# Locomotion-Inspired Robotics: Structural Principles, Force Transmission, and Hydrodynamic Trends

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**Abstract.** Robotics has advanced rapidly across diverse fields, including medicine, industrial manufacturing, and exploration. Yet modern robots still struggle with challenges of movement efficiency, adaptability, and stability in complex environments. Bio-inspired locomotion provides a promising approach to overcoming these limitations by drawing on the structural and functional mechanisms evolved in nature. This paper reviews the structural principles, force transmission mechanisms, and hydrodynamic adaptations found in bio-inspired robots. It explores how biological inspirations—such as the fin movement of fish, the wing flapping of birds, and the undulatory motion of snakes—inform robotic design and improve energy efficiency, flexibility, and terrain adaptability. Key enabling technologies, including soft actuation, innovative materials, and bio-mimetic structural frameworks, are discussed in detail, highlighting their role in achieving compliant motion and enhanced environmental interaction. Additionally, the paper presents applications of locomotion-inspired robotics in medical rehabilitation, search and rescue, and planetary exploration. By integrating principles of biology with modern materials and intelligent control systems, bio-inspired robotics is expected to promote greater autonomy, efficiency, and sustainability. Future research will focus on hybrid systems combining living tissues and artificial materials, multi-material fabrication, and advanced neural control for adaptive and intelligent motion.

**Keywords:** Bio-inspired Robotics; Locomotion Mechanisms; Soft Actuation; Smart Materials; Hydrodynamic Optimization.

## 1. Introduction

As robotics continue to develop, their applications in medicine, industrial manufacturing, disaster relief, and national defense are expanding. Yet modern robotics still faces many challenges in terms of movement efficiency and environmental adaptability. Traditional robots rely on rigid structures and fixed actuation modes. This kind of system often experiences problems with excessive energy consumption, limited flexibility, and reduced stability in complex or unknown environments [1-3]. For example, wheeled robots on rough terrain experience a significant reduction in mobility; humanoid robots have difficulty maintaining balance on uneven ground. These problems not only limit the range of robot applications but also affect their reliability and task execution capabilities in critical scenarios. A bio-inspired method provides a new way to approach these challenges. Biological entities over billions of years have evolved diverse locomotion and force-transmission mechanisms; these characteristics are honed to be the most efficient, adaptable, and robust, helping them survive in complex and dynamic environments [4]. By mimicking the swinging of fish's tail fins to achieve underwater propulsion, learning from the multi-legged gait of insects to improve ground locomotion, or drawing on the flapping wings of birds to optimize aerodynamic design, engineers can build robots with greater maneuverability and adaptability. Especially in the optimization of structural design, force transmission, and fluid dynamics, the bionic approach shows a substantial advantage.

The advantages of bio-inspired locomotion robots lie not only in enhanced mobility performance but also in higher energy efficiency and safety. Some key technologies used in bio-inspired locomotion robots, such as flexible joints and soft actuators, enable robots to adapt to complex terrains and unpredictable disturbances. Moreover, some animals have highly efficient force-transmission structures, and by mimicking them, this paper can reduce unnecessary energy loss in robots, thereby improving endurance. In other scenarios, such as in fluid environments, engineers can simulate the dynamics of birds or fish to reduce drag, thereby significantly increasing operational efficiency. These advantages are making bio-inspired locomotion robots an emerging frontier with great potential in multiple areas.

The movement system of robots is transformed from conventional rigid joints to compliant actuators, and then towards the integration of innovative materials and fluidic actuation. Early robots had rigid structures, which offered a good range of movements but may be limited in the types of movements and in their adaptability to certain terrains. With the invention of flexible actuators made from various innovative materials, robots began to perform more compliant movements. Recent advances, such as neural network control, multi-material 3D printing, and microscale manufacturing processes, have revitalized bio-inspired locomotion and, therefore, their viability in complex environments.

