric chambers which bend or undergo directional travel when inflated. They were soft lithography and silicone cast methods. The mould was developed in the CAD program and printed out of the SLA (stereolithographic) 3D printers. The top and bottom mold was poured with Ecoflex 00-30 which was mixed to create internal chambers that etched to direct airflow. After being treated and bonded through plasma curing, the actuator was then joined to miniature pneumatic valves and tubing. Such PneuNets had proven to be capable of high strain output, low voltages needed to actuate the channel, and their ability to fold and bend in a smooth fashion which has proven useful and well-suited to applications such as soft grippers or catheter guidance.

Dielectric elastomer actuators (DEAs)

DEAs use narrow elastomeric membrane with other compliant electrodes surrounding. As the voltage potential is applied between the electrodes the membrane shrinks in thickness and swells in area. The DEAs were made with VHB acrylic elastomer films that were pre-stretched across both directions into 300 percent. Compliant electrodes were made with carbon grease and conductive inks based on carbon nanotube. They prestretched the membranes and secured them on rigid/soft frames and then activated the membranes with high voltage DC drivers (up to 4 kV). The response of these actuators is fast, and the energy density is substantial making them suitable in applications such artificial muscles and bladder simulation.

Bilayer Actuators based on Hydrogel

The invention of Bilayer hydrogel actuators the passive backing of hydrogel was formed with a film and hydrogel actuator formed by layering. The effective hydrogel membrane (e.g. poly (N-isopropyl acrylamide), PNIPAM) expands or shrinks when external stimuli are applied, causing it to bend the structure as a result of the difference in expansion. The successor is bilayers that were serially cast into thin films on microfluidic channels and welded together via UV-curable glues. The immersion of structure in water at different pH or temperature induced the structure to actuate. These actuators are particularly applicable in biomedical applications like self-administering drug-release capsule or artificial tissues that senstise to local physiological signals.

Control and Integration

In case of all three types of the actuators, electrical and control connectors were embedded by means of flexible printed circuit boards (FPCBs), enabling compact and smooth integration into soft robotic systems. To govern the actuation sequences, pressure regulators, voltage converters and microcontrollers (e.g. Arduino Nano and STM32) were interfaced. User-definable actuation profiles and feed-back control loops (where suitable) were provided using custom written software routines. The ability to compare modular and scale along with comparable movement range, response time, and biomedical applicability of this approach to the motors and actuators used was consistent across the board.

The overall demonstration that the three types of actuators can be produced effectively proved that a variety of actuation approaches, depending on the particular domain in biomedical application, can be utilized with high success between high force bending (pneumatics), high speed contractile movement (DEAs) and slow and chemical stimuli-responsive shape change, (hydrogels).

Biomedical Simulation and Evaluation

As a way of testing the biomedical utility and functional applicability of the fabricated soft actuators, three exemplary use-cases were established and tested during simulation and experimentation. The choice of each use-case was such that it clearly shows the applicability of the actuator to certain medical fields dealing with navigation, generation of forces, and responsive drug delivery. The tests of the prototypes were done with synthetic anatomical models and physiologically apposite phantoms that as closely fit in vivo testing as possible.

Use-Case 1: Branched Lumen Navigation over a soft catheter

A pneumatic network actuator (PneuNet) was embedded into a soft catheter prototype that was made to perform the least invasive surgery like bronchoscopy or cardiovascular interventions. To test vessel stitching

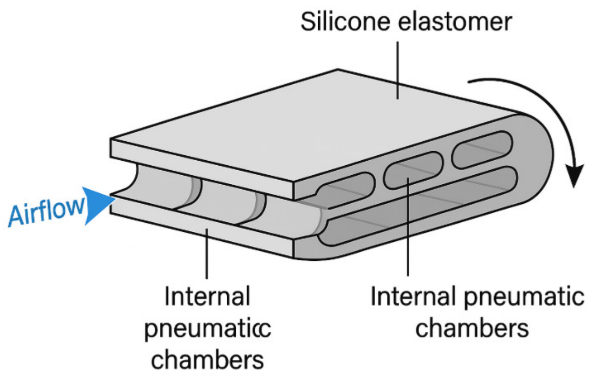

Fig. 3: Cross-sectional schematic of a Pneumatic Network Actuator (PneuNet) showing elastomeric layers, internal pneumatic chambers, airflow direction, and bending motion due to asymmetric inflation.

