

Biomimetic Mapping: A Comparative Analysis of Human Musculoskeletal Kinematics and High-Torque Robotic Actuation Systems

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Abstract:

Biomimetic robotics is a cross-disciplinary area combining human biomechanics, robotics, artificial intelligence, and materials science in the development of robotic systems that can mimic human movements and functionality. The current review explores the connection between human musculoskeletal kinematics and advanced high-torque robotic actuation systems through the discussion of biomechanical theory, robotic actuator technologies, biomimetic mapping techniques, and innovative developments in the field of robotic engineering. Modern approaches such as motion capture, electromyography (EMG), inverse dynamics, biomechanical modeling, and artificial intelligence-controlled systems enable enhanced accuracy of movements, sensor fusion, and human-robot interaction in the robotic systems. Research shows that biomimetic robotics enables enhanced adaptability, efficiency, and safety during interactions with humans; nevertheless, it is still difficult to mimic the complex functionality and energy efficiency of the human musculoskeletal system. In addition, this study focuses on the innovative advancements in the field such as brain-computer interfacing and AI-enabled adaptive robotic systems.

Keywords: Biomimetic robotics, Human musculoskeletal kinematics, High-torque robotic actuators, Artificial intelligence, Electromyography (EMG), Rehabilitation robotics, Prosthetic engineering, Humanoid robotics

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1. INTRODUCTION

Biomimetic robotics refers to the relatively new interdisciplinary branch of study involving the application of human biomechanics, robotics, artificial intelligence, and material sciences in order to create robotic systems that mimic human movement and functionality ^[1]. Human biomechanics represent the highest form of movement biology due to their flexibility, coordination, adaptability, and efficiency. Recently, scientists have turned more attention to researching human biomechanics such as joint kinetics, muscle coordination, tendon elasticity, and nervous system control methods in order to optimize robotic actuators and artificial robotic

systems. Motion capture systems, EMG recording techniques, biomechanics modeling, and artificial intelligence-controlled systems are utilized extensively in order to achieve human-like movement in humanoid robots, prosthesis, rehabilitation, and industry robots.



Figure 1: Human Musculoskeletal [2]

High torque robotic actuation mechanisms such as electrical actuators, hydraulic actuators, pneumatic actuators, series elastic actuators, and even soft robotic actuators have revolutionized robotic movements by increasing their accuracy, flexibility, and adaptability. Biomimicry robotics is now being used in applications that include health care rehabilitations, prosthesis engineering, manufacturing automation, and human-robot cooperation platforms. However, despite significant technology advancements in robotic systems, there remains a gap in robotic systems in terms of their inability to replicate the complexity and sophistication of the human body [3]. It is therefore important to understand the connection between human musculoskeletal biomechanics and robotic actuation systems.

1.1 Background Information and Context

Human biomimetic robotics is an inter-disciplinary technology which utilizes human biomechanics, robotics, artificial intelligence, and material science to create robots capable of mimicking human-like movements and functions. The human body's musculoskeletal system can be considered as one of the best biological movement systems because of its adaptability, flexibility, coordination, and energy efficiency [4]. In recent years, there has been a rise in interest amongst researchers to study human biomechanics such as joint kinematics, muscular coordination, elasticity of tendons, and neurological control processes. Cutting-edge technologies such as motion capture analysis, electromyography (EMG), biomechanical simulation, and artificial intelligence-based control mechanisms are being extensively employed by scientists to mimic human movement using humanoid robots, bionic limbs, rehabilitation devices, and industrial robots. However, despite many technical advancements, it still poses quite a big challenge for engineers to replicate the adaptability, coordination, and efficiency of the human body [5].

1.2 Objectives of the Review

This review aims to examine:

- To analyze the biomechanical principles of the human musculoskeletal system and their role in human movement and stability.
- To examine different high-torque robotic actuation systems, including electric, hydraulic, pneumatic, series elastic, and soft robotic actuators.
- To evaluate biomimetic mapping techniques such as motion capture analysis, electromyography (EMG), biomechanical modeling, and artificial intelligence-based control systems.
- To compare human musculoskeletal functions with robotic systems in terms of flexibility, adaptability, energy efficiency, and sensory coordination.
- To explore the applications, strengths, limitations, and future developments of biomimetic robotics in rehabilitation, prosthetics, humanoid robotics, and industrial automation.

