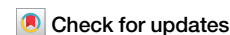


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Fiber-type artificial muscles for robotic actuation



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Fiber-type artificial muscles are emerging as innovative components in robotics due to their lightweight, flexible, and highly adaptable properties that emulate biological muscle functions. This paper presents a comprehensive overview of recent advances in non-fluidic, stimuli-responsive fiber-type artificial muscles, focusing on their structural inspirations and actuation mechanisms for diverse smart material-based robotic applications.

Fiber is an attractive form for electronics and mechanics owing to its flexible, lightweight, and conformable properties, enabling seamless integration with soft or curved surfaces such as the human body and textile materials and supporting advanced features for integration with energy harvesting, storage, and sensing devices^{1,2}.

The development of artificial muscles has been a promising area of research in robotics, particularly in soft and wearable robotics, inspired by the structure and function of biological muscles. Traditional rigid actuators, such as electric motors and hydraulic systems³, offer high power and precision but lack the compliance and versatility required for applications in soft robotics, wearable devices, and bio-integrated systems^{4,5}. Advanced actuator types, including McKibben-type pneumatic actuators and nonfiber artificial muscles such as ionic polymer–metal composites (IPMCs), have been studied extensively; however, those types of actuator or artificial muscle exhibit complex dynamic behavior that complicates control, limitations in the types of actuation they can achieve, and has large volumetric scale which is not proper for wearable robots and microbots^{6,7}. Hydraulically amplified self-healing electrostatic (HASEL) actuators have also demonstrated excellent performance of muscle-mimetic actuation, though they are classified as nonfiber-type actuators⁸. To address these limitations, fiber-type artificial muscles have emerged as a promising solution owing to their lightweight nature, high flexibility and the ability to exhibit multiple degrees of freedom (DOF)^{5,9}.

Fiber-type artificial muscles exhibit diverse movements, inspired by the design of biological muscles. Mimicking structure and function, these artificial muscles use smart materials such as electrochemical and thermal actuators, offering unique advantages for robotic applications¹⁰. This review explores the classification of fiber-type artificial muscles based on different

types of actuation, including bending, torsional, tensile, and isometric movements. It also examines recent advancements and various applications in soft robotics and micro-robotics, biomedical devices, and assistive technologies. Although fiber-type artificial muscles have demonstrated considerable potential, challenges related to mass production, scale-up remain critical areas for further development and commercialization. By summarizing state-of-the-art developments of stimuli responsive and smart material based, fiber-type artificial muscles and their various types of actuation, this review aims to provide insights into their potential and inspire further research in robotics, mainly focused on non-fluidic type fiber muscles.

Biological muscle-inspired, fiber-type artificial muscle

Biological muscles play a crucial role in enabling controlled movement and force generation in living organisms by achieving a variety of motions through the actuation mechanisms of myofibrils^{11,12}. Force and motion are generated via the stroke of the sarcomere, in which myosin filaments slide along actin filaments powered by the hydrolysis of adenosine triphosphate (ATP). This mechanism allows muscle fibers and muscle bundles, composed of myofibrils, to perform various types of scaled-up, large stroke actuation, including tensile, bending, and rotational actuations. For example, the contraction of the biceps, composed of muscle bundles, demonstrates tensile actuation. Bending is facilitated by the coordinated action of antagonistic muscle groups such as the rectus abdominis and erector spinae, which enable the upper body to bend and straighten freely¹³. The supraspinatus, subscapularis, infraspinatus, and teres minor muscles, responsible for tensile actuation, collectively form the rotator cuff, enabling versatile rotational actuations of the shoulder. As above, biological muscle fibers

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Fig. 1 | Overview of actuation in fiber-type artificial muscles for robotics and biological muscles, categorized into tensile, bending, torsional, and isometric actuation.

exhibit a systematic actuation by synergistic actuation, beginning with basic tensile action and sequentially extending to rotational and bending movements. (Fig. 1).

Inspired by natural mechanisms and biological structures, actuation of the fiber-type artificial muscles is primarily governed by changes in internal fiber response to external stimuli, as small-scale myofibrils that generate the basis of actuation for scaled-up, large actuation stroke¹⁴. Based on these mechanisms, fiber-type artificial muscles can hierarchically generate various movements similar to biological muscles. For example, twisted fiber or coiled fiber-based artificial muscles convert motion through torsional actuation generated by the untwisting of the fiber muscle, which then generates twist-induced tensile actuation and stretch-induced bending actuation^{9,15}. Some artificial muscles directly perform tensile, torsional, or bending motions; however, many display a sequential actuation conversion similar to that of biological muscles, with torsional motion often serving as the fundamental movement mechanism.