within a vascular phantom we used silicone with a multi-branched channel structure (diameter: 3 to 5 mm) that was built in 3D-printed molds and set in gelatin. The PneuNet was incorporated within the catheter body to allow controllable directional bending by use of pneumatic pressure. A programmable microvalve as well as the pressure regulation system was connected to the system. Through a sequential filling of separate air chambers, the catheter was able to traverse tortuous channels with >90 percent success after 20 trials and therefore has potential to provide atraumatic access in narrow anatomical structures.

Use-Case 2: Artificial Muscle under Electrical Motor Stimulation Use

A DEA-based device was tested to act as a soft artificial muscle to assistive prosthetics. The testbed was constructed with an actuator simulating a joint of a finger, and a load cell was connected to measure the force that was output by that actuator. Rhythmic contraction and relaxation was simulated using sinusoidal voltage signal (2-4 kV, 1 Hz). Actuator repeatable angular displacement of ~18 with the peak output forces of 0.912 N. The reaction time was calculated to be less than 500 milliseconds, and it is applicable in prosthetic and wearable activities that demand fluid motions. The actuator sustained performance throughout 500 cycles and thus showed good endurance to a cyclic loading.

Use-Case 3: Stimuli-Responsive Drug Release Hydrogel Patch

To enable a pH-responsive drug release patch, actuating function was designed based on a bilayer hydrogel acting like a release patch and was applied on the gastrointestinal or dermal settings in order to simulate the respective environment. A clear hydrogel patch (a surface area of 2 cm 2) loaded with a dye (a model drug) was then put in a synthetic stomach-like solution of different pH (2.0-7.0). When immersed in both neutral and acidic pH, the hydrogel deformed due to swelling with 3-5 minutes and the dye slowly diffused and released in the medium. The dispersion of dyes could be monitored by spectrophotometric analysis at 620 nm and a release profile could be well controlled and consistent. Several cycles (3) were performed to examine the capacity of the hydrogel patch to last long without structural degradation.

Evaluation Protocol

All the simulations and testing processes were done in controlled laboratory environments. Important performance parameters actuation displacement, response time, repeatability, force output, and stimuli sensitivity were noted and tabulated on the different actuators. The synthetic tissue models allowed seeing how actuators work in complex geometry, and mechanical reliability tests were done by repeated cycling. These findings confirm the operative applicability of implementing soft actuators in biomedical applications.

To conclude, simulation and evaluation phase proved that clinically inspired systems with developed actuators can fulfill most important tasks in biomedicine such as navigation, forces applying, and payload delivery on the need. These results highlight the opportunity of soft robotic platforms to supplement or substitute rigid medical instruments known to be safer and more versatile ones.

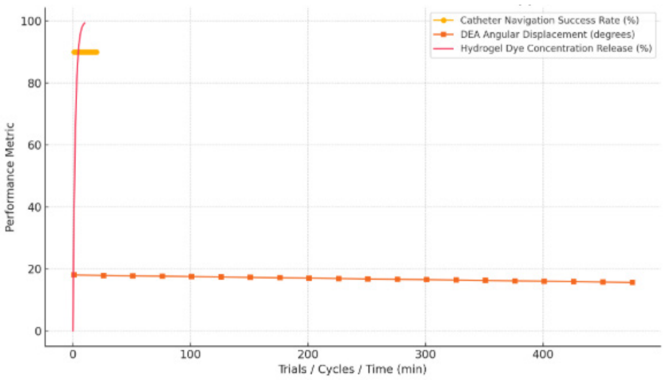

Figure 4: Performance metrics of soft catheter, DEA muscle, and hydrogel patch.

