

Preview

NeuroMuscles: Pioneering materials open a new path to artificial skeletal muscles

Chi Chen,¹ Wenhao Hou,¹ and Ximin He^{1,*}¹Department of Material Science and Engineering, University of California, Los Angeles, Los Angeles, CA, USA*Correspondence: ximinhe@ucla.edu<https://doi.org/10.1016/j.matt.2025.102031>

Human skeletal muscles possess a delicate structure that enables simultaneous sensing and actuation through neuromuscular fiber bundles. However, most current material designs face challenges in integrating these capabilities within a single fiber bundle and instead rely on centralized systems to process signals between separate sensors and actuators. This preview highlights NeuroMuscles, an innovative artificial neuromuscular fiber bundle based on multilayered microfibers with a self-reinforcing sheath, enabling both proprioception and exteroception as an advancement in the development of next-generation artificial muscles.

After billions of years of evolution, biological muscles exhibit extraordinary properties, including a high power-to-weight ratio, compliance, adaptability, large deformations, and rapid feedback responses—features that researchers strive to replicate in artificial muscles. However, current designs face challenges in balancing material properties (e.g., stiffness, hysteresis, and actuation performance) to create bio-level muscles that are soft, flexible, and compliant while enabling seamless and autonomous interaction with the environment. Previous works have developed soft artificial muscles with responsive characteristics to external stimuli, including heat, light, pressure, and electrothermal effects.^{1–3} Additionally, considerable efforts have been directed to bioinspired designs that enable functionalities such as position sensing (proprioception) and agile interaction (exteroception). However, entirely soft designs still face challenges in analyzing shape-morphing signals to enable responsive and controlled sensing-diagnosis-actuation processes in complex environments.^{4–6} Current solutions often incorporate feedback-based control systems within external modules for signal acquisition and processing. Yet, their bulky architectures and design complexity inevitably reduce compliance, create mismatches between soft muscles and rigid systems, and introduce the potential for interference between stimuli and perception signals, compromising accuracy.^{7,8} Therefore, the development of a single monolithic system with integrated feed-

back and self-regulation capabilities is a critical area deserving focused attention.

Inspired by the intricate neuromuscular fiber bundle structure, Wang and co-workers developed an innovative approach to fabricating microtubular fibers that integrate independent channels for actuation and sensing, facilitating real-time signal acquisition and adaptive responses without relying on external control systems.⁹ As shown in Figure 1A, the prepared multilayered microtubular fibers consist of a liquid metal (LM) core, a liquid crystal elastomer (LCE) actuation layer, and a self-reinforcing adhesion sheath. Specifically, the fabrication process begins with a unique rotational molding technique to prepare LCE-based microtubular fibers. During continuous rotation, the centrifugal force facilitates the uniform adhesion of the oligomer to the mold walls, leaving a hollow core in the center. This strategy enables the fabrication of microtubular fibers with dimensions comparable to those of human hair, well-defined thicknesses (as thin as $\sim 10\ \mu\text{m}$), and tailorable diameters (minimum outer diameter of $\sim 50\ \mu\text{m}$). Then, LM is injected into the hollow fibers to establish conductive pathways. As a result, the resulting LM-LCE core-shell fibers demonstrate strain sensitivity of up to 3,500% upon 1 N compression force, as well as resistance stability without noticeable fatigue. Meanwhile, the outer self-reinforcing adhesion layer, composed of boronic-ester-based dynamic crosslinked LCE, mimics the function of endomysium con-

nective tissue in skeletal muscle fibers. This layer enables the seamless welding of multiple microtubular fibers into a bundle (NeuroMuscle) while preventing delamination and enhancing interfacial strength. In general, this approach can potentially be extended to a broader range of fluid polymeric precursor systems for the fabrication of both multilayered fibers and fiber bundles.

