Board 14: Work in Progress: Exploring the Integration of Bio-Inspired Design Inventions in Biomedical Engineering

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Abstract

In this work-in-progress exploratory study, we conducted a literature search and thematic analysis of biologically inspired prosthetics designed to improve functionality for people with injuries and disabilities. The findings revealed that many more biologically inspired prosthetics have been designed for the upper body, such as hands and fingers, than for the lower body.

Introduction

Engineering problems in this modernized world require solutions that are efficient, sustainable, and structurally flexible. As a result, engineers are developing the concept of emulating the mechanisms underlying desirable characteristics in biotic organisms to solve complex problems [1], [2]. This process is referred to as biologically inspired design (BID), biomimicry, bionics, and biomimetics [1]. BID is the application of knowledge of biological systems in research and development to solve technical problems and develop technical inventions and innovations. It is a multidisciplinary approach to problem-solving that uses analogies to biological systems to derive innovative solutions. This approach to problem-solving "leverages the billions of biological designs already existing in nature" [1, p. 229].

Background

Biologically Inspired Design (BID)

Biologically inspired design (BID) has been a source of inspiration for many engineering solutions for years [3]. For instance, Japan's bullet train was inspired by Kingfisher birds to eliminate the sonic boom issue and decrease noise pollution [2]. George de Mestral invented the famous Velcro after getting tired of continually removing burrs from his dog and himself after walking outside [2]. While successful examples of bio-inspired designs are numerous, the majority have either been a result of chance observations that eventually found a problem like Velcro or of very dedicated and problem-motivated studies like the bullet train [2]. Nonetheless, the more substantial benefits of BID include the development of prosthetics that closely mimic real limbs and sensory-enhancing microchips that are interfaced with the brain to assist in hearing, seeing, and controlling instruments [4]. Consequently, this robust and multifunctional strategy is gaining traction in engineering research for design creativity and industry.

Studies have also been conducted to understand the needs of amputees and individuals with disabilities to provide insights into the development of prosthetics to address their needs effectively [5], [6], [7], [8]. Asano et al. [9] have researched a novel musculoskeletal humanoid knee joint to achieve three key functions in the human knee joint: rolling and sliding patella movement and screw-home mechanism. As interest in BID grows in engineering education, it is imperative to explore the various bio-engineering systems that have been inspired by nature, particularly in the design of prosthetics.

The purpose of this work-in-progress study is to survey BID-inspired prosthetics designed for individuals with disabilities and injuries. Thus, in this WIP exploratory study, we aim to conduct a literature search and thematic analysis of BID-inspired prosthetics designed to improve functionality for people with injuries and disabilities.

Methods

Literature search

With the increasing number of publications in BID, searching even with well-defined criteria is difficult. Therefore, we decided to focus on research publications collected on one of the most widely used and accessible web-based databases for this study. The literature search was conducted in December 2023 using the Education Resources Information Center (ERIC). ERIC allowed us to locate a broad array of literature related to all aspects of BID at various educational levels.

Multiple rounds of searches were conducted on the source database using different combinations of keywords and search strategies. The search criteria encompassed "Biologically inspired design prosthetics," Biologically inspired design prosthetics for injuries," "Biologically inspired design prosthetics for sports," and "Biologically inspired design prosthetics for disabilities." For this review, we only considered papers published between 2013 and 2023, and no further restriction was placed on the source of publication. In addition, we strictly followed the following criteria for screening and selection purposes: BID studies conducted for injuries and disabilities. Published research on prosthetics that were not BID-inspired was excluded. Moreover, theoretical and conceptual design papers were also excluded from the analysis. Lastly, articles referenced in the publications we reviewed for this study were also examined. Our literature search yielded 100 publications, most of which did not fit our criteria.

