Title

Enhancing Lower Limb Prosthetic Performance: A Detailed Analysis of the BirdBot Model and Its Instrumentation

Authors
Rahai, Tara
Singh, Sukriti
Kim, Jiho
et al.

Publication Date
2024-10-01

Enhancing Lower Limb Prosthetic Performance: A Detailed Analysis of the BirdBot Model and Its Instrumentation

Sukriti Singh, Jiho Kim, Jennifer Yu, Alinna Villaroman

Research Mentor: Tara Rahai

Public Health and Health Sciences Undergraduate Laboratory at Berkeley

University of California Berkeley

Table of Contents

I. Abstract

There exists a notably high level of dissatisfaction among lower-limb amputee patients fitted with their affiliated prosthetics. Approximately 40%-60% of amputee patients have been surveyed as dissatisfied with their prostheses[1]. Fifty-seven percent are dissatisfied with the comfort of their prostheses, and over 50% report pain while using their prostheses[2]. Rejection of the prosthesis can be seen as the ultimate expression of dissatisfaction with the prosthesis and occurs in up to 31% of cases of prostheses prescribed to armed forces service members with lower limb amputations, mainly as a result of technical problems (e.g., "too much fuss" during use and the prosthesis being "too heavy")[3]. As a solution to this significant surveyed dissatisfaction, our study attempts to utilize a unique model known as the 'BirdBot Model'–a lower limb prosthetic model inspired by the biomechanics of emu and ostrich (flightless birds) leg limbs– to explore how the model's design, movement capabilities, and calculated stability can be applied to improve prosthetic limb functionality for human lower-limb amputee patients[4]. Current literature suggests little on this topic as this model was made for the initial intention of mimicking the emu/ostrich leg movement. Our study aims to consolidate the available information on this model and highlight its mechanistic potential to improve human lower limb movement, encouraging further investigation into its application for enhancing prosthetic efficiency.

[1] Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296
[2] Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296
[3] Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296
[4] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

II. Introduction

This review focuses on analyzing the avian biomechanical mechanisms as represented in the BirdBot model to enhance lower limb prosthetic outcomes. This model showcases an energy-efficient gait inspired by the intrinsic mechanics of emu and ostrich legs, specifically through an avian-inspired leg clutching mechanism. By exploring the model's mechanistic features, we aim to identify how these principles of movement can be applied to human model prosthetic design to improve comfort, functionality, and user satisfaction.

III. Challenges in Agile-Legged Locomotion

Agile-legged locomotion in robots remains a significant challenge at the forefront of robotics research[5]. No current bipedal robot can run quickly, untethered, in natural environments over long distances, unlike many terrestrial animals that accomplish these activities with apparent ease. This disparity highlights the complexity of legged locomotion, which requires robust control of leg-substrate interaction forces amidst terrain variations and sensorimotor noise. Innovations are necessary to design legged robots that achieve low energy consumption locomotion with robust mechanics and simple control[6]. Such systems must handle external perturbations faster than communication delays and actuator response times, minimizing dependence on high-speed communication and sensor quality.

In biological systems, legged animals coordinate joint actuation through antagonistic pairs of muscles controlled by spinal sensorimotor circuits, functioning as "myotatic units."[7] This

[5] Hwangbo, J., Lee, J., Dosovitskiy, A., Bellicoso, D., Tsounis, V., Koltun, V., & Hutter, M. (2019). Learning agile and dynamic motor skills for Legged Robots. *Science Robotics*, *4*(26). https://doi.org/10.1126/scirobotics.aau5872

[6] Silva, A. B., Murcia, M., Mohseni, O., Takahashi, R., Forner-Cordero, A., Seyfarth, A., Hosoda, K., & Sharbafi, M. A. (2024). Design of low-cost modular bio-inspired electric–pneumatic actuator (epa)-driven legged robots. *Biomimetics*, *9*(3), 164. https://doi.org/10.3390/biomimetics9030164