As a result, bonding two multilayered microtubular fibers together (2-NeuroMuscle) achieves exceptional performance, including high contraction ratios ($\sim 98\%$), rapid actuation speeds (within 0.12 s at DC voltage), and a load-bearing capacity of $124\ \text{J kg}^{-1}$. Moreover, varying the DC voltage from 2.5 to 7.5 V allows the 2-NeuroMuscles to undergo geometric transformation between twisted and coiled configurations with a faster contraction speed and higher contraction ratio than traditional actuators.^{8,10}

The balanced performance of high sensitivity, electrothermal actuation, and robust structure makes NeuroMuscles ideal for monitoring both their own state and external stimuli by functioning as analogs to proprioception and exteroception in human muscles. The demonstration that Wang and colleagues developed incorporates multiple artificial neuromuscular fibers—each connected to individual copper wires for electrothermal actuation—one of which is dedicated to sensing the change in contraction length. This design provides independent actuation and sensing channels, effectively reducing hysteresis and enhancing perception accuracy. As a



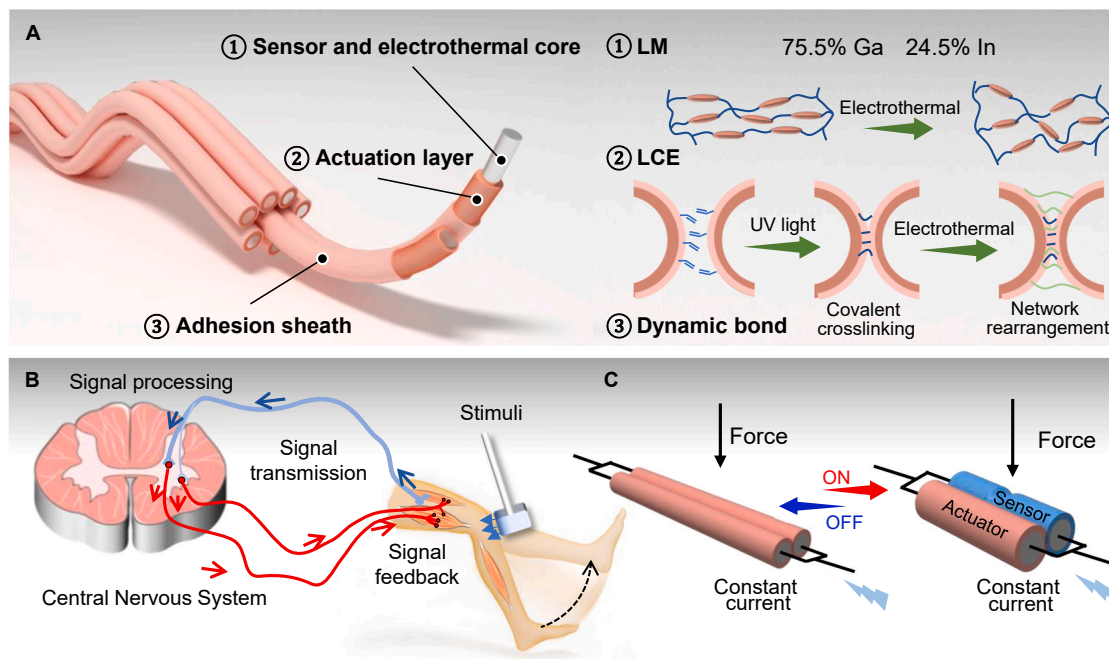


Figure 1. Schematic illustration of the NeuroMuscle design and its adaptive feedback mechanism

(A) Schematic illustration of NeuroMuscles, comprising (1) an electrothermal liquid metal (LM) core for sensing, (2) an actuation layer based on a liquid crystal elastomer (LCE), and (3) an adhesion sheath based on a dynamic bond.

(B) Schematic illustration of the knee-jerk reflex and built-in adaptive feedback in the human body.

(C) Schematic illustration of 2-NeuroMuscles depicts the direct connection between actuator and sensory fibers to enable adaptive feedback.

Adapted from Wang and co-workers.⁹

result, NeuroMuscles exhibit both proprioception and exteroception in artificial fingers, enabling the detection of shapes and textures. For example, with 30 bundled fibers, the artificial finger can sense and distinguish varied surface textures, including convex and concave shapes, with a resolution down to 0.3 mm, allowing it to detect intricate features such as coin inscriptions. By employing different combinations of sensing and actuation components, NeuroMuscles can serve as a versatile tool for artificial tactile systems and soft robotic applications.

Conversely, by reconfiguring wire connections into a parallel circuit, Wang and co-workers incorporate built-in adaptive feedback into 2-NeuroMuscles, mimicking a biological spinal cord system, which facilitates self-regulatory responses to environmental stimuli without relying on additional microcontrollers (Figures 1B and 1C). To replicate the process of a knee-jerk reflex, the authors construct an artificial leg model with 2-NeuroMuscles to demonstrate rapid motion, whereby the lower leg swings forward in response to pricking stimuli from 2 to 7 s. The control mechanism operates

through a redistribution of current in a constant-current model, where pressing forces applied to one fiber increase the current in the other fiber, generating joule heat and inducing contraction. Notably, this feedback mechanism is reversible, stable, and fatigue resistant, as confirmed by cycling stability tests conducted with varying pin-pricking durations.