1.3 Importance of the Topic

It is important to study biomimicry of robotics since it helps develop robotic systems that are adaptable, intelligent, and designed for the benefit of humans. Robotic systems that are based on human body functions find great applications in fields such as healthcare rehabilitation, assistive robotics, prosthetics, industrial automation, and collaborative robots [6]. The application of biological and biomechanical principles in conjunction with artificial intelligence and actuators in the field of robotics allows developing flexible, safe, efficient, and interactive robotic systems. Moreover, biomimicry of robotics might help enhance the mobility of disabled people.

2. BIOMIMETIC ROBOTICS: PRINCIPLES, ACTUATORS, AND CHALLENGES

The study area of biomimetic robotics utilizes the concepts of human musculoskeletal systems and state-of-the-art robotic actuation mechanisms to create flexible and adaptable robots that are also highly energy efficient [7]. Methods like motion analysis, electromyography, AI-based control mechanisms, and biomechanical modeling can help in improving robotic motion, stability, and interaction. Though these methods are beneficial for rehabilitation robotics, prosthetics, and humanoid robots, there are still many obstacles left.

2.1 Human Musculoskeletal Kinematics

- **Structure of the Human Musculoskeletal System:** Biomechanical research has demonstrated the collaboration between bones, muscles, tendons, ligaments, cartilage, and joints in producing stable and efficient movements. The use of techniques like motion analysis and musculoskeletal modeling is common when studying locomotion and forces. Important characteristics include multi-degree of freedom and adaptive force control. This research is relevant for robotic system designs but poses challenges due to the complex nature of biological tissues.
- **Joint Biomechanics and Locomotion:** Investigations into joint mechanics through gait analysis and motion capture technologies have revealed that ball-and-socket joints enable multidimensional motion and that hinge joints facilitate unidirectional motion. Such

research enhanced joint design and mobility in robots. Robotic joints still cannot match the flexibility and adaptability of human joints [8].

- **Muscle Coordination and Force Generation:** The use of electromyography (EMG) and neuromuscular analysis indicated that the combined function of agonist, antagonist, and synergist muscles allows for stable motion. Muscles can generate force based on neural excitation, tendon elasticity, and muscle recruitment. Although these methods allow for muscle function analysis, robotic devices have not been able to emulate biological muscle adaptability.
- **Tendon Elasticity and Energy Efficiency:** Investigations into the biomechanics of tendons found that tendons are capable of storing and releasing energy, leading to enhanced energy efficiency. The study of the Achilles tendon led to the creation of series elastic actuators in robotics. Nevertheless, robots have not yet been able to replicate the tendon's ability to stretch and adapt to changing conditions.
- **Neural Control and Sensory Feedback:** The studies related to neural control mechanisms highlighted that humans regulate their movements by receiving sensory information via proprioception, vision, and vestibular organs. Neural control is involved in balancing, correcting errors, and planning motions. Increasingly, artificial intelligence is being applied to mimic neural control and sensory feedback processes.

2.2 High-Torque Robotic Actuation Systems

- **Electric Actuators:** Research done on electric actuators has indicated that the use of brushless DC motors and servo motors guarantees high positional accuracy, fast response and easy incorporation into a control system. Electric actuators are widely applied in humanoid robots and prostheses. Their advantages are highly accurate movement control while the drawbacks include overheating, low compliance and poor weight-to-torque ratio.
- **Hydraulic Actuators:** Literature on hydraulic actuators suggests the capability of hydraulic actuator systems to produce extremely high torques and operate in heavy robotics applications. Mechanical analysis research has identified excellent load-carrying capacity as a key benefit of hydraulic actuators. However, big size, leakage problems and difficult maintenance are their drawbacks [9].
- **Pneumatic Actuators:** Recent literature on pneumatic actuators revolves around the application of pneumatic systems in soft robotics and assistive robotics. The research revealed the advantages of pneumatic systems that include lightness, flexibility of movements and safe human interaction. Pneumatic artificial muscles demonstrate biological compliance as well. The disadvantages of pneumatic actuators are low accuracy and force control problems.
- **Series Elastic Actuators:** Research on series elastic actuators reveals that elastic elements offer enhanced force regulation, shock dampening, and motion smoothness. This class of actuators simulates tendon behavior and ensures safe human-robot collaboration. Its principal advantage lies in increased flexibility and energy efficiency, while its principal drawback involves complicated control.

