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BIO-ROBOTICS: CREATING A NEW ERA OF HUMAN-MACHINE INTERACTION: A REVIEW

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ABSTRACT
Bio-robotics is an interdisciplinary field that integrates biology, robotics, and artificial intelligence principles to develop robotic systems inspired by biological organisms. This field aims to enhance robotic capabilities by mimicking natural movement, sensory perception, and adaptive behavior in living organisms. Advances in bio-robotics have contributed to various applications, including medical robotics, prosthetics, bio-inspired autonomous systems, and rehabilitation technologies. The development of bio-hybrid robots, which incorporate biological materials with artificial systems, is a growing area of research. This paper explores key aspects of bio-robotics, including biomimetic design, artificial intelligence integration, and prospects. Through a review of recent advancements and emerging trends, the study highlights the potential of bio-robotics in healthcare, industrial automation, and space exploration. The integration of bio-robotics with neuroscience and biomechanics is also discussed, emphasizing its role in improving human-robot interaction. The findings suggest that continued interdisciplinary collaboration will drive innovation in bio-robotics, leading to smarter, more adaptive robotic systems capable of operating in complex environments.

KEYWORDS: Bio-robotics, Biomimetics, Artificial Intelligence, Bio-hybrid Robots, Prosthetics.

INTRODUCTION
Bio-robotics is an interdisciplinary field that integrates biomedical engineering, robotics, and cybernetics[1] to create technologies aimed at developing robotic systems that can interact with living beings, such as robots that mimic animal movements. It leverages advancements in technologies like biomechanics, sensors, and artificial intelligence to enhance precision, performance, and efficacy in scenarios where human- robot interaction is crucial.[2] Animal-like robots are increasingly serving as a vital link between biology and engineering. Currently, bio- robotics stands as an evolving domain for biomedical engineering and robotics, providing an excellent platform for training the next generation of engineers by dissolving the traditional boundaries between engineering disciplines and biological sciences and medicine.[3] The applications of bio-robotics in areas like healthcare, rehabilitation, surgery, treatment, and assistance are explored.[4] This emerging, interdisciplinary field of bio-robotics offers tools for biologists investigating animal behavior and serves as experimental platforms for studying and evaluating potential technological applications of biological processes.[5] Bio-robotics is an interdisciplinary domain that integrates biomedical cybernetics with macro, micro, and nanotechnology to imitate human biological movement. Soft robotics is a specialized area within bio-robotics that employs soft materials and methods to achieve its objectives; these materials are typically lighter and more flexible. Artificial muscles attempt to emulate the movements of natural muscles, including their contraction, expansion, rotation, and blending, among other actions.[6,7] Additionally, bio-robotics encompasses the creation of artificial models of living organisms, including robots that are inspired by biological structures or serve similar purposes.[8] A contemporary example of robotics shaped by biological principles is the hex pedal Rise climber robot.[9]

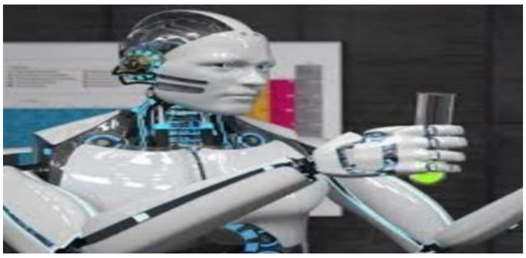

Figure 1: Image of bio-robotics.

Bio-robotics encompasses three primary domains

Robotics in therapy and surgical procedures: Robotic surgery is a method employed by healthcare professionals for less invasive operations.[10] This technology comprises three key components: robotic arms that manipulate tiny instruments, and a high-definition camera that offers an enhanced, magnified, 3D perspective of the surgical site.[11]

- **Robotic surgery:** Surgeons utilize robotic arms to perform intricate surgeries with improved precision and caution.[12]
- **Minimally invasive surgery:** Robotic surgery typically involves smaller incisions, leading to reduced pain, blood loss, and scarring.[13]
- **Robotic endoscopy:** Robotics can also be utilized for endoscopic procedures. The integration of robotics in gastroenterology offers a chance to expand the practice of these intricate procedures. Robotics initially made its entry into the medical domain through surgical applications. In 1994, the U.S. Food and Drug Administration (FDA) granted approval for the Automated Endoscopic System for Optimal Positioning, known as AESOP,[14] which was the first robotic surgical system capable of manipulating a laparoscopic camera through voice commands. Wireless capsule endoscopy (WCE) was launched in 2000 and has become a crucial tool for examining the gastrointestinal tract areas that are not easily reachable by standard upper endoscopy and colonoscopy.[15]

Figure 2: Robotics in gastrointestinal endoscopy.

Robotics for rehabilitation and assistance: The field of rehabilitation robotics has introduced innovative concepts and new assistive devices within the expanding domain of biomedical robotics. The advancement of rehabilitation robotics will advance through collaboration among robotic experts, healthcare professionals, and patients. This area focuses on robotic systems designed to provide therapy for individuals aiming to regain their physical, social, communication, or cognitive abilities and assist those with chronic disabilities in managing their daily activities.[16] Research in assistive and rehabilitation robotics is an emerging, promising, and challenging area driven by diverse social and medical demands, including aging populations and disorders affecting the neuromuscular and musculoskeletal systems. These robots can be utilized in a variety of everyday situations to assist with motor skills, training, and rehabilitation.[17]

Figure 3: Robotic rehabilitation physiotherapy.

Bioinspired and biomimetic robotics: Any device that swims, flies, or walks can be considered to draw inspiration from aquatic, avian, or terrestrial animals; every mobile robot utilizing one of these methods of movement can be classified as biologically inspired.[18] There is some discussion among bio- roboticists about where to establish the boundaries. Some researchers, following the perspective of Ritzmann and colleagues, argue that a robot should incorporate as many characteristics of an animal as possible, even if the functional benefit of a specific feature is unclear. Recently, this methodology has often been referred to as biomimetic robotics. Examples include walking robots and crawling robots.[19]

Figure 4: Bioinspired robot.