In summary, this preview reports a novel rotational molding strategy for fabricating multilayered microtubular fibers with precise control over fiber diameter and shell thickness and thus achieving the integration of sensing and actuation functions within a material system. Furthermore, the incorporation of NeuroMuscles into both artificial fingers and artificial limbs showcases their potential for proprioception and exteroception, opening a new path for the development of artificial muscles in robotics and soft devices.

ACKNOWLEDGMENTS

This work was funded by grants N000142212595 and N000142412187 from the Office of Naval Research (ONR).

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

- Truby, R.L., Wehner, M., Grosskopf, A.K., Vogt, D.M., Uzel, S.G.M., Wood, R.J., and Lewis, J.A. (2018). Soft somatosensitive actuators via embedded 3D printing. *Adv. Mater.* 30, 1706383. <https://doi.org/10.1002/adma.201706383>.
- Zhao, Y., Liu, Z., Shi, P., Chen, C., Alsaïd, Y., Yan, Y., and He, X. (2025). Antagonistic-contracting high-power photo-oscillators for multifunctional actuations. *Nat. Mater.* 24, 116–124. <https://doi.org/10.1038/s41563-024-02035-3>.
- Hou, W., Wang, J., and Lv, J.A. (2023). Bio-inspired liquid crystalline spinning enables scalable fabrication of high-performing fibrous artificial muscles. *Adv. Mater.* 35, 2211800. <https://doi.org/10.1002/adma.202211800>.
- Kim, I.H., Choi, S., Lee, J., Jung, J., Yeo, J., Kim, J.T., Ryu, S., Ahn, S.K., Kang, J., Poulin, P., and Kim, S.O. (2022). Human-muscle-inspired single fibre actuator with reversible percolation. *Nat. Nanotechnol.* 17, 1198–1205. <https://doi.org/10.1038/s41565-022-01220-2>.
- Liu, H., Tian, H., Li, X., Chen, X., Zhang, K., Shi, H., Wang, C., and Shao, J. (2022).

- Shape-programmable, deformation-locking, and self-sensing artificial muscle based on liquid crystal elastomer and low-melting point alloy. *Sci. Adv.* 8, eabn5722. <https://doi.org/10.1126/sciadv.abn5722>.
6. Ma, Z., Huang, Q., Xu, Q., Zhuang, Q., Zhao, X., Yang, Y., Qiu, H., Yang, Z., Wang, C., Chai, Y., and Zheng, Z. (2021). Permeable superelastic liquid metal fibre mat enables biocompatible and monolithic stretchable electronics. *Nat. Mater.* 20, 859–868. <https://doi.org/10.1038/s41563-020-00902-3>.
7. Dong, L., Ren, M., Wang, Y., Wang, G., Zhang, S., Wei, X., He, J., Cui, B., Zhao, Y., Xu, P., et al. (2022). Artificial neuromuscular fibers by multilayered coaxial integration with dynamic adaption. *Sci. Adv.* 8, eabq7703. <https://doi.org/10.1126/sciadv.abq7703>.
8. Kotikian, A., Morales, J.M., Lu, A., Mueller, J., Davidson, Z.S., Boley, J.W., and Lewis, J.A. (2021). Innervated, self-sensing liquid crystal elastomer actuators with closed loop control. *Adv. Mater.* 33, 2101814. <https://doi.org/10.1002/adma.202101814>.
9. Chen, Y., Valenzuela, C., Liu, Y., Yang, X., Yang, Y., Zhang, X., Ma, S., Bi, R., Wang, L., and Feng, W. (2025). Biomimetic artificial neuromuscular fiber bundles with built-in adaptive feedback. *Matter* 8, 101904. <https://doi.org/10.1016/j.matt.2024.10.022>.
10. Lu, H.F., Wang, M., Chen, X.M., Lin, B.P., and Yang, H. (2019). Interpenetrating liquid-crystal polyurethane/polyacrylate elastomer with ultrastrong mechanical property. *J. Am. Chem. Soc.* 141, 14364–14369. <https://doi.org/10.1021/jacs.9b06757>.