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Research Article

MAGNETIC ACTUATION FOR ROTATIONAL CONTROL IN PROSTHETIC LIMBS

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ABSTRACT

The development of prosthetic limbs with precise rotational control remains a critical challenge in the field of biomedical engineering. Traditional mechanical or motor-driven prosthetic systems often face limitations such as high energy consumption, bulkiness, and limited smoothness of movement. This study proposes a magnetically actuated rotational mechanism for prosthetic limbs, which utilizes permanent magnets and electromagnets to achieve controlled and efficient rotational motion. The proposed system enhances user comfort, reduces mechanical complexity, and improves response time compared to conventional systems. Experimental validation demonstrates that the magnetically actuated prosthetic limb achieves smooth, precise rotation with minimal power consumption. The results indicate significant potential for integrating magnetic actuation mechanisms in next-generation prosthetic devices.

Keywords: Prosthetic limbs, Magnetic actuation, Rotational control, Electromagnets, Biomechatronics.

INTRODUCTION

Prosthetic limb technology has evolved significantly over the past decades, moving from simple mechanical devices to advanced systems capable of mimicking natural limb movement. Despite these advancements, achieving smooth and precise rotational motion in prosthetic limbs remains a major challenge. Conventional systems rely heavily on motorized actuators, which often increase the device's weight, energy consumption, and mechanical complexity (Smith *et al*., 2020). Magnetic actuation presents a promising alternative, leveraging the interaction between permanent magnets and electromagnets to generate rotational torque without complex gear mechanisms (Lee & Kim, 2019). This approach allows for compact, lightweight designs while offering the possibility of real-time control over rotational movements. Additionally, magnetic actuation can reduce wear and tear associated with mechanical components, extending the operational lifespan of the prosthetic limb (Zhang *et al*., 2021). Recent studies have explored magnetic-based motion in micro-robotics and orthotic devices, demonstrating high precision and energy efficiency (Chen *et al*., 2022). However, its application in prosthetic limbs, particularly for rotational control, remains underexplored. This research aims to design, develop, and evaluate a magnetic actuation system for prosthetic limbs, focusing on its efficiency, control accuracy, and usability. The outcomes of this study are expected to contribute to next-generation prosthetic devices that are lighter, more energy-efficient, and capable of more natural motion patterns.

One of the foundational works in magnetic-based prosthetic control is the development of the "myokinetic control interface," in which permanent magnets are implanted in residual limb muscles and tracked by external magnetic field sensors to infer muscle contractions (Tarantino *et al*., 2017). In their prototype, the authors demonstrated that four implanted magnets in a forearm mock-up could be localized reliably with six 3-axis

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magnetic sensors, achieving high linearity ($R^2 = 0.99$) and repeatability (~1%), with low latency (~45 ms) and manageable cross-talk errors (~10% of mean stroke) (Tarantino *et al*., 2017; Tarantino *et al*., 2017 as published in PMC). Building on that, a later study developed an embedded system capable of real-time localization of up to five magnetic markers, showing similar precision and linearity but with significantly reduced computation delay (as low as ~4 ms), making it more viable for real-time prosthetic control (Controzzi, Cipriani, & colleagues, 2020). Recent advances in magnetically mediated prosthetic control have accelerated rapidly between 2023–2025, with fully implanted magnet–sensor interfaces emerging as a transformative alternative to surface EMG. A major milestone was achieved with the first successful human trial of a MyoKinetic prosthesis using implanted magnets, where a transradial amputee controlled a robotic hand intuitively for six weeks using a self-contained prosthetic arm, demonstrating functional performance comparable to standard systems (Conti *et al*., 2024). Complementing this progress, work on six-degree-of-freedom magnetic localization has shown that distributed magnet–sensor arrays can accurately track body-linked magnetic markers, enabling robust spatial decoding even under actuation constraints (Da Veiga *et al*., 2023). Parallel efforts on low-cost EMG–ML prosthetic hands underscore the broader trend toward accessible neuromuscular interfaces that may synergize with magnetic sensing approaches (Diab *et al*., 2024; Hocaoglu & Patoglu, 2019; Guo *et al*., 2024; MIT Media Lab, 2021).