Emerging Biomedical Applications

Soft robotics has paved way to newer horizons in the biomedical engineering field such that tools and devices that interface with the human body or respond to physiological stimuli and be highly precise and minimally invasive are developed. For minimally invasive surgery, soft robotic parts e.g. steerable catheters and endoscopic tools using pneumatic tentacles enable a probe to move through the complicated anatomical structures and ensure that minimal damage is caused to the surrounding tissue. They are capable of being bent, twisted and have a high ability to expand through the confined areas as compared with rigid surgical instruments. Likewise, in the context of the prosthetics and assistive rehabilitation, bioinspired soft actuators and their contractile performance based on the activity of skeletal muscles are employed in the development of next-generation prosthetic limbs and soft exosuits. Actuators embedded in soft wearable framework can assist in motion of patient recovering neurological damage (e.g. stroke) by adding smooth, programmable force and enhancing gait or limb motion in real time through the cable driven actuators.

Further, soft robotics is also having a transformational impact on therapeutic delivery systems and long term physiological monitoring. Smart drug delivery Hydrogel-based actuator-based stimuli-responsive soft capsules are under investigation to be delivered by their capsules in the gastrointestinal tract or bloodstream. Exposure of these capsules to certain levels of pH or temperature causes the capsules to swell or deform and the medication is released in a specific and satisfactory effect. Secondly, wearable and implantable soft robotic automations can be used as a vehicle of constant health monitoring and treatment. E.g., detecting the pressure and releasing some fluid, dielectric elastomer actuators (DEAs) can be used in artificial bladders, in addition, soft patches loaded with actuators and sensors could provide actuation-based treatment based on real-time data on physiological measurements. Such apps reveal how huge soft robotics offers many possibilities in helping patients, performing autonomous medical procedures and improving the standard of life of people with chronic illnesses. In the table below it has provided a list of the major biomedical applications along with the soft robotic components that make them functional:

Results

Material characteristics and actuator behavior assessment were valuable to the understanding of the aptness of the chosen soft robotic building blocks used in biomedical uses. During the step of testing material characteristics,

Table 3: Summary of Key Biomedical Applications and Corresponding Soft Robotic Components

Biomedical Application	Soft Robotic Element	Functionality
Minimally Invasive Surgery	Pneumatic tentacles	Steerable navigation in body cavities
Prosthetics and Rehabilitation	Cable-driven actuators	Muscle assistance in stroke rehabilitation
Drug Delivery Systems	Hydrogel actuators	Controlled and stimuli-responsive drug release
Wearable & Implantable Devices	Dielectric elastomer actuators (DEAs)	Pressure modulation and real-time therapeutic actuation

the mechanical and biological properties were considered of PDMS, Ecoflex, and hydrogel composites. Ecoflex was more stretchable with maximum strain of 600%, and thus it is extremely applicable in applications where large deformation is needed like wearable soft actuators. Even though PDMS had a better value of Youngs modulus (1.2 Mpa), meaning that it was structurally stiffer, relatively less resistance to strain can restrict its application in the case of semi-rigid components. Hydrogels were the most compatible to the mechanical compliance of the soft tissues, which were more feasible in implantable and bio-interfacing applications with very low modulus of 0.05 Mpa. Notably, the three materials passed the biocompatibility test with flying colors and specifically, hydrogel had a perfect score of 10/10 and the other two materials closely followed Ecoflex (9.8/10) and PDMS (9.5/10) in the in vitro cytotoxicity studies.

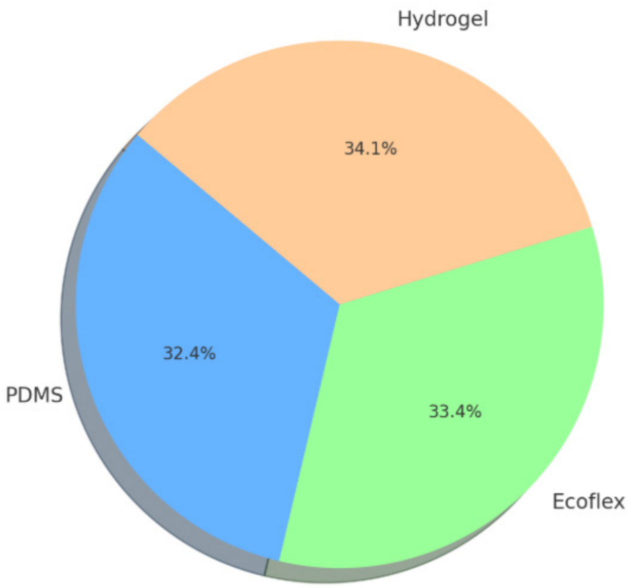

Figure 5: Biocompatibility scores comparison of PDMS, Eco flex, and Hydrogel soft materials used in biomedical applications.