- **Soft Robotic Actuators:** Research on soft robotics highlights the superiority of flexible actuators constructed from intelligent materials, which ensure enhanced adaptability and safe interaction with humans. This type of actuator finds increasing use in rehabilitation robotics and wearable robotic applications. The primary advantage is their biological tissue-like flexibility, while limited load-bearing capability and material durability problems represent key disadvantages ^[10].

2.3 Strengths and Weaknesses

Strengths

- **Human-Like Movement and Flexibility:** One of the significant advantages of biomimetic robots is their ability to mimic natural movements by humans. Scientific experiments about musculoskeletal kinematics reveal that the coordination between muscle tissues, tendons, and joints helps create smooth, adaptable, and efficient movements. The findings have led to advancements in humanoid robots, artificial limbs, and robotic exoskeletons.
- **Movement and Flexibility of Robotic Joints:** Experiments conducted about joint biomechanics have made substantial contributions to the creation of more flexible robotic joints. Motion capturing and gait analysis experiments have helped create robotic systems with better movement flexibility.
- **Advanced Muscle-Inspired Force Control:** Studying muscle coordination in humans with the help of EMG and neuromuscular studies has enhanced our knowledge regarding force production and stability in movement. Such advancements can be used to develop robotic actuators that will provide controlled movements ^[11].
- **Efficient Design of Actuators:** Through research on tendon biomechanics, it was discovered that tendons can act as a storage system for elastic energy while walking, thereby reducing energy expenditure. Such discoveries have been used to create compliant robots.
- **Enhanced Sensory Feedback and Adaptive Control:** Studies of neural control and sensory feedback have made robotic control more adaptive. With artificial intelligence and sensors, robots can maintain balance, plan their movements, and correct any errors that occur during movement execution.

Weaknesses

- **Difficulty in Replicating Human Tissue Complexity:** Among the major disadvantages of biomimetic robots are the failure to completely replicate the complexity, adaptability, and flexibility of human muscle, tendon, and ligament tissue. There is a degree of dynamic regulation within biological tissues which has not been achieved yet by current robotic materials.
- **Limited Adaptable Movement of Robotic Joint:** While robotic joint mechanism has advanced significantly over the years, there are still issues with their multidirectional adaptability and smooth movement. They usually involve simpler forms of rotational movements compared to biological tissues.

- **Replicating Neuromuscular Coordination:** Another issue with existing robotic technology is the challenge in replicating the coordination between agonist, antagonist, and synergist muscles in biological tissues. Neuromuscular control mechanism of human body is very adaptive to environmental conditions unlike those of current robotic control system.
- **Failure to Mimic the Elasticity of Tendons:** Current robotic technology does not allow for replication of the elasticity and energy recovery of human tendon.
- **Limitation of Sensory Processing:** While significant advancement has been made through artificial intelligence in enhancing robotic control system, sensory processing of robotic devices still fails to compete with the speed and accuracy of biological tissues.

3. BIOMIMETIC MAPPING TECHNIQUES AND ROBOTIC APPLICATIONS

Robotics biomimetics applies concepts of human motion, artificial intelligence, and biomechanics in designing adaptive robots that assist in rehabilitation, prosthetics, humanoid robotics, and industry. Even though robotics technology has advanced considerably, imitating human movement is difficult [12].

3.1 Biomimetic Mapping Techniques

Motion Capture Analysis

One of the most popular methodologies in biomimetics robotics is motion capture analysis that helps to understand patterns of human movements. Motion capture analysis makes use of cameras, reflectors, inertial measurement units, and computer systems that allow recording movements of the body with high accuracy. Motion capture systems give information about joint angles, limb positions, gaits, postures, and movements coordination. The collected data can be used by researchers to investigate various movements of humans including walking, running, lifting loads, and upper limb activities [13].