This paper aims to summarize the current state of bio-inspired locomotion robots, covering biological principles, structural design, driving mechanisms, and adaptive mechanisms. This article is organized as follows: Section 2 presents a brief overview of bio-inspired locomotion robot design principles, and then Section 3 discusses emerging pivotal technologies in the field, featuring soft actuation, innovative materials, and bio-mimetic structures; Section 4 focuses on robots' possible application areas, including medicine, industrial service, and exploration systems; Then, contribution perspectives are summarized in Section 5, with a review of existing research achievements and challenges ahead as well as future directions. This paper is intended to provide a theoretical reference and inspiration for the further development of bio-inspired locomotion robot research and engineering applications arising from such cooperation.

## 2. Basic Principles of Bio-inspired Locomotion Robot Design

### 2.1. Application of bio-inspired kinematics in robot design

One crucial skill for integrating natural locomotion into robotics is understanding the principles and underlying physics of animal locomotion.

Fish locomotion uses caudal fin oscillation and body undulation to create thrust through vortices. The motion generates thrust by creating and shedding vortices. By studying the three-dimensional structure, fin motions, and vortex wave dynamics, scientists and engineers can apply the principles of how marine animals generate propulsion in water to aquatic robots [5].

Birds exploit vortex structures, wing compliance, tandem interactions, and aeroelastic effects to produce lift efficiently by flapping their wings. Engineers can replicate these principles by designing robots that mimic wing flapping and use a lightweight skeletal structure to achieve efficient propulsion. [5]

Snake locomotion relies on lateral undulation, concertina motion, and sidewinding to press against the ground and generate propulsion. This kind of locomotion endows them with incredible maneuverability and flexibility. So, engineers can mimic these patterns with modular joints and segments to design robots capable of navigating complex, confined environments, such as disaster relief and pipeline inspection [6].

These are just a few examples of bio-inspired locomotion strategies used in engineering. They each represent a honed solution through evolution, providing valuable insights for developing robotic systems.

### 2.2. Structural Elements of Locomotion Design

Effective locomotion relies on thoughtful design and material choices that best replicate the mobility and flexibility of biological entities. Flexible joints are the best option in this case, as they offer a greater range of motion, compliance, and energy absorption than traditional rigid joints.

Meanwhile, material selection is also critical for performance. For example, in aerial robots, high-strength-to-weight materials such as carbon fiber are highly preferred to reduce energy consumption and improve agility. Similarly, aquatic robots need materials that are strong enough to withstand high hydrodynamic pressure without significantly reducing maneuverability.

## 3. Key technologies in the design of modern bio-inspired robots

The emulation of biological locomotion in modern robotics relies on a cooperative integration of soft actuation, flexible structures, and the force transmission of different bio-inspired locomotion strategies. This section will take a close look at specific key technologies required to design bio-inspired locomotion robots.

### 3.1. Soft Actuation and Smart Materials

Soft actuation and innovative materials enable lifelike, adaptable movement. Unlike conventional rigid actuators, such as electric motors, solenoid actuators, and hydraulic actuators. Soft actuators made primarily of fluids, gels, or elastomers can mimic the elastic properties of biological tissues such as skin and muscle.

A pneumatic actuator is a dominant method for powering soft robots. They function by pressurizing air within the elastic chamber to move. A famous example is the McKibben actuator, which is composed of an inflatable bladder embedded within a non-extensible shell [7,8]. During pressurization, the bladder expands, forcing the shell to retract and shortening the actuator, thereby producing a tensile force. This closely mimics the contraction of animal muscles, which is essential because it provides reversible changes in shape and rigidity, crucial for both powered assistance and passive compliance.

Moreover, many new cutting-edge soft actuators are now built from innovative materials that respond to specific external stimuli. They are preferred for soft actuation due to their admirable lightweight, compact design, and instinctive response to specific external stimuli, which produces smooth, muscle-like motion. This reduces the need for complex mechanical parts and allows for more natural interaction with the environment. Here are some examples of the most famous innovative materials used in soft actuation.