APPLICATION

Medical and Healthcare

- **Prosthetics and Exoskeletons:** Bio robotics is employed to develop prosthetic limbs and exoskeletons that replicate the functions of human limbs, assist movement for those with neurological disabilities, or offer therapeutic interventions for individuals with such conditions. These devices are frequently engineered to respond to neural signals, allowing for intuitive control. The objective is to create devices that prioritize accessibility, user-friendliness, and effectiveness.[20, 21] To ensure these devices are useful in practical situations, they need to be agile and non- intrusive. Robotic prosthetics and exoskeletons will enable natural mobility and provide a sense of touch to those with missing or paralyzed limbs. People experiencing hip or knee issues can benefit from using a robotically enhanced walker or wheelchair.[22]
- **Robotic Surgery**: The use of surgical robots marks

a notable improvement in minimally invasive procedures, offering enhanced precision, flexibility, and control compared to conventional techniques.[23] By employing robotic systems like the da Vinci Surgical System, surgeons can conduct intricate operations through small cuts, which results in less trauma, reduced blood loss, and quicker recovery times for patients.[24]

- **Rehabilitation Robots:** Robots designed for rehabilitation aid patients in regaining motor functions following strokes, spinal cord injuries, and various neuromuscular disorders that result in bodily impairments. These robots support physical therapy by delivering specific exercises that contribute to the enhancement of muscle strength and coordination.[25]

Biological Research

- **Biomimetic Robotics:** The creation of robots that mimic biological systems is a prevalent objective in the field of bio-robotics research.[26] For instance, by employing animal-inspired robots like robotic fish or insects, researchers can gain a deeper understanding of the mechanics behind biological movement and behavior, which can also be utilized for environmental monitoring.[27,28]
- **Cell Manipulation:** Robots that can execute micro-manipulations, such as the isolation of individual cells or the movement of particles on a microscopic scale, are employed in biological laboratories to study cellular behavior and interactions. A variety of micro-tools have been developed to ensure safe and precise handling of micro-objects, including micropipettes[29,30] contactless tweezers[31,32,33], and micro-grippers[34,35,36] with different actuators and end- effectors designed to achieve accurate manipulations while minimizing potential damage to micro- objects.

Environmental Monitoring and Conservation

- **Autonomous Underwater Vehicles (AUVs):** Robots designed after marine animals, such as fish, whales, or octopuses, can be utilized to investigate underwater environments, collect data on the health of the ocean, or observe marine life in less intrusive ways compared to traditional methods.[37] Robotic systems are essential for exploring and ensuring the environmental safety of the extensive and deep oceans and other water bodies. Two types of unmanned underwater robotic systems are "Autonomous Underwater Vehicles (AUVs)" and "Remotely Operated Underwater Vehicles (ROVs)".[38] The first AUV, known as "SPURV (The Self-Propelled Underwater Research Vehicle)," was created by Stan Murphy and Bob Francois in 1957 at the Applied Physics Laboratory at the University of Washington (Remotely Operated Vehicle Committee of the Marine Technology Society).[39, 40, 41] The "SPURV" operated at speeds of 2–2.5 m/s and reached depths of up to 3600 m, as noted by Windisch (1973).[42] Autonomous underwater vehicles (AUVs) have emerged as a fascinating area of ocean-related research due to their potential applications in military operations, national security, hydrographic surveys, mineral field investigations, environmental monitoring, and oceanographic studies. Over the years, significant efforts have been made to develop resilient AUVs capable of addressing the challenges of oceanographic exploration and resource exploitation. Recently, advancements in AUV technology have focused on enhancing operational range and endurance for extended data collection in oceanography and coastal management.[43]

Figure 5: Autonomous underwater vehicle.

Agriculture

- **Precision Farming:** The increasing global population has created a demand for a high- quality food supply.[44] In 1961, there was a noticeable decrease in the number of farmers and agricultural laborers in Asia, especially in Japan.[45] To address this issue, researchers are focused on developing long-term, low-tech solutions through the mechanization and automation of the agricultural sector by using highly advanced robots that can take over tasks where human performance may not match the accuracy, reliability, or efficiency of automated machines. Robots demonstrate greater effectiveness in planting, monitoring, and harvesting crops while reducing the impact on the environment and labor needs.[46]
- **Pest Control:** Robots that imitate the behaviors of specific insects can be employed in precision pest management, reducing reliance on chemical pesticides and helping to safeguard the environment.[47]

(A) (B)

Figure 6: (A) (B) Agricultural Robots.

Military and Search & Rescue Operations

- **Search and Rescue:** The global population is continually on the rise, particularly in urban settings. Disasters like earthquakes, fires, tsunamis, and armed conflicts have significant and lasting effects on individuals. As the frequency of natural disasters increases and more people are affected, these events are becoming a greater global health issue.[48] Search and rescue (SAR) missions incorporating human-robot collaboration are expected to provide support to those in need. Various types of SAR robots are currently available, with snake robots demonstrating considerable promise; they can be equipped with sensors to transport tools to dangerous or confined locations that are inaccessible to both other robots and humans. Search and Rescue (SAR) operations are performed with human involvement to assist individuals in crisis situations. The United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA) has classified different SAR scenarios based on the type of terrain involved (e.g., structural collapse, confined spaces, fire, and water), and these scenarios can occur in various combinations. These situations pose challenges and risks even for highly trained human responders. Therefore, researchers are keen to leverage technology to reduce risks for both potential victims and human rescuers.[49]

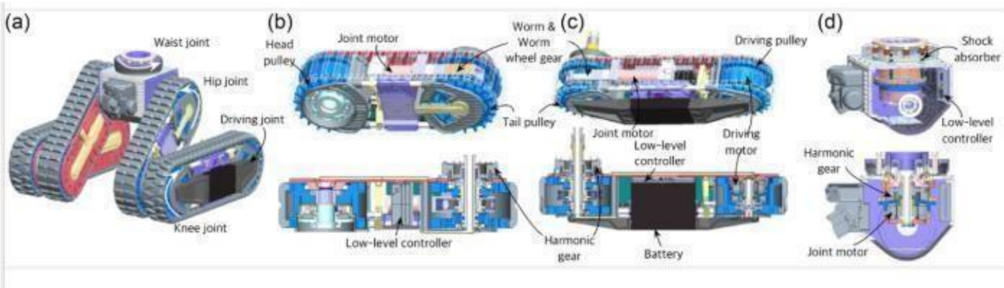

Figure 7: Disaster and Recovery using Search and Rescue.