While biological muscles primarily rely on tensile actuation in the sarcomere as the fundamental actuation, fiber-type artificial muscles often use torsional actuation to achieve various modes of movement and this characteristic makes them particularly suitable for soft robotics, prosthetics, and any other advanced actuator systems based applications. Accordingly, optimizing twisting, tension, bending, and isometric actions in artificial muscle design is essential for the development of more efficient and bio-mimetic systems. The following section provides a detailed discussion of these diverse actuation modes, each of which plays a crucial role in the functioning of artificial muscles.

Stimuli-induced actuation mechanisms and structures of fiber-type artificial muscles

Fiber-type artificial muscles represent a promising class of soft actuators owing to their intrinsic flexibility, low weight, and mechanical adaptability. These attributes make them particularly appealing for emerging applications in soft robotics, wearable electronics, biomedical devices, and adaptive textiles. The actuation behavior of these systems is driven by dynamic modifications in their internal material properties in response to external stimuli. Key mechanisms include molecular reorientation, variations in internal volume expansion owing to the infiltration of guest materials or income of external stimuli, and changes in inter-fiber spacing⁵. (Fig. 2A).

Fiber-type artificial muscles can be actuated by various external stimuli, including light, electrical, thermal, chemical, and exposure to solvents or

vapors. Each type of stimulus interacts with the fiber material in a distinct manner, activating specific actuation pathways. Vapor-based stimuli, such as ethanol vapor or humidity, can induce swelling or deswelling in hydrophilic polymer matrices, resulting in significant volumetric modulation. (Fig. 2B)^{16–20} For example, ethanol vapor can promote rapid expansion in specific polymeric fibers through solvent-polymer interactions, while humidity-responsive fibers can curl or contract in response to environmental moisture changes. Photo stimuli, such as ultraviolet (UV) light, can induce reversible photo-isomerization in embedded photo-responsive molecules, resulting in nanoscale conformational changes that translate to macroscale deformation. (Fig. 2C)²¹ Magnetic stimuli can induce motion by applying torque or generating localized heating in magnetically responsive materials, thereby enabling movement through magnetic alignment or thermally induced actuation²².

Chemical stimuli often initiate actuation via molecular interactions; for example, the infiltration of glucose or other analytes may alter bonding dynamics, affecting fiber geometry or mechanical stiffness. (Fig. 2D)²³ Thermal stimuli, including photo-thermal, electro-thermal particularly elevated temperatures, can trigger polymer phase transitions or matrix softening, leading to internal volume expansion and actuation (Fig. 2E)^{12,16,24–29}.

The diversity of actuation mechanisms is further enhanced by the material composition and architectural design of the fibers. The incorporation of stimuli-responsive materials has facilitated the development of artificial muscles capable of large strains, rapid response times, and high durability, such as carbon nanotubes (CNTs), graphene, conductive polymers, and hybrid composites^{26,30}. The structural design of fiber-type artificial muscles is critically influenced by three main factors: the type of actuation, enhancing performance, and target applications. Structures are selected or engineered to match specific actuation modes, for example, twisted yarns for torsional actuation and overtwisted coils for tensile actuation^{31,32}. To enhance performance, engineered structures like helical structures or mandrel coils are used to increase tensile stroke performance, for example²⁸. Additionally, structural configurations have suitable application, textile-based structures for instance, braided or woven structure enable scalable integration, while their designs offer flexibility and compatibility for biomedical and wearable applications³³. Together, these considerations enable the rational design of high-performance artificial muscles for diverse uses.

Actuation of fiber-type artificial muscles

Torsional actuation

Torsional actuation is considered the most fundamental mode of movement in fibrous artificial muscles. In some studies, artificial muscle materials exhibit direct torsional motion; for example, the torsional behavior of spider dragline silk-based muscles arises from the structural asymmetry of protein molecules and variations in hydrogen bonding patterns, resulting in macroscopic twisting motion³⁴. However, most torsional artificial muscles rely on pre-inserted twist introduced during fabrication. When such pretwisted fibers undergo internal volume expansion in response to an external stimulus while maintaining a constant axial length, they exhibit torsional actuation, untwisting around the fiber axis, as shown in Fig. 2A¹⁷.