An electrically responsive actuator, inspired by how the nervous system uses electrical pulses to coordinate responses, uses a material that deforms when an electric field is applied, offering fast response times. The most widely used ones include dielectric elastomers (DEAs), which expand when high voltage is applied. And ionic polymers (IPMCs), which bend when low voltage is applied and work exceptionally well under water [9,10].

Thermally responsive actuators, which change shape and stiffness with temperature, are commonly used in bio-inspired robots because they can replicate muscle-like motion. They include Shape Memory Alloys (SMAs), which contract when heated above a specific temperature, offering a high power-to-weight ratio [11]. Shape Memory Polymers (SMPs) and Liquid Crystal Elastomers (LCEs). SMPs can retain their original shape. They can be temporarily deformed but recover to their original shape after heating [12]. On the other hand, LCEs offer reversible deformation; they contract when heated and expand when cooled, which can often be used to create inchworm and caterpillar locomotion [13].

Bio-hybridization is a form of actuation that integrates synthetic materials with biological components, such as muscle tissue or gene- and protein-based circuits, to generate motion [14-16]. Such a biohybrid system offers a potential solution to the energy density limitation of batteries, as biological components can be powered by chemical fuels such as sugars, which are much more energy-dense, significantly reducing the weight and size of the robot [14,17].

In conclusion, the field of soft actuation is characterized by the synergy between pneumatic systems and innovative materials. However, this paper may seem to be on the right track toward more lifelike robotics through soft actuation. A key drawback is that many soft actuation technologies may still suffer from durability, precision, and low energy efficiency, limiting their scalability and real-world applications. The choice of actuation technology involves a trade-off among factors such as response time, force output, precision, and power requirements.

### 3.2. Bio-mimetic Structures

Understanding the structure of biological systems is pivotal for translating bio-inspired locomotion into viable engineering ideas, as they provide efficient and inherently compatible blueprints for locomotion.

This section explores two primary and prevalent categories of bio-inspired locomotion: undulatory locomotion and continuum structures. But the field of bio-inspired locomotion applied in robotics is much broader; engineers draw on movement strategies from a wide range of animals and plants.

The undulatory locomotion mechanism mimics the wave motion animals create, which travels down their bodies to provide propulsion for crawling and swimming. The fundamental principle of this mechanism is to create a phase delay between adjacent segments of the robot’s body, so that when actuators are activated in a sequential pattern, each segment lags slightly behind the one before it, thereby generating a wave that pushes against the surrounding medium for propulsion. Take snake-inspired robots, for example: they use lateral undulation, which allows them to bend left and right to navigate rough terrain. The principle of their movement is frictional anisotropy, in which robots generate a lateral wave down their bodies, and their segments push sideways against high-friction points, propelling them forward [18]. Fish-inspired robots are another example; they mimic carangiform swimming, in which only the tail moves side to generate thrust, while the rest of the body remains relatively stiff. The motion creates a wave that moves rearward, producing forward thrust for the robot.

Continuum and soft-bodied structures are also commonly applied to robots. These robots are not segmented and do not have rigid joints; they mimic the infinite degree of freedom seen in nature, like an octopus arm. This high dexterity, adaptability, and degree of freedom are ideal for safe human-robot interaction and navigating through unknown environments.

A key advantage of the system is distributed deformation, meaning the entire body contributes to motion rather than localized joints in traditional systems. Soft actuators, such as pneumatic networks, shape-memory alloys, and dielectric elastomers, are used to emulate muscle-like contraction, providing controllable, compliant motion [19]. For example, octopus-inspired soft robots use muscular hydrostat principles for omnidirectional bending, and elephant-trunk-inspired robot arms use tendon or cable-driven backbones

## 4. Application of Bio-inspired Locomotion Robotics

### 4.1. Medical and Rehabilitation Robotics

Principles of bio-inspired locomotion have delivered real insights into the design of robots for rehabilitation and medicine, yielding better control, adaptability, and alignment with human biomechanics.