- **Autonomous Military Robots:** These machines are designed to perform difficult tasks such as navigating minefields and deactivating unexploded ordnance. Armed robots can undertake these responsibilities without fear, serving in place of individual soldiers or helping to keep troops safe from danger. They can take on risky missions like traversing caves or urban environments during conflicts, which can lead to a reduction in casualties. Military robots do not experience fatigue, do not require rest, and do not possess the capability for fear; they are remotely.[50]

Figure 8: Autonomous Military Robots.

Space Exploration

- **Space Robotics:** Bio-inspired robotic systems are being suggested for use in space exploration. For instance, robots designed based on octopuses or other adaptable organisms could assist in exploring alien terrains or repairing satellites and space stations.[51]
- **Robotic Astronauts:** Some proposals involve the creation of robotic versions of astronauts to conduct experiments or make repairs in space environments, thereby minimizing risks to human astronauts. Upcoming space initiatives necessitate advancements in space AI and robotics technology for the construction, repair, and maintenance of satellites and space structures in orbit.[52]

Education

- **Educational Robots:** Bio-robotics is being used to create interactive robots aimed at teaching programming, robotics, or biology. These robots may mimic the traits of humans or real animals to engage children in education. Educational Robotics (ER) serves as a tool that enhances the educational process and offers substantial advantages in learning and teaching. ER provides students with the chance to learn, develop, and apply their knowledge to real-world problems. The impact of ER includes enhancing critical thinking and creativity while promoting teamwork and collaborative skills.[53]

- Educational robotics is highly endorsed in special education to assist students with learning disabilities, attention deficit hyperactivity disorder, and autism, particularly concerning student inclusion.[54]

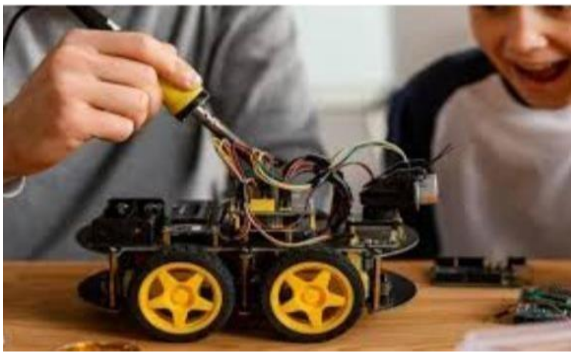

Figure 9: Robotic Education.

BENEFITS

Medical Innovations

- **Prosthetics and Exoskeletons:** Bio-robotics has transformed prosthetic devices, allowing for more natural movement and improved functionality for individuals with disabilities. Exoskeletons assist individuals in regaining mobility and provide advantages for both those with disabilities and healthy individuals.[55]
- **Surgical Robots:** The use of robotic surgery marks a notable enhancement in minimally invasive procedures, delivering greater precision, flexibility, and control compared to conventional techniques.[56]
- **Rehabilitation:** The field of assistive and rehabilitation robotics is expanding, driven by various social and medical demands such as aging populations and neuromuscular and musculoskeletal disorders. These robots can be used in everyday tasks or to aid in training, motor function, and rehabilitation.[57,58]

Advancements in Education and Research

- The cross-disciplinary nature of bio-robotics encourages collaboration among computer science, engineering, and biology, creating new opportunities for research and education. Institutions like the University of California, Berkeley, and ETH Zurich lead the way in bio-robotics research.[59,60]

Cutting-edge Research

- **Animal Models and Biological Research:** Bio-robots often mimic the movements and behaviors of animals, which helps in studying biological processes and animal interactions with their environments. This research could promote advancements in evolutionary biology, neurology, and artificial intelligence.[61]

Enhancement of Human Abilities

Technologies such as exoskeletons and assistive robotic devices exemplify reusable bio- robotics that enhances human capabilities. These innovations help individuals with disabilities regain mobility and perform tasks they might otherwise struggle with.[62] In industrial contexts, wearable robotics significantly enhances worker safety and efficiency.[63]

Energy Conservation

- A bio-robotic system often mimics the efficiency of natural mechanisms and is generally designed to consume less energy than traditional robots. For instance, a robot that imitates animal locomotion may use less power while achieving smoother, more sustainable movement.[64]

Integration with Biology

- **Adaptation to the Environment:** Robots inspired by biological forms are typically created to adjust to natural settings (e.g., robots that replicate animal movements). This could lead to applications in areas such as search and rescue operations, environmental monitoring, or exploration of risky zones.[65]
- **Bio-hybrid Systems:** The field of bio-robotics combines biological tissues with robotic components to develop bio-hybrids—such as robots equipped with living muscle fibers. These systems may provide benefits in energy efficiency and functionality, as they can "heal" or adapt in ways that conventional machinery cannot.

