

Preview

A miniature humanoid biorobot on the run

Hyegi Min,¹ Woong Kim,¹ and Rashid Bashir^{1,2,3,4,*}¹Holonyak Micro and Nanotechnology Laboratory, The Grainger College of Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA²Department of Bioengineering, The Grainger College of Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA³Department of Biomedical and Translational Sciences, Carle Illinois College of Medicine, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA⁴Chan Zuckerberg Biohub Chicago, Chicago, IL 60642, USA*Correspondence: rbashir@illinois.edu<https://doi.org/10.1016/j.device.2024.100358>

Biohybrid robots that combine rigid and bio-inspired soft materials offer advantages in self-healing, learning, adaptation, and chemical to mechanical power conversion. In a recent report in *Matter*,¹ Kinjo and co-workers reported a bipedal humanoid robot integrating skeletal muscle tissue and elastomers, which enable it to perform forward-stopping and turning motions.

The integration of biological tissues into mechanical systems offers features that are otherwise not easily achievable in synthetic mechanical systems, such as self-repair, high energy conversion efficiency, and bending flexibility.² These robotic systems, known as biohybrid robots, by using the contraction and relaxation behaviors of cardiomyocytes or skeletal muscle myotube tissues coupled with rigid components, have demonstrated basic functionalities like swimming,^{3–5} walking,^{6–8} and picking.⁹ In earlier designs, the movements of these muscle tissues depended on mechanical systems that use electrical pulse stimulation for activating voltage-gated ion channels. More recently, researchers have used the transduction of light-gated ion channels, e.g., channel rhodopsin in skeletal muscles that would respond to optical stimulation, enabling selective and remote actuation. On-board optoelectronics on biohybrid robots have shown potential for wireless control and multifunctional bioelectronic applications in engineering, biology, and medicine.⁷ While previous biohybrid robots are mostly limited to straight-line locomotion, large angle turning has been demonstrated in designs using dual bi-pedal actuators that can be stimulated and controlled asymmetrically and individually.⁶ For prior walking robots, the direction of muscle contraction is typically parallel to the surface of locomotion where muscle strips or ring tissues are anchored across a scaffold with two frictional points at the surface

to act as the feet. By exploring two-legged upright humanoid-like robot designs where muscle tissue contraction is perpendicular to the locomotion surface, one may be able to endow these robots with new degrees of freedom and expand their potential applications.

In the March 2024 issue of *Matter*, Kinjo and co-workers reported a biohybrid bipedal robot powered by skeletal muscle tissue with a vertical tissue design.¹ As depicted in the [Figure 1A](#), the bipedal structure is more humanoid and is composed of 3D-printed structures, polydimethylsiloxane (PDMS) elastic substrates, and anchored skeletal muscle tissue. Their robot features a low-density float structure at the upper part of the robot to provide buoyancy at the air-liquid interface, allowing the robot to align vertically and stand. Below the float, skeletal muscle tissues are anchored on the frame with PDMS elastic substrates perpendicular to the planar solid surface on which the robot is walking. The contraction of the muscle induces the deformational bending of the elastomer. At the bottom of the robot, the scaffold representing the feet is attached to the end of each muscle tissue and acts as a weight for gravitational landing and vertical alignment.

The research team utilized primary myoblasts with a hydrogel block to form the skeletal muscle tissues ([Figure 1B](#)). After detaching the tissue from the block, they transferred the muscle tissue onto the anchoring structures. This process is

similar to the prior reports of formation of muscle rings and strips^{6,7} and is scalable toward potential use of multi-actuators and higher order structures. After assembling muscle tissues into the bipedal robot, the authors confirmed the forward movement of the bipedal robot with the application of electric fields to actuate the muscle in an alternating manner ([Figure 1C](#)). The demonstrated forward motion speed of 5.4 mm/min is similar to prior reports.⁶ Similarly, turning was also possible by positioning the electrodes on one side of the muscle to apply the electric field of only half of the body, leaving the other axial leg stationary. This sequence of actions allows the robot to turn in a desired direction with a high turning index of 1.4°/s. Turning is a higher order functionality that was also demonstrated in one prior report where remote wireless optical stimulation of a pair of optogenetic transfected muscles allowed for turning.⁸