Movement data recorded using motion capture systems are widely used in fields such as humanoid robotics, prosthetic limb development, and rehabilitation robotics as the source of natural human motions trajectory. Moreover, motion capture analysis helps to enhance robot's stability, balance, and efficiency in movements. However, motion capture technology may require advanced equipment and controlled environments, which can increase costs [14].

Electromyography (EMG)

Electromyography, or EMG for short, is a neurophysiological and biomechanical method that can be employed to assess the electrical activity of muscles when they are contracting [15]. Data gathered from EMG tests helps determine muscle coordination, timing, and force production. The study of EMG in humans has greatly advanced our knowledge on the neuromuscular control of movements.

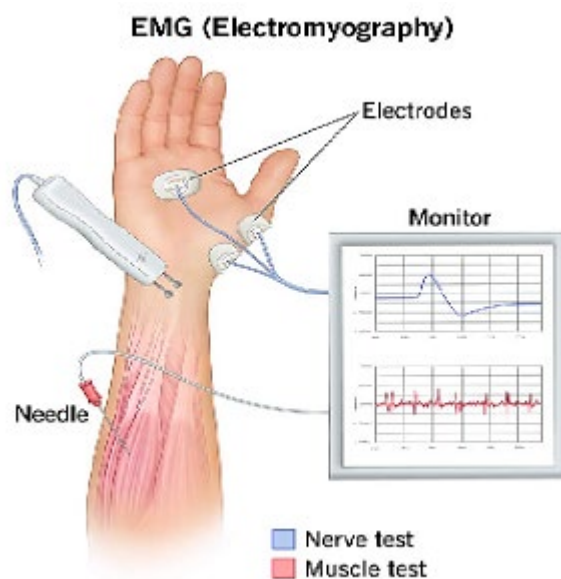


Figure 2: Electromyography (EMG) [16]

Robotics control systems based on EMG have been more commonly adopted in artificial limbs, exoskeletons, and other assistive robots. These robotics systems have the capacity to detect muscular signals and react according to them, hence providing more natural movement and interactivity for users. There is always a possibility that the quality of the signals received will be compromised due to muscle fatigue and other factors [17].

✚ Inverse Dynamics and Biomechanical Modeling

The process of inverse dynamics is a mathematical approach that involves the calculation of joint forces, torques, and loading using measured movements and forces [18]. Investigators frequently employ the use of motion capture techniques together with force platform measurement for estimating various biomechanical values in movement.

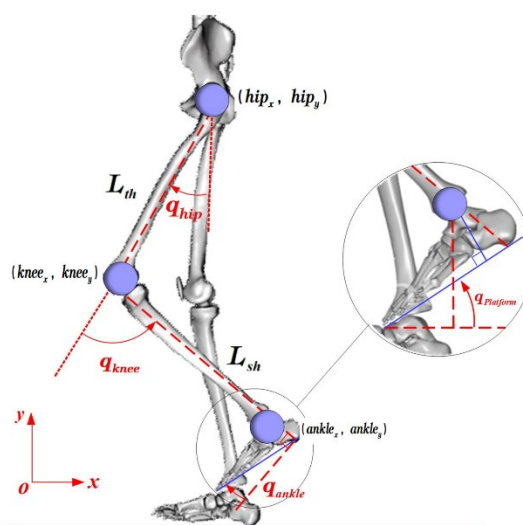


Figure 3: Inverse Dynamics [19]

Such approaches are of great importance in robotics system creation, as they aid engineers in optimizing the placement, movements, and force regulation within biomimicry robots. Furthermore, biomechanical simulation is useful in creating rehabilitation equipment and prosthesis systems. However, biological models used for such simulations can sometimes overlook specific details of human anatomy that could affect their representation of actual motion dynamics [20].

Artificial Intelligence-Based Control

Machine learning algorithms and AI are increasingly employed in biomimetic robotics for adaptive movements, sensory processing, and intelligent decision-making of robots. AI software analyses massive amounts of data collected using sensors, motion-capture tools, and EMG signals to enhance robotic capabilities [21]. By implementing machine learning algorithms, robots become capable of improving their ability to move accurately and flexibly by learning continuously.