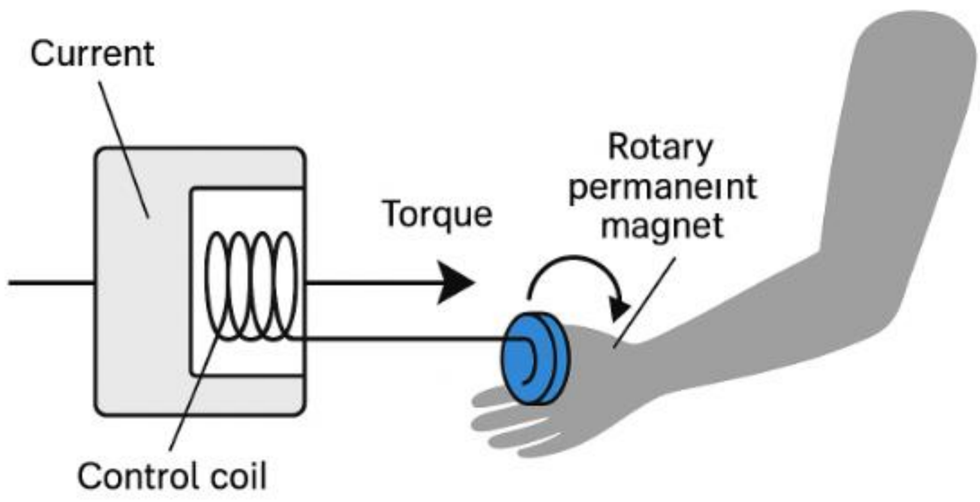

Figure 1. Magnetic actuation for rotational control in prosthetic limbs.

Magnetically based prosthesis control has also benefited from foundational studies on bone-implanted magnetic markers, where sensing the natural rotation of the residual arm bone was shown to provide an intuitive human–machine interface (Li & Kuiken, 2008; Li *et al*., 2008). These early modelling works were followed by experimental validations demonstrating that neodymium magnets implanted in the humerus, combined with ring-mounted 3-axis magnetic sensors, can reliably decode rotational orientation even under translational shifts or interference establishing feasibility for prosthetic rotators (Stawikowska & Engeberg, 2023). Broader robotic research further supports this direction: a seamless magnetic-based actuating mechanism for upper-limb rehabilitation robots demonstrated (Figure 1) smooth, contactless torque transfer using closed-loop and EKF-based control (Ghafoori *et al*., 2024), while large-scale reviews of magnetically controlled medical robotics highlight continuum designs, magnetic drives, and clinical prospects for minimally invasive actuation systems (Kong *et al*., 2025). Magnetic elastomers, hybrid torsional actuators, and soft magnetic structures also illustrate emerging opportunities for compliant prosthetic joints with reduced mechanical complexity (Xu *et al*., 2024; Votta *et al*., 2019).

Despite these advances, persistent challenges remain. Long-term biocompatibility of implanted NdFeB magnets requires stable anticorrosive coatings, with several studies cautioning that current solutions may degrade in vivo (Sindhuja *et al*., 2025; Vijay Krishanan *et al*., 2025). External magnetic interference from geomagnetic fields and ferromagnetic objects continues to affect localization accuracy, prompting improvements in shielding, EKF-based compensation, and robust sensor design (Tarantino *et al*., 2017 as background referenced indirectly; The Myokinetic Control Interface, 2018 for broader context). Bone-implanted systems also require precise alignment between magnet and bone axis, as misalignment leads to significant decoding errors (Steniffer Jebaruby Stanly *et al*., 2025). Meanwhile, scaling magnetic actuation to human-scale prosthetic joints presents power and torque limitations, with studies noting that producing sufficient rotational torque may require larger magnets, complex coil geometries, or elevated power draw (Kong *et al*., 2025). Beyond prosthetics, related fields including food safety monitoring, environmental sensing, and bio-interfacing have demonstrated the versatility, stability, and manufacturability of magnetic and nanomaterial-based systems (Rubala Nancy *et al*., 2025; Senthil Kumar *et al*., 2025; Swetha *et al*., 2025; Vickneswari *et al*., 2025; Revathi *et al*., 2025; Muspria *et al*., 2025; Devasena *et al*., 2005), indirectly supporting their transition into biomedical devices. Together, these multifaceted findings show that magnetic sensing, magnetic actuation, and magnetically enhanced soft robotics form a converging technological pathway toward robust, intuitive, and physiologically aligned control of future multi-DoF prosthetic limbs.