[7] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

concept is mimicked in the Birdbot Model, where joint extension and flexion are controlled by separate actuators at each joint, often through complex, optimized algorithms reliant on internal robot models and rapid sensory feedback loops[8]. Phase transitions in the model are controlled through contact and load sensors at the feet or within the leg structure, or through "proprioceptive" sensing within the actuator's electrical circuits[9]. Fast sensory feedback and communication allow the model to transition smoothly through gait cycles and react to unforeseen perturbations. Evidence suggests the potential for embodied, intrinsic mechanics and interjoint mechanical coupling in vertebrates' legs to simplify control[10]. Multiarticular muscle-tendon coupling can also facilitate energy transfer between joints and improve efficiency by allowing muscles to work closer to optimal length and velocity.

Passive mechanical walking robots, which operate with minimal actuation under open loop control, have illustrated principles for walking by identifying sources of energy loss and fluctuation[11]. Despite their efficiency, these robots are limited to flat, smooth terrain and are sensitive to small perturbations. In contrast, BirdBot demonstrates how an avian-inspired linkage mechanism can replace much of the neural circuitry required for leg control, using a multiarticular spring network to guide leg trajectory and provide rapid phase transitions between stance and swing. Inspired by large ground-moving birds like emus and ostriches, BirdBot's design achieves consistent inter-joint coordination and economical gait with minimalistic feedforward control, offering a promising model for improving the agility and efficiency of legged robots.

---

[8] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

[9] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

[10] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

[11] Tedrake, R., Zhang, T. W., Ming-fai Fong, & Seung, H. S. (2004). Actuating a simple 3D passive dynamic Walker. *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*. https://doi.org/10.1109/robot.2004.1302452

IV. Birdbot Model Mechanistic Features and its Application to Prosthetics

The BirdBot model employs a multiarticular spring tendon network designed to support locomotor loads during stance, coordinate mechanical load transfer among joints, and enable automatic phase transitions between stance and swing[12]. This approach mimics the biomechanics of bird legs, using a global spring tendon (GST) and a dedicated tendon disengagement mechanism to achieve efficient, natural movement. The distal segment of BirdBot's leg (the foot) leverages the global spring tendon to automatically adjust joint states during touchdown, distributing torques among joints during stance. A bistable joint mechanism facilitates the transition from stance to swing by utilizing elastically stored energy[13]. This design ensures coordinated leg flexion during the swing and creates sufficient ground clearance for swift leg protraction. BirdBot's mechanical design, detailed in Badri-Spröwitz et al. (2022), is minimally actuated with two actuators per leg—hip joint protraction and retraction and knee flexion actuators—controlled in feedforward mode[14].

The BirdBot model demonstrates how intrinsic mechanical coupling can replace complex neural control, as observed in existing human prosthetics. In animals, joint actuation is coordinated through antagonistic muscle pairs controlled by spinal sensorimotor circuits, functioning as "myotatic units"[15]. This principle is applied in BirdBot by controlling joint extension and flexion through separate actuators at each joint, managed by optimized algorithms that rely on internal robot models and rapid sensory feedback loops. Phase transitions in BirdBot are controlled by contact and load sensors within the leg structure, enabling smooth transitions

[12] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

[13] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

[14] Mo, A., Izzi, F., Gönen, E. C., Haeufle, D., & Badri-Spröwitz, A. (2023). Slack-based tunable damping leads to a trade-off between robustness and efficiency in legged locomotion. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-30318-3

[15] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

through the gait cycle and reactions to unforeseen perturbations. Measurements of joint angular coupling in an emu cadaver leg validated the mechanical principles underlying BirdBot. By manually flexing and extending the ankle joint, researchers observed strong coupling with the tarsometatarso-phalangeal (TMP) joint, confirming the passive mechanical connectivity in bird limbs. This evidence supports the hypothesis that multiarticular tendon networks can facilitate coordinated joint movement without active neural control. The mechanical coupling of distal joints in the ratite leg is significant, with the ankle and TMP joints showing a correlation coefficient of 0.96 for extension and 0.99 for flexion[16]. This strong coupling indicates that the passive elasticity of tissues can effectively coordinate joint movements, a principle that BirdBot successfully replicates.