Control systems that employ AI technology are very helpful when dealing with humanoid robots, prosthetic and rehabilitative devices, as well as other autonomous robotic applications, where movement adaptation is essential. These technologies facilitate better balance, obstacle avoidance, predictive movement planning, and interactions with humans. On the other hand, AI-based systems tend to require powerful computational power and extensive amounts of training data [22].

3.2 Comparative Analysis Between Human and Robotic Systems

Structural Comparison

Human musculoskeletal structure is characterized by complex, flexible, and adaptable muscular and skeletal frameworks. The biological nature of muscles implies that they are flexible and have self-regulated force mechanisms, which make movements more coordinated. However, the design of robotic devices depends largely on inflexible mechanical joints and controlled movement systems powered by actuators [23].

While the contemporary development of robotic technology tends to mimic biological structures using soft robots and compliant actuators, replicating the level of adaptability exhibited by human biological tissues is difficult.

Energy Efficiency

Human motion is very energy-efficient because of tendon elasticity, muscle synergy, and efficient neuromuscular control. Tendons store elastic energy while moving, hence minimizing the use of muscular energy. As a result, humans are able to engage in prolonged motions without utilizing much energy.

Robotic devices, particularly those that employ electric and hydraulic actuation mechanisms, require higher amounts of energy and produce more heat during sustained operations [24]. While innovations such as series elastic actuators and soft robotics have enhanced the energy efficiency of robots, existing robotic technologies have not yet been able to achieve the same level of efficiency exhibited by living beings.

Adaptability and Learning

Humans show an excellent ability to adapt their movements based on sensory information and neural control systems. The motor system of humans can quickly adapt their movements according to the environment, terrain, and obstacles that may occur unexpectedly.

Robotics also need to be programmed using artificial intelligence techniques to adapt to such changes. There have been improvements in robotics, particularly in machine learning systems, which have made robots better learners than before [26]. Nevertheless, robotics have slower adaptation speeds and less flexibility than humans.

Safety and Compliance

Natural muscle-tendon units have shock-absorbing qualities and force regulation characteristics, ensuring a lower incidence of injuries and better movement efficiency. The use of biomimetic robot designs with compliant actuators, pneumatic artificial muscles, and flexible robotics materials provides for safer robot-human interaction than conventional robotic systems.

It is particularly important when designing rehabilitation robotics, wearable exoskeletons, and collaborative robots. It should be noted that creating a system that can provide flexibility and robustness at the same time is quite difficult from an engineering perspective.

3.3 Applications of Biomimetic Robotics

Rehabilitation Robotics

There is an increased use of biomimetic robots in rehabilitation treatment for people suffering from neurological problems, musculoskeletal problems, and mobility issues. Robotic exoskeletons and aids assist patients to restore movement, improve gait performance, and enhance muscle coordination while undergoing rehabilitation.

The advantage of these robotic systems is that they provide repetitive movements to patients who are recovering from strokes and spinal cord injury.

Prosthetic Engineering

Modern prosthetic limbs incorporate biomimetic principles to provide more natural movement and improved user comfort. Advanced prosthetic systems integrate EMG sensors, artificial intelligence-based control systems, and compliant actuators to interpret muscular signals and generate coordinated movement.

These technologies improve prosthetic responsiveness, movement precision, and user adaptability. However, challenges such as high cost, limited battery life, and complex control mechanisms continue to affect widespread clinical accessibility.

Humanoid Robotics

Humanoid robots are built to emulate human gait, balancing, and interaction. Biomimicry is utilized to enhance locomotor stability, posture regulation, and coordination of limbs. Motion-capture studies, biomechanical models, and AI control systems are some approaches that have been applied for designing such robots [27].

Humanoid robots are widely utilized in healthcare support services, research applications, customer services, and dangerous conditions. The problem of replicating the entire spectrum of human movement and adaptability still persists.

Industrial Robotics

Man-made robotic devices are becoming more common within industrial settings that call for flexibility and precision movements in their processes. The use of biomimetic robots allows for efficient performance of various assembly, manipulation, and inspection operations.

Cobots, or collaborative robots, are robots that are programmed to operate in tandem with people. They have been built to ensure human safety during operations by incorporating compliant actuators and smart controllers. However, they continue to experience problems associated with high energy needs, maintenance costs, and costs of operation.