When fibers are twisted, they form a bias angle of fiber surface (α) and a torsional angle (θ), generating shear stress. The relationship between α and θ is described as

$$\theta = \frac{l \tan \alpha}{r} \quad (1)$$

where r denotes the radius of the fiber muscle and l denotes the fiber length. The amount of twist inserted per precursor fiber length, T is defined as

$$T = \frac{\theta}{2\pi l} \quad (2)$$

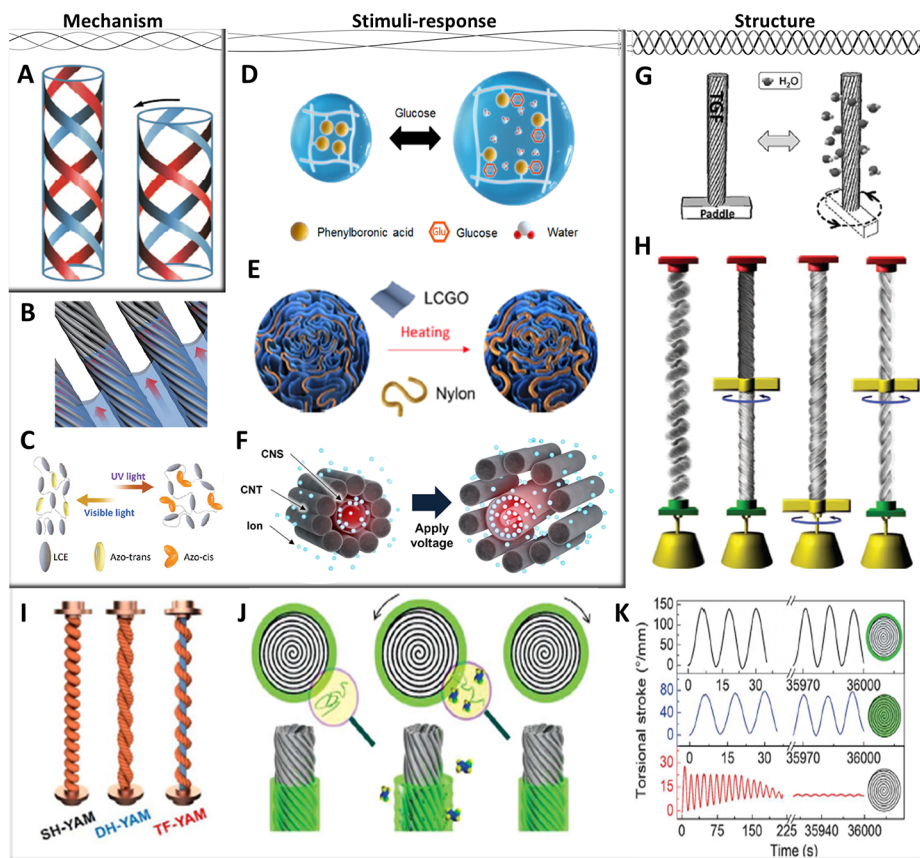


Fig. 2 | Mechanism of actuation of fiber type artificial muscle and performance of torsional actuation. **A** Schematic representation of the torsional actuation mechanism in fiber-type artificial muscles, illustrating the inter-bundle twisting motion. Reproduced with permission⁵⁰. Copyright 2019, American Association for the Advancement of Science. **B–F** Illustration of the stimuli-induced inter-structural changes that lead to torsional or tensile actuation. **B** Moisture-powered torsional artificial muscle based on carbon nanotube (CNT). Reproduced with permission⁸³. Copyright 2015, Springer Nature Limited. **C** Light-powered coiled azobenzene-functionalized semi-crystalline liquid crystal elastomer (LCE). Reproduced with permission⁹. Copyright 2024 Wiley-VCH GmbH. **D** Glucose-responsive self-helical artificial muscle fiber Reprinted (adapted) with permission from²³. Copyright 2020 American Chemical Society. **E** Graphene oxide (GO) and nylon composite wet spun fiber for torsional and tensile actuation driven by thermal stimuli. Reprinted with permission from ref. 26. Copyright 2018 American Chemical Society. **F** Electrochemically-powered artificial fern muscle with a double nano carbon structure. Reproduced with permission⁴⁴ under CC-BY-NC-ND 4.0

license, copyright 2024, Elsevier. **G** Reversible torsional actuation of twisted GO fiber showing twist-induced torsional actuation. Reproduced with permission¹⁰⁰. Copyright 2014 WILEY-VCH Verlag GmbH & Co. KGaA. **H** Tethering configuration of torsional artificial muscles to enhance the performance of the actuation of twist-spun CNT yarns. Reproduced with permission³¹. Copyright 2011, American Association for the Advancement of Science **I** Tendril-twined fasciated yarn-structured, high-performance torsional artificial muscles, showing different configurations. Reproduced with permission³⁸. Copyright 2023, Donghua University, Shanghai, China. **J** Principle of the sheath-run artificial muscle, where a guest material coating is utilized to amplify torsional actuation performance. Reproduced with permission⁴¹. Copyright 2019, American Association for the Advancement of Science **K** Real-time measurement of torsional actuation performance in sheath-run artificial muscles, displaying torsional motion characteristics over time. Reproduced with permission⁴¹. Copyright 2019, American Association for the Advancement of Science.