Reduction of Healthcare Costs

- By enhancing diagnostic accuracy and automating repetitive tasks, bio-robotic technologies such as autonomous diagnostic devices and robotic caregivers can help reduce healthcare costs. These advancements have the potential to improve healthcare service efficiency and alleviate some of the financial pressures on the healthcare system.[66]

FUTURE CHALLENGES OF BIOROBOTICS

Biological Integration and Interaction

- **Challenge:** A significant challenge lies in merging living tissues with robotic systems while ensuring their long-term stability and effectiveness. Bio-robotics can connect robots with biological entities, including cells, tissues, and the human nervous system.
- Example: Creating systems that can effectively communicate with humans, such as brain- machine interfaces or prosthetics, while safeguarding the health and integrity of both biological and robotic parts.[67]

Ethical and Safety Concerns

- **Challenge:** The advancement of bio-robotics introduces complex ethical and health issues. Concerns surrounding privacy, approval processes, and the potential risk of harm arise from robots interacting with biological systems, particularly in healthcare settings (e.g., surgical robots, prosthetics, or assistive devices).
- **Example:** Guaranteeing the safety, dependability, and respect for the individual's autonomy and privacy of robots operating on or within human settings.[68]

Miniaturization and Flexibility

- **Challenge:** The creation of robots those are compact, lightweight, and flexible enough to function in biological environments, such as within the human body or when interacting with microorganisms, pose a challenge.
- **Example:** Designing autonomous robots or minimal-incision robotic surgical tools for tasks like targeted drug delivery.[69]

Human-Robot Interaction (HRI)

- **Challenge:** As robots become more integrated into human environments, the demand for intuitive and logical human-robot interactions increases. This involves enhancing communication, trust, and collaboration between humans and robots.
- **Example:** Crafting robots that can interpret and respond to human emotions and behaviors, particularly in healthcare or elder care settings.[70]

Energy Efficiency and Power Supply

- **Challenge:** Energy consumption poses a significant issue, especially for bio-robots designed for prolonged operation within the body or in remote locations. Effective energy storage and management are crucial for the function of bio-robots, particularly for implantable devices.
- **Example:** The challenge lies in powering wearable robots or prosthetics without the necessity for frequent recharging.[71]

Material Challenges

- **Challenge:** Finding materials that can emulate biological tissues and their functions continues to be a major hurdle. These materials need to be biocompatible, durable, and able to endure the mechanical demands placed on robots while remaining flexible and adaptable to biological conditions.
- **Example:** Developing soft robots or prosthetic limbs from materials that can bend and flex like human tissue while also offering adequate structural support.[72]

Regulation and Standards

- **Challenge:** With the evolution of bio-robotics, establishing clear regulations and standards is necessary to guarantee safety, quality, and effectiveness. This is especially essential for medical devices and robots utilized in healthcare facilities.
- **Example:** Creating universal standards for implantable devices or robots employed in surgical procedures.[73]

Table 1: Timelines of bio-robotics.

Sr. No.	Year	Innovation
1.	1956	The concept of bio-robotics begins to form. W. Grey Walter builds one of the first autonomous robots, a turtle robot, which moves based on simple biological principles, laying the foundation for future bio-inspired robotics.
2.	1960s	Development of early robots like Shaky, the first mobile robot developed at Stanford Research Institute (SRI), helped demonstrate the potential for robotics influenced by biological systems, though not yet focused on bio-robotics specifically.
3.	1970s	Research on neuromorphic engineering began to model how biological neural systems might influence robotic design.
4.	1973	The Cybergenic Robot, designed by P. P. K. Chu, explores the idea of using living organisms to control robotic systems
5.	1980s	Development of early robotic prosthetics that combined artificial limbs with biological inputs. Myoelectric prostheses, controlled by the electrical signals in muscles, emerged.
6.	1990s	• Bio-inspiration becomes more prominent. Researchers begin exploring soft robotics and bio-inspired systems such as artificial muscles. • The Pneumatic Artificial Muscle (PAM), developed by Joseph L. McKibben, is one of the first bio-inspired actuation systems modeled after biological muscles.
7.	1999	The development of the Robotic Fish, a bio-inspired robot designed to mimic the movements of fish. It is used for underwater exploration and studies on animal locomotion.
8.	2001	MIT's Biomimetic Robotics Lab, led by Professor Rodney Brooks, developed

		the Cheetah Robot, which can run and change direction like a cheetah. It is an example of bio-inspired design in robotics.
9.	2004	The Darpa Robotics Challenge spurs developments in autonomous robots capable of performing human-like tasks in disaster situations.
10.	2007	The first cyborg insects (like the Robbe) emerge, where researchers attach small robots to the body of insects, giving them remote-controlled capabilities for tasks like pollination or environmental monitoring.
11.	2010s	The field of soft robotics and biomaterials flourishes, with an emphasis on creating robots that can work alongside biological organisms or even merge with them.
12.	2015	Researchers at Harvard University create a soft robotic hand using 3D printing and soft materials inspired by the human hand's dexterity and flexibility.
13.	2016	The Robbe, a biohybrid robot capable of flying, is created at Harvard's Wyss Institute for Biologically Inspired Engineering.
14.	2018	The development of bio-hybrid robots using living cells for muscle-like movements. For instance, researchers at MIT create robots powered by living muscle tissue.
15.	2020s	• AI and machine learning are increasingly integrated into bio- robotics, improving the autonomy and functionality of these robots. • Researchers explore further advancements in biocompatible materials that can interact with human tissue and even integrate with human prosthetics and implantable devices.
16.	2022	Researchers in Japan create a bio-hybrid robot made from living heart cells. This robot is capable of moving by contracting its muscle tissue, a step toward creating more autonomous, biologically integrated robots.

DESIGN OF BIOROBOTICS

- Creating robots or robotic systems that resemble biological organisms in terms of their structure, behavior, and/or functionality is known as biomimetic robotics, or bio-inspired robotics.[74] The goal is to create robots that are more capable of completing tasks quickly, adjusting to changing conditions, and occasionally displaying the flexibility and independence of living things.[75]

Figure 10: Design of bio-robotics.