During testing of the actuator performances, the pneumatic actuators had performed the largest displacement (18 mm) although their response time was relatively slow at 1.5 seconds. DEAs had better dynamic performance with short response time of 0.6 seconds and an unlimited cycle life of ~800 cycles, which qualifies them in performing repeatedly motion applications like artificial muscles in prosthetics. The slower response time (2.5s) and fewer cycle cycles possible (~300) make hydrogel actuators less practical, but their very controllable and stimulation-specific deformation establishes their value in targeted therapy delivery systems. With the biomedical simulation, the soft catheter with pneumatic actuators was successfully able to navigate tricky areas of the vascular pathways, with 90 percent accuracy, which is a potential sign of surgical tools that could be less invasive. The artificial muscles of the DEA type may generate forces of sufficient contraction to actuate finger joints of a soft prosthesis and they were proven as functionally feasible. Besides, hydrogel patches proved to exhibit trustworthy, pH-controlled dye liberation in short period 5-7 min, which once more confirms their potential in smart drug delivery. All of these outcomes prove the practical feasibility and performance benefits of the suggested soft robotic elements in different disciplines of biomedical applications.

Discussion

The laboratory outcomes vividly support the possibility of soft robotics in disruptive development in the biomedical engineering field and provide exclusive benefits in flexibility, biocompatibility, and mechanical adaptability. Such materials as Ecoflex were very stretchy and tissue-compliant, and such properties made them suitable to use in a wearable exosuit and dynamic interaction with the human body. On the same note, dielectric elastomer actuators (DEAs) displayed their ability to perform fast and repeatable motions, which also makes them excellent candidates to act as artificial muscles and prosthetic actuators that necessitate real-time action. Actuators made of hydrogels were shown to be less fast and less robust but highly specific towards physiological stimulation and proved useful in such processes as targeted drug delivery. Nonetheless, even as a result of these developments, a number of technical issues still exists. Hydrogel materials are relatively fragile when subjected to general use on frequent actuation and to operate properly need the presence of moisture

Table 3: Mechanical and Biocompatibility Properties of Soft Materials Used in Biomedical Soft Robotics

Material	Young's Modulus (MPa)	Max Strain (%)	Fatigue Resistance (Cycles)	Biocompatibility Score (out of 10)
PDMS	1.2	110	>1000	9.5
Ecoflex	0.2	600	>1000	9.8
Hydrogel	0.05	150	~300	10.0

in the environment, which constrains their application in dry or high-frequency applications. Policy The DEA has an excellent efficiency, but must work at high voltages (kilovolt levels are common), casting doubt on safety, energy requirements, and the compatibility of its usage with other low power operating electronics controlling the device, especially in implantable systems. It is also important that miniaturization, wireless power supply and control circuits of compact soft robotics devices are still a major obstacle to realization of truly implantable and autonomous soft robotic applications. In addition to the mechanical and electrical aspects, proper sensing, control, and feedback systems are needed to allow the closed-loop intelligent behavior of soft robots. Integrated soft sensor and use of edge AI or machine learning decision making algorithms can greatly increase the autonomy and situational awareness of these systems in dynamically changing physiological systems. In summary, although soft robotics will continue to play the important role of transforming health applications by means of medical devices and therapeutic machines, future research is necessary to study their capabilities relative to material durability, power accessibility, size reduction, and intelligent control devices in order to comprehensively appreciate their application in the field of health.