The model's leg design incorporates a spring-loaded pantograph mechanism to stabilize the leg and provide compliance in the leg angle direction[17]. The GST coordinates the motion of all leg joints during stance and transitions them to a flexed position during swing. This mechanism ensures consistent load distribution among joints, preventing catastrophic failures and supporting elastic energy cycling. When the leg is unloaded, the distal joint is released from its clutched, digital-extended position, allowing the GST to become slack and the leg joints to become loose. This transition is crucial for achieving rapid, low-resistance leg flexion during swing, reducing the effort required for leg retraction, and improving ground clearance. The stance-to-swing transition in BirdBot involves a rapid switch from a load-carrying leg to a configuration with all joints slack, allowing quick leg shortening with low resistance. This is achieved through a tendon disengagement mechanism that reduces the work and power required

---

16 Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

17 Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

for leg disengagement. During stance, a joint hard stop allows angles close to its snap-through angle, and a biarticular disengagement flexor tendon (DFT) wraps around the joints, loading the DFT increasingly during stance. In the late stance phase, the DFT's force pushes the joint over its snap-through angle, slacking the GST and rapidly transitioning the leg into the swing phase. This design mimics the natural disengagement mechanics observed in birds and is critical for efficient gait transitions.

BirdBot's observed gait patterns emerge naturally from its mechanical design, with the robot's foot already in the air when the femur angle switches from protraction to retraction. At a stride frequency of 1.5 Hz, BirdBot reaches a speed of 0.75 m/s, demonstrating effective leg retraction and propulsion[18]. The knee actuator applies minimal torque during swing, significantly lower than what would be required in a non-clutching design, illustrating the efficiency of the BirdBot model.

V. Enhancing Human Lower Limb Prosthetic Outcomes Using the BirdBot Model

BirdBot achieves consistent inter-joint coordination and rapid, automatic control of stance and swing transitions through its innovative leg design. The rapid transition to swing is facilitated by the action of the spring tendon network on a bistable joint, which disengages the stance leg spring. This mechanism ensures stable and efficient gait patterns without the need for complex control algorithms. Applying this principle to prosthetic limbs can greatly enhance their stability and ease of use. For instance, a prosthetic leg incorporating BirdBot's bistable joint mechanism could automatically adjust to different phases of movement, providing a smoother

[18] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

and more natural gait for the user. This automatic adjustment would not only improve the user's walking efficiency but also reduce the risk of falls and injuries, enhancing overall safety.

BirdBot's leveraged global spring tendon (GST) also allows for the distribution of torques among joints during stance, ensuring compliant bodyweight support with elastic energy cycling. This mechanism allows for efficient energy storage and release, mimicking the natural dynamics of bird locomotion. Measurements of joint angular coupling in an emu cadaver leg confirmed strong passive mechanical connectivity, with correlation coefficients of 0.96 for extension and 0.99 for flexion. In prosthetic limbs, similar load distribution mechanisms can reduce the strain on individual joints and enhance overall limb durability. By incorporating elastic energy cycling, prosthetic limbs can store and release energy during movement, reducing the metabolic cost for the user. This would make prosthetics more efficient and less tiring to use, significantly improving the quality of life for amputees.

BirdBot’s design is inspired by the structural features of emus and ostriches, which have an elevated digitigrade posture and a long tarsometatarsus segment. These features enable effective load-bearing and energy efficiency. The model's multiarticular network of ligaments and tendons, combined with sesamoid bones and sheaths to guide slack tendons, creates a robust and flexible leg structure. Integrating these bioinspired features into prosthetic limb designs can enhance their functionality and adaptability. For example, using a similar multiarticular tendon network in prosthetics can provide better support and flexibility, allowing for more natural movements. The inclusion of sesamoid structures can improve joint stability and reduce wear and tear, extending the lifespan of the prosthetic.