After reading each paper carefully, we noted the BID-inspired solutions for injuries versus disabilities the studies focused on and discussed in their results. Using an inductive thematic analysis approach, we first organized the papers according to the categories (injuries vs. disabilities). This was followed by further reviewing the resources discussed in the research and labeling them as upper body (i.e., arms, hands, etc.) or lower body (i.e., legs, ankles, etc.) and designed for injury or disability. After organizing the literature, we recognized that much of the work in BID was centered on the upper body and amputees. Hence, we present prosthetics developed for both of the categories, as there were many more for disabilities, specifically focusing on amputees.

Results

The finding revealed that the human body offers a natural template for many prosthetics designed to mechanistically function similarly to the human body while also addressing user needs. These BID-inspired prosthetics have been designed for the upper and lower body.

Upper Body Prosthetics

Most studies related to BID prosthetics are related to the upper body (i.e., hands). For instance, Carrozza et al. [10] designed a "compliant under-actuated prosthetic hand" [10, p. 3]. The hand structure, which includes the palm and fingers, is molded as a "soft polymeric single part with compliant joints and embedded tendon driven under-actuated mechanism for providing adaptive grasp" [10, p. 3]. The prosthetic design is biologically inspired by human hands and is designed using a bio-mechatronics approach. Similarly, Fourie et al. [11] designed and developed a mechatronic prototype hand. The fingers and hand were 3D printed from ABS plastic, and two microcontrollers were used to control the movement of the motors in the fingers and wrist [11]. Luo et al. [12] adapted principles of human neuromuscular control to develop a prosthetic hand

that can mimic human-like compliance. In their study, they examined the effects of "feedforward EMG decoding and proprioception on the biomimetic controller" [12, p. 67] and explored its utility for guiding the future design of prosthetic hands. The authors found that the BID prosthetic control that mimicked biological properties consistently outperformed compared to the one "with linear models in the force-control experiment" [12, p. 72]. Park et al. [6] developed an upper limb prosthetic for basketball athletes. They used muti-material 3D printing technology to create "novel force-sensing springs and apply them to a basketball prosthetic" [6, p. 24]. The design was inspired by biomechanics principles of basketball shoots to compensate for wrist flexion and finger motion in the prosthetic hand.

Lower Body Prosthetic

Biologically designed solutions, while not many, have also been applied to prosthetics designed for the lower body (i.e., ankles, legs, knees). Prinsen et al. [13] developed BID-inspired microprocessor-controlled prosthetic knees to study gait initiation. Mooney et al. [14] developed a novel ankle-foot prosthetic that can replicate the biological ankle's natural stiffness behavior. The authors found that the pneumatic ankle prosthesis was shown to provide biologically appropriate trends and magnitudes of torque, angle, and stiffness behavior when compared to the passive ESR prosthetic foot. Osborn et al. [15] created sensorized synthetic skin that mimicked the natural multi-layered nature of mechanoreceptors found in healthy glabrous skin to provide tactile information. While there are many more, these [16] are a few examples of BID-inspired prosthetics.

As evident in the findings, most work in BID is related to the upper body and on amputees, with an aim to address the limitations that amputees encounter in their quality of life as a result of missing or injured limbs. This research centers around increasing functionality via the implementation of complex control, mechanical design, and novel actuation techniques [17].

Limitations

For this study, we only used the ERIC database to conduct the literature search focusing on empirical studies in biologically inspired design, specifically studies that discussed BID-inspired prosthetics. Thus, this review is limited in its scope. Future studies need to expand the research scope to include other reputable databases and specialized journals. A future search may also incorporate non-empirical resources, such as reports. Additionally, keywords such as "Biologically inspired design inventions" and "Biologically inspired design tools may retrieve more publications. The current search only reviewed studies between 2013 and 2023. Future searches need to expand the search time to include studies published in 2024.

Conclusion

The study highlights the significance of BID solutions for the engineering education community. The findings can aid in furthering the discussion on the integration of BID across engineering disciplines in higher education and industry. The paper presents the initial findings of this review. Plans are in place to conduct a more in-depth comparison of BID solutions for both categories and a comprehensive evaluation for future research.

This work does not use data from humans and, therefore, does not meet the definition of human subjects research; IRB review is not required.