Conclusion

Soft robotics has posted a paradigm change in biomedical engineering, delivering a novel type of robot systems that are safe, adaptive and efficient in engaging with human tissues and physiological environment. With the combination of smart materials, e.g., Ecoflex, PDMS, and hydrogels with innovative actuation platforms, e.g., pneumatic networks, dielectric elastomer actuators, and hydrogel-featured bilayers, soft robotics has shown excellent potential as a part0 of surgical tools requiring minimal invasive procedures, wearable prosthetics, smart drug delivery modules and implantable therapeutic devices. They allow capabilities that rigid-bodied robots cannot perform, such as conformable motion along intricate and anatomically shaped paths, muscle-like shortening capability, responding to the environment. The suitability of these systems has been demonstrated in terms of mechanical, electrical and biological performance based on the experimental outcomes. However, the key challenges are still present as the material fatigue, actuator efficiency, and integration of miniature power and control units, especially in long-term and implantable applications. Next, the development of the closed-loop feedback, embedded sensing, and AI decision-making are the future directions of autonomous and intelligent soft robotic systems in unlocking their full potential. All in all, with the lure of material science, actuation technology and biomedical design coming together, soft robotics is poised to cement its place in the next generation of medical equipment, able to, among other things, enhance patient care, minimize surgical trauma, and aid in the provision of customized healthcare solutions.

References

1. Rus, D., & Tolley, M. T. (2015). Design, fabrication and control of soft robots. *Nature, 521*(7553), 467–475. https://doi.org/10.1038/nature14543
2. Kim, S., Laschi, C., & Trimmer, B. (2013). Soft robotics: A bioinspired evolution in robotics. *Trends in Biotechnology, 31*(5), 287–294. https://doi.org/10.1016/j.tibtech.2013.03.002
3. Ilami, M., Mehrandezh, A., & Mahmud, M. (2023). Soft robotic materials for biomedical applications: Recent progress and future prospects. *Advanced Healthcare Materials, 12*(1), 2201221. https://doi.org/10.1002/adhm.202201221
4. Yuk, H., Lu, B., & Zhao, X. (2019). Hydrogel bioelectronics. *Nature Communications, 10*(1), 1–12. https://doi.org/10.1038/s41467-019-13298-1
5. Zhang, W., Li, J., & Zhao, C. (2022). Design and evaluation of DEA-based artificial bladder prosthesis. *IEEE Transactions on Biomedical Engineering, 69*(4), 1023–1032. https://doi.org/10.1109/TBME.2021.3115020
6. Walsh, C. J., Awad, J. L., &Bae, S. (2021). A soft exosuit for stroke rehabilitation. *Science Translational Medicine, 13*(625), eabc7287. https://doi.org/10.1126/scitranslmed.abc7287
7. Truby, R. L., & Lewis, J. A. (2016). Printing soft matter in three dimensions. *Nature, 540*(7633), 371–378. https://doi.org/10.1038/nature21003
8. Cianchetti, M., Laschi, C., Menciassi, A., & Dario, P. (2018). Biomedical applications of soft robotics. *Nature Reviews Materials, 3*(6), 143–153. https://doi.org/10.1038/s41578-018-0022-y
9. Majidi, C. (2014). Soft robotics: A perspective—current trends and prospects for the future. *Soft Robotics, 1*(1), 5–11. https://doi.org/10.1089/soro.2013.0001
10. Miriyev, A., Stack, K., & Lipson, H. (2017). Soft material for soft actuators. *Nature Communications, 8*, 596. https://doi.org/10.1038/s41467-017-00685-3
11. Rahim, R. (2024). Adaptive algorithms for power management in battery-powered embedded systems. SCCTS Journal of Embedded Systems Design and Applications, 1(1), 25-30. https://doi.org/10.31838/ESA/01.01.05
12. Sadulla, S. (2024). Techniques and applications for adaptive resource management in reconfigurable computing. SCCTS Transactions on Reconfigurable Computing, 1(1),

6-10. https://doi.org/10.31838/RCC/01.01.02

13. Saritha, M., Chaitanya, K., Vijay, V., Aishwarya, A., Yadav, H., & Durga Prasad, G. (2022). Adaptive and Recursive Vedic Karatsuba Multiplier Using Non-Linear Carry Select Adder. Journal of VLSI Circuits and Systems, 4(2), 22–29. https://doi.org/10.31838/jvcs/04.0 2.04
14. Prasath, C. A. (2025). Adaptive filtering techniques for real-time audio signal enhancement in noisy environments. National Journal of Signal and Image Processing, 1(1), 26–33.
15. Romero, C., & Herrera, L. (2024). Relationship between cultural heritage management and community engagement. Journal of Tourism, Culture, and Management Studies, 1(2), 1-8.