An outline of some of the essential elements used in the creation of biomimetic robots is provided here:

Mobility and Biomechanics

- **Creating for Natural Motion:** Biomimetic robots frequently try to mimic the motions of living things. For instance, a robot that is meant to resemble a cheetah might be constructed with an emphasis on the limb and spine mechanics in order to run swiftly. The focus of a fish-inspired biomimetic robot could be on undulating fins for effective swimming.[76]
- **Actuators and Artificial Muscles:** The secret to attaining fluid and adaptive movement is the use of actuators or artificial muscles (such as electroactive polymers or pneumatic actuators) that resemble biological muscles.[77]
- **Legged Robotics Carpi:** It is difficult to balance agility and stability while maintaining the flexibility and responsiveness of the leg joints.[78]

Senses and Perception

Advanced sensory systems such as cameras, microphones, infrared sensors, or proximity sensors are frequently used by biomimetic robots to recreate sight, hearing, touch, and even echolocation in order to replicate biological perception.[79] The creation of "artificial skin" for tactile feedback enables robots to perceive their surroundings in a manner similar to that of living things. This is accomplished by means of stretchable materials, temperature sensors, or pressure sensors.[80]

Energy Sources and Efficiency Energy Harvesting: Biomimetic robots frequently need creative approaches to power management. In the same way that animals use muscle energy to move efficiently, robots can imitate biological energy systems by using energy-harvesting technology, solar panels, or batteries.[81] Low Power Consumption: Certain designs try to mimic the ways in which animals maximize their energy use, such as the gliding motion of birds or the slow-moving, energy-efficient creatures, in robotics.[82]

- **Design of Materials and Structures**

Flexible Materials Biomimetic robots are generally made of lightweight, flexible materials that are designed to resemble the structure of biological things. As an illustration, consider soft robotics composed of composites or flexible elastomers that mimic the elasticity of biological tissues.[83] Building robots that resemble biological beings in terms of their movements, structures, and functions is the main goal of bio-robotics design. These robots are designed to integrate biological elements, such as the effectiveness, adaptability, and flexibility present in nature. In order to enhance how robots interact with the actual world, bio-robotics development usually integrates computer science, biology, and engineering. A closer look at the crucial elements of biorobot design is provided below.[84]

Essential Design Elements for Bio robotics

- **Self-Healing Materials**: Some robots use materials (such as self-healing polymers) that can mend themselves after harm, drawing inspiration from the capacity of biological things to do so.[85]
- The primary objective of bio-robotics design is to create robots that are similar to biological entities in terms of their movements, structures, and functions. The efficacy, versatility, and flexibility found in nature are among the biological components that these robots are made to incorporate.[86] Computer science, biology, and engineering are typically integrated in bio- robotics development to improve the way robots interact with the real environment. The essential components of biorobot design are examined in more detail below.[87]

Copying biological systems

- **Legged robots:** These mimic the gaits or sprinting motions of insects, canines, or people. For these robots to balance and move, precisely engineered joints, actuators, and feedback systems are needed.[88]
- **Aquatic Robots:** Robots built for underwater mobility frequently imitate the propeller-like tails or undulating fins of fish and other marine animals. Flying Robots: To fly steadily, these robots need wings, sensors, and lightweight materials that resemble the flight patterns of birds or insects.[89]
- **Flexible Structures:** A lot of biorobots are made of soft materials that function similarly to biological tissues. To accomplish movements that stiff robots cannot, such squeezing into small spaces or altering shape, soft robots that are modelled after octopuses or squids use flexible actuators and materials.[90]

Artificial Muscles: Actuators used in biorobots frequently replicate the actions of organic muscles. They might consist of:

- **Pneumatic actuators:** These work similarly to how muscles contract and expand by using air pressure.[91]
- Materials known as shape-memory alloys (SMAs) mimic muscle contractions by changing shape in response to heat or electrical currents.
- **Electroactive polymers:** These polymers, which operate as actuators for robots, alter shape in response to an electric field. These actuators enable the robot to move in a variety of flexible and adaptive ways, such as the fluid, continuous motion of a human hand or the accurate manipulation of an insect's wings.[92]

Resources and Construction

Soft Robotics: A lot of biomimetic designs use soft materials, which make robots more pliable, adaptive, and able to navigate delicate situations and people safely. Flexible composites, silicone, and elastomers are some of the materials that can be used in soft robots. Some sophisticated biorobots are equipped with self-healing materials, which are modelled after biological organisms' capacity to regenerate.[93]

Figure 11: Resources and constructions.

Bioinspired Surfaces: Biorobots frequently make use of specialized surfaces that, like the sticky feet of geckos or the self-cleaning qualities of lotus leaves, replicate the texture and characteristics of biological surfaces.[94]

Supplies for Biorobots

- Inorganic materials, mainly nickel (Ni) and Fe3O4 magnetic particles, are increasingly being used in bio-robotics because of their superior magnetic responsiveness compared to organic materials. Robotic mobility requires highly regulated, fuel-free propulsion, which these materials make possible. A Ti layer is added to these coatings to lessen their toxicity and make them safer for use in biomedical applications. Perfluorocarbon coating the surface of Ni-based robots allows them to navigate the complex biopolymer structures inside the eyes, which is an innovative method of enhancing the delivery of ocular medications. Additionally, targeted cancer treatments using nanorobots have made use of vitreous Fe3O4 nanoparticles. With the use of electromagnetic fields, these robots may be remotely guided to tumors and deliver chemotherapy drugs directly to the malignancy.[95]
- This hyperthermic activity enhances the anticancer effects of treatments and controls the release of medications. These developments show how inorganic materials can revolutionize medication delivery systems through improved functionality and design. Despite the advantages of these materials, their limited biodegradability and likely toxicity necessitate the development of safe post-treatment procedures. For example, DNA origami techniques can be used to generate sophisticated three-dimensional structures with customized drug delivery capabilities. DNA- based structures are ideal building blocks for developing unique biorobots due to a number of their characteristics.