References

1. H. H. Farzaneh. “Bio-inspired design: the impact of collaboration between engineers and biologists on analogical transfer and ideation,” *Research in Engineering Design*, vol. 31, no. 3, pp. 299-322, 2020.
2. H. I. Hassan, L. A. Rodriguez, A. Chatterjee, and A. Layton, “Bio-inspired engineering design: The impact of information representation on access to inspiration from outside one’s discipline,” In *2023 ASEE Annual Conference & Exposition*, 2023.
3. J. M. Benyus, “*Biomimicry: Innovation inspired by nature*,” Morrow New York, 1997.
4. R. James and C. T. Laurencin, “Regenerative engineering and bionic limbs,” *Rare Metals*, vol. 34, no. 3, pp. 143-155, 2015.
5. Y. Bar-Cohen, “Biomimetics—using nature to inspire human innovation,” *Bioinspiration & Biomimetics*, vol.1, no. 1, pp.1, 2006.
6. J. W. Park, B. Greenspan, T. Tabb, E. Gallo, and A. Danielescu, “3D printed energy return elements for upper limb sports prosthetics. *Prosthesis*, vol. 5, no. 1, pp. 13-34, 2023.
7. C. Gentile, F. Cordella, and L. Zollo, “Hierarchical human-inspired control strategies for prosthetic hands,” *Sensors*, vol. 22, no. 7, pp. 2521, 2022.
8. A. C. Etoundi, C. L. Semasinghe, S. Agrawal, A. Dobner, A. Jafari, “Bio-inspired knee joint: trends in the hardware systems development,” *Frontiers in Robotics and AI*, vol. 8, no. 613574, 2021.
9. M. Asano, P. Rushton, W. C. Miller, and B. A. Deathe, “Predictors of quality of life among individuals who have a lower limb amputation. *Prosthetics and Orthotics International*, vol. 32, no. 2, pp. 231-243, 2008.
10. M. C. Carozza, G. Cappiello, G. Stellin, F. Zaccone, F., Vecchi, S. Micera, and P. Dario, “On the development of a novel adaptive prosthetic hand with compliant joints: experimental platform and EMG control,” *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1271-1276, IEEE, 2005.
11. R. Fourie, and R. Stopforth, “The mechanical design of a biologically inspired prosthetic hand, the touch hand 3*,”* pp. 38-43, IEEE, 2017.
12. Q. Luo, M. Bai, S. Chen, K. Gao, L. Yin, and R. Du, “Enhancing force control of prosthetic controller for hand prosthesis by mimicking biological properties,” *IEEE Journal of Translational Engineering in Health and Medicine*, 2023.
13. E. C. Prinsen, M. J. Nederhand, J. Olsman, and J. S. Rietman, “Influence of a user-adaptive prosthetic knee on quality of life, balance confidence, and measures of mobility: a randomized cross-over trial,” *Clinical Rehabilitation*, vol. 29, no. 6, pp. 581-591, 2015.
14. L. M. Mooney, C. H. Lai, and E. J. Rouse, “Design and characterization of a biologically inspired quasi-passive prosthetic ankle-foot,” In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 1611-1617, IEEE, 2014.
15. L. Osborn, H. Nguyen, J. Betthauser, R. Kaliki, and N. Thakor, “Biologically inspired multi-layered synthetic skin for tactile feedback in prosthetic limbs,” In *2016 38th annual international conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 4622-4625, IEEE, 2016.

16. Q. Tan, C. Wu, L. Li, W. Shao, and M. Luo, “Nanomaterial-based prosthetic limbs for disability mobility assistance: A review of recent advances. *Journal of Nanomaterials*, pp. 1-10, 2022.
17. E. Thompson-Bean, R. Das, and A. McDaid, “Methodology for designing and manufacturing complex biologically inspired soft robotic fluidic actuators: prosthetic hand case study,” *Bioinspiration & Biomimetics,* vol. 11, no. 6, 2016.