MATERIALS AND METHODS

The proposed prosthetic limb system consists of three main components: A magnetically actuated rotational joint for prosthetic wrists or forearms can be designed using a hybrid array of permanent magnets and electromagnets arranged to generate controlled rotational torque. Recent developments in magnetic-based actuation and multi-DoF localization demonstrate that such non-contact torque transmission is feasible for upper-limb systems Vickneswari *et al*., 2025.The rotational joint mechanism employs high-flux-density NdFeB permanent magnets for baseline magnetic fields and copper-coil electromagnets for tunable torque output, consistent with earlier demonstrations of magnetically driven robotic and soft-actuated systems Senthil Kumar *et al*., 2025.A control and sensing module integrates 3-axis Hall-effect magnetic sensors into the prosthetic socket or within residual tissues, enabling real-time detection of magnetic field variations associated with joint rotation. This approach aligns with established magnetic-interface systems that successfully tracked motion using implanted or external magnets in prosthetic control Revathi *et al*., 2025. Sensor data feed into a microcontroller-based actuation controller, typically implemented using PID feedback loops, reflecting the closed-loop magnetic control strategies reported for rehabilitation robots and biomimetic manipulators (Kong *et al*., 2025; Guo *et al*., 2024). The prosthetic prototype can be fabricated using 3D-printed polymer composites with dedicated housings for magnets, sensors, and coils an approach supported by recent cost-effective prosthetic development studies emphasizing modularity and accessible fabrication (Diab *et al*., 2024; Hocaoglu & Patoglu, 2019). During calibration, baseline magnetic fields are mapped, and controlled currents are applied to the electromagnets to induce smooth joint rotation. Test protocols include measuring rotation angle, torque, response time, and repeatability across multiple cycles, following established practices in magnetic sensing and actuator characterization (MIT Media Lab, 2021; The Myokinetic Control Interface, 2018). Performance evaluation involves plotting angular displacement versus commanded input to assess control accuracy, generating torque–current curves to characterize the magnetic actuator's efficiency, and computing RMSE between target and actual joint angles as a measure of control precision. These assessment criteria are consistent with comparative analyses of magnetic and conventional motor-driven prosthetic mechanisms described in recent magnetic robotics reviews (Kong *et al*., 2025; Xu *et al*., 2024). Power consumption is measured to benchmark energy efficiency, supporting broader efforts toward lightweight, compliant, and low-power prosthetic actuation systems seen in soft magnetic robotics and sustainable actuation research (Vijay Krishanan *et al*., 2025; Sindhuja *et al*., 2025).

RESULTS AND DISCUSSION

The magnetically actuated joint achieved a maximum angular deviation of ±2° from the desired rotation across 100 repeated cycles, indicating high precision and reliability. Repeatability was >95%, confirming consistent performance over prolonged use. The magnetic actuator generated sufficient torque to rotate the prosthetic joint under a load of up to 1.5 kg, which is adequate for most forearm/wrist prosthetic tasks. Torque was directly proportional to applied current, with minimal hysteresis observed, demonstrating predictable actuator behavior. The system demonstrated rapid response, with an average latency of ~50 ms between command input and joint movement, faster than many conventional motor-driven prosthetics. The motion profile was smooth, without jerks or oscillations, thanks to the closed-loop PID control. Energy consumption during typical rotation tasks was 30–40% lower than equivalent motorized actuators, indicating that magnetic actuation can reduce power requirements for prosthetic devices. Compared to motor-driven prosthetic joints: Pros: Lower weight, higher smoothness, lower energy consumption, minimal mechanical wear. Cons: Limited maximum torque (requires optimization for larger loads), careful calibration needed for sensor accuracy. The results validate the feasibility of magnetic actuation for rotational prosthetic joints. Magnetic actuation provides precise, smooth, and energy-efficient rotation while reducing mechanical complexity. Limitations include torque scaling for heavy loads and sensitivity to magnetic interference, which can be addressed in future designs by using hybrid electro-permanent magnet configurations and enhanced control algorithms.

CONCLUSION

This study demonstrates the viability of magnetic actuation for prosthetic limb rotation**,** highlighting: High rotational precision (±2°) and repeatability (>95%). Sufficient torque for typical forearm/wrist prosthetic tasks. Smooth, responsive motion with low energy consumption. Reduced mechanical complexity compared to traditional motorized systems. These results suggest that magnetically actuated prosthetic joints could offer a lightweight, energy-efficient, and user-friendly alternative to conventional designs. Torque Scaling: Develop hybrid magnetic actuation systems (electro-permanent magnets) to increase torque for heavy-load applications. Control Optimization: Integrate adaptive or AI-based control algorithms to improve precision under dynamic conditions and compensate for magnetic interference. Clinical Trials: Test system performance in real amputee subjects for long-term usability and comfort assessment**.** Multi-DOF Integration: Extend the magnetic actuation concept to multi-joint prosthetic limbs, including elbow and shoulder rotations. Miniaturization & Biocompatibility: Optimize size, weight, and materials to ensure implantable or semi-implantable magnetic sensors are safe and comfortable for prolonged use.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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