The use of the floats allows for the vertical positioning of the robot and a humanoid-like design, but also limits the height of the robot to be the same as the distance between the floor to the liquid surface. This could be circumvented by having a flexible linker/tube that connects to the top of the robot and goes up to the surface. An alternative approach toward a vertical humanoid-like design that does not have a float could be to move the center of gravity in the lower part of the body of the robot by altering the design to add more weight toward the



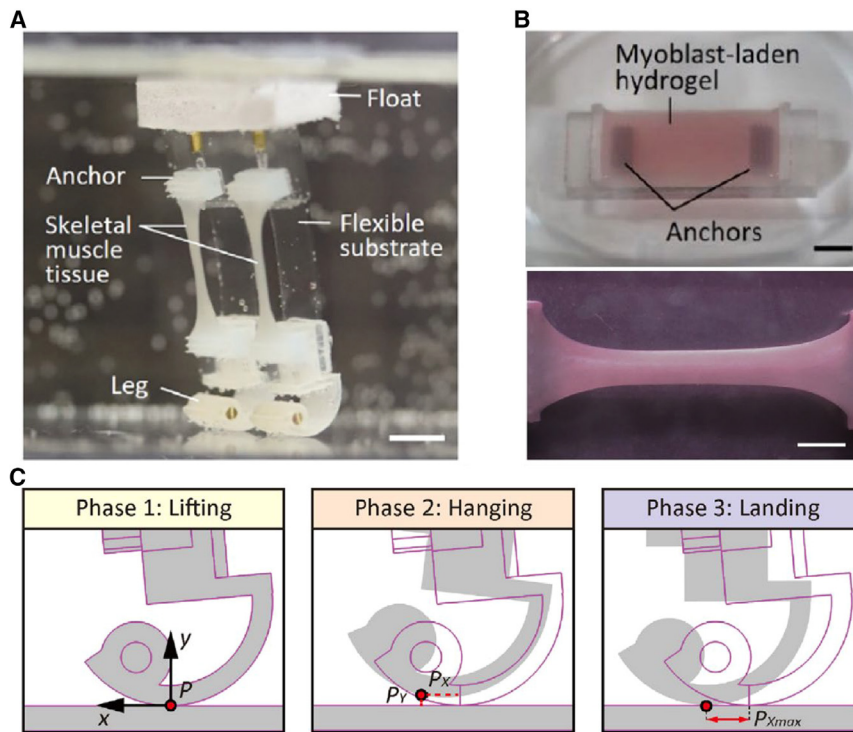


Figure 1. Development of biohybrid bipedal robots reported in this paper¹

(A) Illustration and picture of a biohybrid bipedal robot and its components.
 (B) Preparation of skeletal muscle tissue and its visual characterization.
 (C) Detailed forward movement mechanism in three steps: lifting, hanging, and landing.

legs. This might also require making larger muscles to allow for the movement of heavier skeletons.

Many exciting directions are possible for this design, all of which are also applicable to other biohybrid robots designs. For example, including electrical stimulation from on-board power sources could eliminate the wires currently used in the reported design. The increase in weight due to the added hardware has to be accounted for when designing the muscle actuator to achieve higher forces. Of course, direct electrical stimulation could result in electrolysis and generation of gases that could degrade the muscles over time. Long-term continuous stimulation studies should be done to explore the lifetime of such electrically driven actuators. If the muscles were optogenetically transfected and optically actuated, integrated LEDs could eliminate the risks of electrolysis or electrochemical reactions. Transfection of different color opsins could also allow for differential excitation of actuators, allowing for selective stimulation of different legs.