The intricate patterns that DNA may self-assemble into through base pairing can now be precisely predicted thanks to sophisticated computer simulations[96] pairing. The development of various DNA aptamers enables the construction of DNA bio robotic platforms with precise binding characteristics, tissue targeting capabilities, and adaptable environmental sensing.[97] Furthermore, there is a lot of promise for protein-based robots, particularly in the development of motors that make use of structural proteins like those present in squid ring teeth These proteins can be engineered into chemical fuel-storing and -releasing nanocrystals, which would enable self-propelled mobility and controlled drug delivery. The incorporation of iron oxide nanoparticles into these structures allows for magnetic field-guided movement, highlighting the therapeutic potential of protein-based systems.[98] Protein-based structures have the benefit of being biodegradable despite being constructed at the microscale e-form of Biorobots.

- It is necessary to develop nano/micro-sized robots that can efficiently convert energy into directed thrust in the harsh environment of physiological fluids, overcoming obstacles such low Reynolds numbers and Brownian motion. The geometry of a robot greatly influences its motion control, and helical designs modelled after bacterial flagella are particularly effective. Rotating in a magnetic field, these robots advance with minimal resistance. Conical shapes improve fluid speed and maneuverability over cylindrical shapes, which is advantageous in specific biological settings like the esophagus or stomach. Effective swimming in viscous environments, such as intestinal or stomach mucous, is a notable characteristic of helical robots with bioinspired structures.[99]
- Studies show that helical robots with optimized geometry, such as conical helices, outperform traditional microhelices in terms of speed and trajectory control when subjected to magnetic manipulation.[100] This makes them valuable for applications such as cell transport and medication administration. However, their very small surface areas limit their cargo capacity, which compromises their therapeutic efficacy. Complex manufacturing processes like two- photon polymerization can make large-scale manufacturing difficult. Spherical robots are particularly effective in applications where little contact is desirable, such as drug retention and release. They use asymmetric designs for directional propulsion and are frequently propelled by chemical reactions on metallic surfaces. For instance, using the propulsion produced by hydrogen bubbles, magnesium-based spherical micromotors coated with pH- sensitive polymers can neutralize stomach acids and improve drug release efficiency.[101]

Engine for Biorobots

Since it regulates propulsion, the engine is an essential part of biorobot design, particularly for smaller robots than nano or microscale ones. Because of the low Reynolds number environment, which makes locomotion control more challenging, these designs are crucial for targeted drug distribution and Brownian motion, which lower inertial forces. However, they also enable advanced navigation and obstacle handling. This method is safe for tissues and the environment since magnetic fields efficiently direct and move robots without the use of external fuel. These robots can also accurately dispense medicinal medications. However, because of the possibility of capillary blockage, the robot's application is limited to micro-sizes as its propulsion power declines with reduction in size. Additionally, in intricate anatomical areas, magnetic waves can generate Ultrasound is another promising control mechanism, owing to its deep tissue penetration and biocompatibility. Ultrasound- did nanowire motors generate movement through fluid streaming.[102] This method has been used to enhance gene silencing through rapid intracellular delivery of siRNA and for bacterial capture through acoustically propelled nanowires. Ultrasound-driven robots face limitations in areas containing air or bone, owing to poor ultrasound transmission. In addition, long-term ultrasound applications can generate unwanted heat. Thermal response engines utilize materials such as N-isopropylacrylamide that undergo changes in their properties in response to temperature fluctuations. Drugs can be released by these engines at target locations with temperatures higher than the body's typical temperature. However, the success of this method depends on the thermal stability of the cargo because heat-sensitive drugs are susceptible to degradation. Applications of thermally responsive engine biorobots may need to address the temperature fluctuations in the body and varying heat dissipation rates in different body parts. Temperature control must be carefully monitored to avoid thermal damage to surrounding tissues when near infrared (NIR) laser treatment is used to induce heat generation.[103], targeting deep tissues can be challenging because of the shallow penetration of NIR lasers. Chemical engines use reactions between metals and outside substances, like hydrogen peroxide or acids, to create propulsion for instance, magnesium-based motors can improve drug delivery in gastrointestinal circumstances by reacting with gastric acid. Despite their effectiveness, by- products of chemical reactions, such as gas bubbles, may cause embolisms, restricting their use in systemic applications. Chemical engines rely primarily on the reaction rates of chemical fuels and external environmental conditions. Therefore, precise control over the release rate and number of chemical reactions over time requires the rational design of biorobot carriers. The key parameters to consider include the amount of chemical fuel, sustained reaction rates, and the formation of gas, whether directed or nondirected.[104]

Figure 12: Engine of bio-robotics.

- Microrobots can be equipped with living cells, which offer independent propulsion. When paired with drug-loaded liposomes, bacteria like Magneto coccus marinus, which are used for magneto taxis, may efficiently enter tumor tissues. Biohybrid robots, which blend artificial materials and organic things, provide novel solutions including fluorescence-guided therapy using magnetic microalgae. One significant drawback of using biological creatures in robotic construction is the potential for host rejection. Modifications to camouflage are necessary to prevent attacks on the host immune system. Furthermore, it can be challenging to ensure consistent performance and efficacy in biorobots based on live engines due to batch manufacturing variations. Because each propulsion technique has unique benefits and drawbacks, it is important to carefully evaluate the particular uses and operating conditions of a biorobot.[105]

TARGET DISEASES

Cancer

- Cancer patients have a heavy burden because there are currently few effective treatments available to provide a complete cure.[106] Several studies have shown that aberrant redox signaling and a shift in the redox balance are significant contributors to cancer progression and treatment resistance. Changes in oncogenic factors, such as metabolism, genetics, and the tumor microenvironment, cause tumor cells to continually create large levels of reactive oxygen species (ROS)[107] factors including cell division and DNA alterations that are connected to the development of cancer.
- Recent studies have found that altering the antioxidant pathways can make tumor tissues more resilient to elevated ROS levels. Along with preserving redox homeostasis, the tumor microenvironment—which consists of both cellular and non-cellular components—promotes cancer.[108]

Figure 13: Cancer diseases.