For instance, in bionic prosthetics, tendon dynamics are emulated to improve force transmission and joint coordination, and to provide a more natural walking pattern for users with limb loss or neurological disorders. The transition from rigid frames to soft robots, often driven by actuating pneumatic artificial muscles (PAMs), makes physical interaction with the human body safer and more comfortable [20]. Furthermore, these principles are also being applied to upper-limb and post-stroke rehabilitation. As a result, bio-inspired medical robots are revolutionizing rehabilitation through their unique flexibility and adaptability.

In addition, bio-inspired microrobots are a well-studied field in medicine, where researchers try to mimic the locomotion of bacteria and sperm cells, as well as to move within fluids [21,22], which allows for the propulsion of such robots inside the human body to perform precise tasks, such as microsurgery or drug delivery directly to cancer cells.

### 4.2. Rescue and Service Robots

Bio-inspired locomotion robots also play an essential role in search and rescue, industrial maintenance, and service environments, thanks to their mobility and flexibility in navigating unstructured settings. Such as snake-inspired robots that mimic undulatory motion, demonstrating superior maneuverability for research-and-rescue missions in confined or collapsed environments [21]. Insect-inspired robots utilize multiple legs to employ distributed control for stability on uneven surfaces.

Meanwhile, bio-inspired microrobots that replicate the swimming mechanisms of bacteria and sperm cells are also widely used for pipeline inspection. This fully exploits their hydrodynamic efficiency, maneuverability, and flexibility in confined fluidic environments, which are increasingly valuable for infrastructure maintenance and oil and gas inspection [23].

### 4.3. Exploration Robots

Compared to traditional wheeled exploration systems, which often faced limitations in rough terrains. The ability of bio-inspired locomotion robots to navigate through confined, complex environments is desirable for environmental exploration.

For planetary exploration, robots replicate the locomotion strategies of insects and snakes to traverse uneven or granular surfaces such as sand or rock. For example, multi-legged robots inspired by insects can adapt and maintain stability across bumpy terrains. At the same time, snake-inspired robots can slither through narrow or granular terrains where it is hard to find the point of force [24, 25]. Additionally, engineers are exploring bio-inspired approaches for aerial and aquatic exploration systems, such as flapping-wing drones and fish-inspired robots that leverage hydrodynamic principles observed in nature to achieve high maneuverability and energy efficiency.

With the support of these locomotion strategies, engineers can enhance terrain adaptability and robustness, qualities essential for the exploration of unknown areas that humans are unable to or find it difficult to reach.

## 5. Conclusion

The development of locomotion-inspired robots is a transformative intersection of biology, engineering, and material science. By studying evolutionary mechanisms in nature, scientists can translate them into robotics, enabling more versatile and adaptive ways of force transmission and movement.

This paper identified key technologies for designing locomotion-inspired robots—soft actuation, which endows robots with flexible motion. Innovative materials, such as electrically and thermally responsive materials, play a crucial role in enabling adaptive and efficient movement. Furthermore, biomimetic structures, such as undulatory and continuum structures, offer versatile means of navigating terrain, enhancing the maneuverability of robots. Together, they form the core of modern bio-inspired robotics and a targeted focus on achieving higher maneuverability, adaptability, and flexibility.

In the future, the field of bio-inspired locomotion robotics still has room to improve, with a focus on combining intelligent control, multi-functional materials, and computational design. Improvements in machine learning and neural control architectures could greatly facilitate the teaching of adaptive behaviors and the optimization of real-time motions. On the other hand, multi-material 3D printing and nanoscale fabrication will enable closer integration of sensors and actuators that exploit the entire structure of the robot. Furthermore, a bio-hybrid system that combines living tissues with robots may significantly enhance the energy efficiency of robotics, elevating its autonomy and endurance.

The integration of biology into robots is taking them to a new level of efficiency, adaptability, and sustainability. This opens many avenues for exploration, services, and interactions that could revolutionize how this paper society operates.

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