The model also demonstrates the feasibility and benefits of bioinspired designs for prosthetics, achieving economical COT and robust mechanics with simple control systems. This efficiency is crucial for developing prosthetic limbs that minimize user effort and energy expenditure. BirdBot's success in reducing the knee-flexing torque to a tenth of that required by non-clutching leg designs, such as the Cheetah-cub robot[19]. This efficiency is particularly important for prosthetic users, as it translates to less energy consumption and greater comfort, reducing the physical and cognitive burden on users.

Incorporating these principles into prosthetic limb designs can greatly enhance their functionality and user experience. For instance, a prosthetic leg incorporating BirdBot's bistable joint mechanism could automatically adjust to different phases of movement, providing a smoother and more natural gait for the user. This automatic adjustment would not only improve the user's walking efficiency but also reduce the risk of falls and injuries, enhancing overall safety. Additionally, integrating elastic energy cycling into prosthetic limbs can store and release energy during movement, reducing the metabolic cost for the user and making prosthetics more efficient and less tiring to use, significantly improving the quality of life for amputees.

By mimicking these natural mechanisms, BirdBot can provide insights into enhancing prosthetic limb designs. The robot's ability to achieve a stable and efficient gait with minimal control input suggests that similar principles can be applied to prosthetics, improving their functionality and user experience. For instance, incorporating a multiarticular spring tendon network in prosthetic limbs can provide better load distribution and energy efficiency, reducing

[19] Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

the physical and cognitive burden on users. The inclusion of sesamoid structures can also improve joint stability and reduce wear and tear, extending the lifespan of the prosthetic.

VI. Conclusion

Future research should focus on refining these bioinspired mechanisms and testing their efficacy in human prosthetic applications. Hybrid designs that combine BirdBot's passive mechanical control with direct actuation and sensory feedback could merge the benefits of both systems, achieving even greater efficiency and functionality. BirdBot's success in achieving economical COT and robust mechanics with simple control systems offers a promising blueprint for future prosthetic designs. By reducing the need for complex sensory feedback and high-powered actuation, these bioinspired prosthetics could be more accessible and affordable, particularly benefiting users in low-income regions. This approach aligns with modern perspectives on muscle synergies controlling functional modules for whole-leg tasks, such as leg stiffness, bodyweight support, propulsion, and balance correction. The potential applications of BirdBot's design extend beyond robotics to prosthetics and exoskeletons.

References

1. Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296

2. Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296

3. Baars, E. C., Schrier, E., Dijkstra, P. U., & Geertzen, J. H. B. (2018). Prosthesis satisfaction in lower limb amputees. *Medicine*, *97*(39). https://doi.org/10.1097/md.0000000000012296

4. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

5. Hwangbo, J., Lee, J., Dosovitskiy, A., Bellicoso, D., Tsounis, V., Koltun, V., & Hutter, M. (2019). Learning agile and dynamic motor skills for Legged Robots. *Science Robotics*, *4*(26). https://doi.org/10.1126/scirobotics.aau5872

6. Silva, A. B., Murcia, M., Mohseni, O., Takahashi, R., Forner-Cordero, A., Seyfarth, A., Hosoda, K., & Sharbafi, M.

7. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

8. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

9. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

10. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

11. Tedrake, R., Zhang, T. W., Ming-fai Fong, & Seung, H. S. (2004). Actuating a simple 3D passive dynamic Walker. *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*. https://doi.org/10.1109/robot.2004.1302452

12. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

13. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

14. Mo, A., Izzi, F., Gönen, E. C., Haeufle, D., & Badri-Spröwitz, A. (2023). Slack-based tunable damping leads to a trade-off between robustness and efficiency in legged locomotion. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-30318-3

15. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

16. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

17. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

18. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055

19. Badri-Spröwitz, A., Aghamaleki Sarvestani, A., Sitti, M., & Daley, M. A. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Science Robotics*, *7*(64). https://doi.org/10.1126/scirobotics.abg4055