4. EMERGING INNOVATIONS AND FUTURE TRENDS IN BIOMIMETIC ROBOTICS

Recent developments in bio-inspired robots emphasize the use of soft biological materials, the development of adaptive mechanisms using artificial intelligence, human-robot interaction, and brain-computer interface technology to enhance flexibility and motion efficiency in robots. Nevertheless, there are still issues regarding energy efficiency, sustainability, and integration of sensing capabilities that need more exploration ^[28].

Soft Bioinspired Materials

The emerging technologies in the field of biomimicry robots involve developing bio-inspired soft materials. This is aimed at mimicking the flexibility and elasticity of human tissue. Smart polymers and shape memory alloys are some of the technologies being developed for use in robotics. Their application is increasing especially in wearable robotics and soft robotics.

Human–Robot Collaboration Systems

Modern bio-inspired robotic systems are being developed to function cooperatively with human beings in the medical, manufacturing, and assisting sectors. Improved sensors, flexible actuators, and intelligent control systems enhance safety and efficiency while interacting with human beings. Robotic collaboration is highly significant in the realms of therapeutic rehabilitation, industrial automation, and elder care assistance.

Brain–Computer Interface Integration

There have been advancements in brain–computer interface (BCI) technologies which can be seen to offer promise in biomimetic robotics applications. This technology allows interaction between the human nervous system and robotic machinery via neural processing. There have been studies involving BCIs being applied in the control of robotic devices among people with physical disabilities ^[39].

AI-Driven Adaptive Robotics

Technologies related to artificial intelligence and machine learning are proving to be extremely beneficial in enhancing the ability of robots to adapt and make decisions autonomously. Intelligent robotic systems have the ability to assess the environment and determine the needs of movement so that they can work optimally.

🌟 Future Challenges and Research Opportunities

Although there have been many developments in this area, a number of problems still exist in biomimetic robotics. These problems include the need to optimize energy usage, the ability to reduce the size of actuators, material endurance, and sensory feedback integration within real time. Future studies should concentrate on achieving biomechanical realism, simplifying the complexity of the design, and making robotic devices lighter and more adaptable ^[30].

Table 1: Summary of Literature on Biomimetic Robotics, Prosthetic Control, and Autonomous Robotic Systems ^[31]

Author(s) & Year	Study Focus	Methodology/Approach	Key Findings
Wang et al. (2025) ^[32]	Motion intention mapping and direct myoelectric control for prosthetic knees using LSTM networks	Pilot study integrating electromyographic signal analysis, LSTM networks, and human-machine coupling models	Reported that LSTM-based algorithms improved the accuracy, responsiveness, and adaptability of prosthetic knee movements. The study found that the human-machine coupling model enhanced coordination between users and prosthetic devices, enabling more natural and stable locomotion.
Wang et al. (2025) ^[33]	Differential-mechanism-based leg configuration for quadruped robots	Experimental mechanical design and actuator load-balancing analysis for robotic locomotion	Demonstrated that the differential leg mechanism effectively balanced load distribution among actuators and improved locomotion efficiency. The study highlighted enhanced energy efficiency, dynamic adaptability, and stability in quadruped robotic movement within complex environments.
Yan et al. (2024) ^[34]	Design, sensing, and autonomy of biomimetic robotic fish	Comprehensive review of fish-inspired robotic systems, sensing technologies, and autonomous mechanisms	Reported significant advancements in flexible body structures, propulsion systems, underwater sensing, and autonomous navigation. The study found that biomimetic robotic fish achieved improved

			maneuverability, energy efficiency, and adaptability for underwater exploration and monitoring applications.
Yan et al. (2024) ^[35]	Integration of sensing technologies and artificial intelligence in biomimetic robotic fish	Review of AI-driven sensing systems, machine learning algorithms, and autonomous robotic control strategies	Highlighted that advanced sensors and AI-based autonomy enhanced robotic perception, adaptive swimming, and obstacle avoidance capabilities. The study concluded that intelligent sensing and soft robotics technologies would further expand practical underwater robotic applications.
Yang (2023) ^[36]	Design and investigation of a biomimetic anthropomorphic robotic arm with human-like biomechanical capabilities	Empirical research involving robotic engineering, biomechanical modeling, and performance evaluation	Reported that the robotic arm achieved enhanced dexterity, flexibility, and coordinated movement patterns similar to human upper limbs. The study demonstrated that biomimetic joint structures improved motion precision and operational efficiency for rehabilitation, prosthetics, and industrial automation applications.