A grand challenge for all biorobots actuated by mammalian cells is whether these can operate in air by adding a “skin” layer, such as collagen or living skin tissue. This could be a very useful direction to pursue,¹⁰ especially for applications other than implantable or medical. This is a challenging but exciting direction, as this would require careful design of the skin barrier system to control exchange of energy and evaporation of the fluid inside, maintain the pH of the media inside the closed system, and more. Another very exciting direction would be to form neuromuscular junctions for the stimulation of the muscle by motor neurons.^{4,8} The neuronal signaling can control muscle contractions, opening new engineering applications in learning and memory, and biomedical applications in drug efficacy studies and pathophysiological analysis. The reported work by Kinjo and co-workers is an important advance in the development of biohybrid robots by providing a new humanoid-like design and it opens up new locomotion modalities for these miniature machines.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Kinjo, R., Morimoto, Y., Jo, B., and Takeuchi, S. (2024). Biohybrid bipedal robot powered by skeletal muscle tissue. *Matter* 7, 948–962. <https://doi.org/10.1016/j.matt.2023.12.035>.
2. Ricotti, L., Trimmer, B., Feinberg, A.W., Raman, R., Parker, K.K., Bashir, R., Sitti, M., Martel, S., Dario, P., and Menciassi, A. (2017). Biohybrid actuators for robotics: A review of devices actuated by living cells. *Sci. Robot.* 2, eaaq0495. <https://doi.org/10.1126/scirobotics.aaq0495>.
3. Park, S.-J., Gazzola, M., Park, K.S., Park, S., Di Santo, V., Blevins, E.L., Lind, J.U., Campbell, P.H., Dauth, S., Capulli, A.K., et al. (2016). Phototactic guidance of a tissue-engineered soft-robotic ray. *Science* 353, 158–162. <https://doi.org/10.1126/science.aaf4292>.
4. Aydin, O., Zhang, X., Nuethong, S., Pagan-Diaz, G.J., Bashir, R., Gazzola, M., and Saif, M.T.A. (2019). Neuromuscular actuation of biohybrid motile bots. *Proc. Natl. Acad. Sci. USA* 116, 19841–19847. <https://doi.org/10.1073/pnas.1907051116>.
5. Lee, K.Y., Park, S.-J., Matthews, D.G., Kim, S.L., Marquez, C.A., Zimmerman, J.F., Ardoña, H.A.M., Kleber, A.G., Lauder, G.V., and Parker, K.K. (2022). An autonomously swimming biohybrid fish designed with human cardiac biophysics. *Science* 375, 639–647. <https://doi.org/10.1126/science.abh0474>.
6. Raman, R., Cvetkovic, C., Uzel, S.G.M., Platt, R.J., Sengupta, P., Kamm, R.D., and Bashir, R. (2016). Optogenetic skeletal muscle-powered adaptive biological machines. *Proc. Natl. Acad. Sci. USA* 113, 3497–3502. <https://doi.org/10.1073/pnas.1516139113>.
7. Kim, Y., Yang, Y., Zhang, X., Li, Z., Vázquez-Guardado, A., Park, I., Wang, J., Efimov, A.I., Dou, Z., Wang, Y., et al. (2023). Remote control of muscle-driven miniature robots with battery-free wireless optoelectronics. *Sci. Robot.* 8, eadd1053. <https://doi.org/10.1126/scirobotics.add1053>.
8. Shin, M., Ha, T., Lim, J., An, J., Beak, G., Choi, J.H., Melvin, A.A., Yoon, J., and Choi, J.W. (2024). Human motor system based biohybrid robot-on-a-chip for drug evaluation of neurodegenerative disease. *Adv. Sci.* 11, 2305371. <https://doi.org/10.1002/adv.202305371>.
9. Morimoto, Y., Onoe, H., and Takeuchi, S. (2018). Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues. *Sci. Robot.* 3, eaat4440. <https://doi.org/10.1126/scirobotics.aat4440>.
10. Morimoto, Y., Onoe, H., and Takeuchi, S. (2020). Biohybrid robot with skeletal muscle tissue covered with a collagen structure for moving in air. *APL Bioeng.* 4, 026101. <https://doi.org/10.1063/1.5127204>.