- Recent research suggests that altering the antioxidant pathways can aid tumor tissues in adjusting to increased ROS levels. The cellular and non-cellular components of the tumor microenvironment not only preserve redox homeostasis but also encourage cancer. A compelling strategy in contemporary cancer treatment methods is to target the tumor microenvironment.[109] The common characteristics of redox dysregulation in tumor tissues have led to the use of the expression of several different components as targets for the design of robotic delivery systems, such as the extracellular matrix, excess metabolites, and marker proteins. Today's chemotherapy is not very selective and has numerous side effects when used to treat female reproductive tumors, such as ovarian or cervical cancer.[110] The use of specific More and more interest has been shown in sperm-based biohybrid robots that provide medication to the female reproductive system. In a recent study, biohybrids of sperm and 3D printed materials were used to magnetically direct the distribution of anticancer medications. Because sperm cells naturally mimic swimming in these circumstances, they are superior to produced micromaterials when it comes to using sperm- based micromotors to treat cancer in the female reproductive system.[111]
- Sperm membranes protect drugs against premature release, enzyme degradation, and immune system attacks. A 3D-printed magnetic tubular microstructure was guided by magnetic fields to move and uncap when it hit the tumor cell walls, releasing the material, according to a study by Xu et al. " One unique feature of this system is the fusion of sperm and cancer cell membranes, which facilitates the intracellular delivery of anticancer drugs.[112] However, there are several limitations that must be considered. For example, sperm origin compatibility, fertilization risk, and sperm cell survival should all be carefully considered in clinical practice. In order to employ Biorobotics to release medications, a number of research have attempted to modify the tumor microenvironment using extracellular proteases.[113]

- Matrix metalloproteinases (MMPs) are extracellular proteases found in tumor tissues that have a major effect on angiogenesis and tumor progression. Tumor cells secrete MMP-2 to break down collagen, the main component of the extracellular matrix, which promotes tumor cell escape and dissemination.[114] Thus, elevated MMP-2 levels in tumor tissues have been used in numerous investigations to initiate the release of medications. Due to the high levels of MMP-2 found in tumor tissues, a collagen-based helical micro robotic swimmer was developed.[115] The helical swimmer approached the tumor site under magnetic guidance, carrying model therapeutic and diagnostic cargo.[116] Imaging agents and macromolecular drugs were released as a result of collagen expanding and dissolving due to MMP-2 enzymatic activity.[117]

Gastrointestinal diseases

- Disorders of the Digestive System Ingestible drugs are used to treat patients with stomach disorders like Helicobacter pylori infections, gastric ulcers, and enteritis.[118] The most frequently authorized drug delivery systems for these treatments are oral solutions, ingestible tablets, or capsules. Food and drugs are transferred via peristaltic motions in the dynamic gastrointestinal tract. Therefore, one of the main issues with treating gastrointestinal disorders is the insufficient residency time for therapies in the target regions.[119]

Figure 14: Gastrointestinal diseases.

- A prevalent infection that affects half of the world's population is Helicobacter pylori. Peptic ulcers and gastric cancer may eventually result from this chronic inflammation of the stomach.[120]
- Current guidelines state that proton pump inhibitors and antibiotics are used in conjunction to reduce stomach acid levels in order to treat H. pylori infections.[121] Oral administration of antibiotics via passive delivery systems makes it difficult to eradicate H. pylori because of a number of factors, such as the antibiotics' poor stability in gastric acid, their low concentration in the mucus layer where H. pylori is found, the bacteria's short exposure time, and antibiotic peristaltic movement. H. pylori infection was effectively eliminated by oral administration of a clarithromycin-assisted stomach acid-sensitive autonomous propeller.[122] The stomach mucosa was protected from the antibiotic clarithromycin by using a Eudragit polymer.[123] When the microparticles are combined with a magnesium hydrogen-gas-generation engine, The acid-sensitive micromotor firmly stuck to the mucus layer and moved on its own.[124] Hydrogen gas production effectively eliminated H. pylori in the stomachs of infected mice and improved the local concentration of drugs and made them easier to discharge.[125] Furthermore, since proton depletion rapidly neutralizes the acidic environment, co-treatment with proton pump inhibitors is not required.[126]
- This concept may be used to treat H. pylori infections by actively delivering medication. More study is required to compare the antibacterial potency of this technique with that of traditional drugs in order to elucidate its efficacy and safety for long-term use in humans.[127] One of the challenges in developing a reliable system for the management and visualization of treatments in real time is imaging of deep tissue in gastrointestinal conditions.

A recent study shown that a micro robotic system controlled by photoacoustic computed tomography (PACT) can be used to track movement in the mouse colon.[128]

- The migration of the drug-loaded microrobot was monitored in real time after it was administered orally.[129] PACT imaging's deep penetration, excellent anatomical contrast, and spatiotemporal resolution enable accurate tracking of microrobot migration in the gastrointestinal tract. Near- infrared light irradiation deformed the particle once it reached its destination. This also activated the magnesium engine in the intestinal fluid, which drove the insertion of the mucus layer for prolonged microrobot retention times and the release of medication.[130] A new era in the treatment of gastrointestinal illnesses has begun with the advent of autonomous microrobots with self-propelling engines.[131]

Ocular diseases

- Conditions In order to treat diseases including glaucoma, diabetic macular oedema, diabetic retinopathy, and macular degeneration, ocular drug administration is essential. Topical therapies and other conventional medication delivery modalities are frequently used to treat the anterior eye. The back of the eye does not retain much medication and is ineffective whether injected intravitreally or systemically. The retina is sensitive to degeneration; thus, medications passively diffuse into it gradually. Several recent studies have investigated the development of microrobots for intravitreal medication delivery. A magnetic field-driven nanorobot has been used to break through the high-viscosity barrier of intravitreal habitats.[132]

Figure 15: Ocular diseases.