5. DISCUSSION

The field of biomimetic robotics has contributed significantly to the improvement of robotic mobility, flexibility, and human-robot interactions through the combination of human biomechanics, artificial intelligence, and modern actuators. Nevertheless, there are still many obstacles to achieving full adaptation, sensory coordination, and energy conservation by the human body's musculoskeletal system ^[37].

5.1 Interpretation and Analysis of the Findings

From the literature review findings, it is apparent that significant strides have been made in biomimetic robotics through incorporation of musculoskeletal biomechanics and actuation technologies and AI. From research involving human musculoskeletal biomechanics, it was found out that coordination among bones, muscles, ligaments, tendons, and neurological system

provides for efficient, adaptive, and flexible movement [38]. Techniques used in biomimicry such as motion capture, EMG, inverse dynamics, and biomechanical modeling have greatly aided in understanding human movement and developed robotic devices that can mimic the natural human movements. Moreover, highly torqued actuators such as electric, hydraulic, pneumatic, series elastic, and soft robotic actuators have been instrumental in enhancing robotic efficiency and flexibility.

5.2 Implications and Significance

The combination of biomechanics, robotics, and artificial intelligence carries great significance within the fields of healthcare rehabilitation, prosthetics engineering, industry automation, and humanoid robotics. The use of biomimetic robotic technology has facilitated advancements in rehabilitation processes through adaptive motion assistive and personalized therapeutic procedures for individuals with neuro-musculo-skeletal conditions [39]. Modern prosthetic devices that utilize EMG sensors and AI-controlled mechanisms have enhanced naturalness of motion, user comfort, and restoration of motor abilities. Within industry, the introduction of collaborative robots with compliant actuators and intelligent control systems has increased workplace safety and efficiency. Furthermore, future technologies like soft bioinspired structures and brain-computer interfaces hold substantial promise for enhancing robotic adaptation and sensor integration.

5.3 Gaps, Limitations, and Future Research Directions

Although great progress has been made, there are also several drawbacks and areas that need further investigation in biomimetic robotics. Modern robotic systems do not yet provide full imitation of the flexibility, adaptability, sensory coordination, and energy savings of the human musculoskeletal system. Robot joints have poor multidirectionality and biomechanical compliance compared to biological joints, whereas robotic actuators have problems with imitation of elastic and energy-saving properties of human muscles and tendons. Moreover, robotic systems with an artificial intelligence component require large amounts of computational power, data, and sensor integration and thus become more complex and expensive to develop [40]. There are also some limitations in terms of actuator miniaturization, material wear resistance, energy storage, and sensory processing. Therefore, future research should be aimed at the creation of lightweight, energy-saving, and adaptive robotic systems through application of new soft bio-inspired materials, compliant actuators, sensory feedback systems, and artificial intelligence.

6. CONCLUSION

This research concludes that the field of biomimetic robotics is a very promising interdisciplinary approach that integrates the study of human musculoskeletal biomechanics with artificial intelligence and advanced robotic actuation systems for the development of adaptive, flexible and energy efficient robotic technologies. The review showed that biomimetic mapping methods like motion capture analysis, electromyography (EMG), biomechanical modeling and AI-based control systems have made significant advances in the precision of robotic movement, integration of sensory data and human-robot interaction. Robotic actuators, such as electric, hydraulic, pneumatic, series elastic, and soft robotic actuators, with a high torque have

additionally boosted applications in rehabilitation robotics, prosthetic engineering, humanoid robotics and industrial automation. However, existing robotic systems have limitations in mimicking all of these elements of the human musculoskeletal system, namely: complexity, adaptability, Sensorimotor coordination, and energy efficiency. However, further research is needed to create safer, light-weight and highly adaptive robotic systems with advanced soft materials, intelligent control mechanism, energy efficient actuator, and real-time integration of sensory system for more human-to-robot interaction in next-generation biomimetic robotic systems.

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