- The size of the robotic system has a major effect on the vitreous matrix's mobility and distribution efficiency. A previous study found that the mesh size of the vitreous matrix is around 550 nm. This makes it possible for a robotic system smaller than 550 nm to maneuver and pass through the vitreous matrix with nearly no problems. A helical nano propeller with dimensions of 400 nm in length and 120 nm in diameter was made using silica particles coated with Ni to produce a magnetic reaction. In a particularly violent medium, the nano propeller outperformed large helical control in terms of step-out frequency.[133]
- The navigation and movement speeds of this carrier are therefore expected to be suitable for intravitreal delivery. But nonetheless, the small size of the nanomotor may limit the amount of medication it can transport.[134] In a different study, retinal disease was treated at the microscale using active drug delivery using a magnetic propeller or an appropriate design. Because the actuation and drug-loading capabilities are restricted to nanoscale platforms, it is advantageous to increase the propeller size. As a result, scaling up Biorobotics while guaranteeing successful penetration into very viscous and porous biological fluids is challenging.[135]
- Similar to previous studies, the micro propeller was driven by its helical structure and included a 500 nm-diameter spherical head that matched the pore size of the vitreous matrix. The In order to alter the surfaces of medical equipment and ensure their biocompatibility, this coating material is commonly applied. In the pig eye model, the micro propeller travelled 15 mm in 30 minutes from the center of the eye to the retina.
- The 340-nm albumin/hyaluronic acid particles required 6 hours to passively diffuse in the 10 mm range, which is different from previous passive particle studies. These studies raise the active concept of wireless, regulated delivery systems for ocular disorders. Even though proof- of-concept studies have been carried out to meet the biophysical challenges of intravitreal systems, it is still necessary to examine their drug-loading and release capacities. Most significantly, the materials used to make these robotic devices are currently biocompatible but not biodegradable.[136]

Brain diseases

- Brain Illness It is difficult to transport drugs to the central nervous system (CNS). The blood– brain barrier (BBB), a sophisticated system of blood vessels, protects the brain and other CNS components, including the spinal cord.[137] The CNS's metabolite transport and exchange are tightly regulated by the BBB.[138] As a result, getting large amounts of medication molecules into the brain is challenging. Recombinant proteins, peptides, antibodies, DNA, and RNA are examples of macromolecular therapies that do not all passively diffuse into the brain. The most widespread misunderstanding is that tiny chemicals can cross the blood-brain barrier. In fact, almost 98% of tiny molecules are unable to pass through the blood-brain barrier.[139] Consequently, methods to enhance medication delivery to the central nervous system. Several approaches have made use of logically constructed nano delivery devices to promote BBB penetration.[140] Exosomes, lipoprotein nanoparticles, virus-based delivery systems, and cell membrane-based nanoparticles are a few examples. The majority of these tactics use biomimetic carriers that target the BBB receptors precisely.[141] Some disorders, including brain tumors, Alzheimer's, Parkinson's, tight junction opening, inflammation, and endothelial cell function collapse, cause pathological BBB leakage. Nanoparticle passive diffusion may be aided by this BBB leaking. In order to transfer drugs through the BBB efficiently, Biorobotics have been created.[142]

Figure 16: Brain diseases.

In a recent study, active medication administration via the blood-brain barrier was accomplished by taking advantage of the brain's high glucose consumption.[143] Joseph et al. developed a glucose- gradient-sensitive nano self-propeller that has promise as a therapy for brain illnesses. Since 20% of the body's glucose is used by the brain, glucose is the most efficient substrate for bridging the blood- brain barrier. The polymer was used to power a dual-enzyme engine, which caused the polymer to propel itself in the presence of a glucose gradient. Catalase and glucose oxidase are Coen stuck in polymerases.[144]

- The enzyme glucose oxidase catalyzes the transformation of glucose into hydrogen peroxide and D-glucan-d-lactone. Catalase then transforms hydrogen peroxide into oxygen and water. Because polymerases have an asymmetric structure, active diffusion across the blood-brain barrier is driven by oxygen escaping from one side of the particles.[145] This investigation showed a significant build-up of polymerases throughout the Diffusion through the BBB This study showed that the accumulation of polymerases across the BBB in a rat model was four times higher than that of non-enzyme-equipped polymerases.[146] While the concept showed that enhanced delivery with a glucose gradient at the BBB is feasible, there are concerns about the immature activation of this system in the bloodstream, where the glucose level is always maintained at 4-7.8 mm. Additionally, because the nano propeller uses glucose as fuel for its engine, there is a noticeable glucose deprivation during treatment, which may have a transitional effect on brain function, but repeated dosing in the treatment of brain diseases should be carefully taken into.

CONCLUSION

Biorobotics is a rapidly evolving field that bridges biology and robotics, offering innovative solutions for healthcare, automation, and human-robot interaction. By integrating biomimetic principles, artificial intelligence, and biomechanics, bio-robotics enhances robotic adaptability, efficiency, and functionality. The advancements in bio-hybrid robots and medical robotics have significantly improved prosthetics, rehabilitation devices, and autonomous systems, demonstrating the potential for real-world applications.

Despite its progress, challenges such as ethical considerations, technological limitations, and integration complexities remain. Future research should focus on refining bio-inspired designs, improving AI-driven adaptability, and enhancing energy efficiency for sustainable robotic solutions. Collaboration among scientists, engineers, and medical professionals will be crucial in driving further innovations.

In conclusion, bio-robotics holds immense promise for transforming industries, improving quality of life, and expanding the frontiers of robotics in both terrestrial and space applications. Continued advancements and interdisciplinary efforts will pave the way for more intelligent, responsive, and human-friendly robotic systems.

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