This twisting produces torque (M), which is related to the twist through

$$M = 2\pi GJT \quad (3)$$

with G representing the fiber shear modulus and J representing the polar moment of area. When the fiber response to external stimuli, a change in torque (ΔM) occurs, given by

$$\Delta M = \pi G A r^2 [(1 + \alpha d \Delta \theta)^4 (T + \Delta T) - T], \quad (4)$$

where A denotes the cross-sectional area of the fiber and αd denotes the thermal expansion coefficient of the polymer. The change in twist density ΔT is connected to a change in fiber diameter Δd , expressed as

$$\Delta T = -T \Delta d / d \quad (5)$$

exhibiting a linear relationship^{28,35,36}.

The material undergoing volume expansion varies depending on the type of external stimulus applied. For artificial muscles actuated by ethanol vapor or moisture, rotation occurs owing to equilibrium volume expansion, which is induced either by capillary action between internal fibers or by the adsorption of liquid or vapor onto the fiber surface (Fig. 2B)^{16,17,37–41}. In thermally actuated artificial muscles, as shown in Fig. 2E, untwisting is driven by the difference in thermal expansion coefficients between the guest material embedded within the fiber and the fiber matrix itself, and this process increases the gap between filaments, leading to volume expansion. In electrochemical actuation^{42–46}, introduced in Fig. 2F, the application of a bias voltage causes electrolyte ions with opposite polarity to infiltrate the spaces between CNT filaments, including carbon nanoscrolls⁴⁴.

Twisted-fiber artificial muscles, fabricated from various materials such as carbon nanotube yarns, graphene fibers, and shape memory polymers, have garnered considerable scientific interest. Their classification is also influenced by the type of external stimulus applied. The performance of each fiber-type torsional artificial muscle is typically evaluated based on key

Table 1 | Actuation mechanism and performance of fiber type, torsional artificial muscles

Stimuli	Material	Structure	Torsional Stroke (°/mm)	Peak Torsional Speed (rpm)	Work capacity (J/kg)	Torque-to-mass ratio (N.m/kg)	Ref
Electric field	CNT/ Rubber	Twisted	4.44				47
Electrochemical	CNT	Twisted	52				42
	CNT	Two-end-tethered, twisted		590			50
	CNT/PSS	Two-end-tethered, twisted	6.4	150-200		0.89	43
Electro-thermal	NiTi alloy	Two-end-tethered, twisted	16	10500	8 ~ 10	8	48
Solvent vapor	PEO-SO ₃ /CNT	Sheath-core	143	507			41
	CNT	Twisted	447.5	2050	26.7	0.63	86
Thermal	LCE	Twisted	243.6	2400		10.1	91
	CNT/Polymer	Two-end-tethered, twisted	60	11500		8.42	31
	Graphene Oxide/Nylon	Twisted	14.85				26
Moisture							
	Viscose/PET	Sheath-core	581.5		23.5		38
	Silk	Twisted	547	975		0.063	40
	Spider silk	Nontwisted	255	5.83		7.59×10^{-4}	34
	Lotus fiber yarn	Twisted	200		0.488		39
	Human hair	Twisted	104		6.35		17
Magnetic	CNT	Two-end-tethered, twisted	0.79			8.42	22
Light	Graphene Oxide/ Sodium Alginate	Twisted		500			16

parameters, including torsional stroke, torsional speed, work capacity, torque, and power density. A comparative summary of results obtained using different materials and actuation methods is listed in Table 1.

The performance of various torsional artificial muscles under different stimuli is compared based on the data presented in the table. Vapor-powered muscles, particularly those actuated by moisture or ethanol, demonstrate large torsional strokes. In terms of torsional speed, the highest values recorded were 11,500 rpm and 10,500 rpm, achieved by a heat-powered CNT/polymer composite and electrothermally powered NiTi alloy fiber, respectively^{47,48}.

There is some structural modification that can enhance the torsional performance of fiber-based artificial muscles, which is muscle tethering³¹. For example, one end tethered CNT yarns tethered at one end exhibit larger, but irreversible, rotation owing to structural deformation and snarling. By contrast, two-end tethered CNT yarns demonstrate smaller, yet reversible, rotation owing to balanced torsional distribution. The hysteretic behavior observed in one-end tethered yarns leads to permanent structural changes, whereas tension-induced twist in two-end tethered configurations allows for recovery to the original state. These distinct characteristics make one-end tethered CNT yarns suitable for applications requiring a single, large rotational output, while two-end tethered yarns are more appropriate for repeated, controlled actuation, offering improved stability and long-term reliability^{36,49}. Another structural design for enhancing performance is the guest material-filled sheath-core configuration, as demonstrated by sheath-run artificial muscles, which exhibit high stroke and rotational speed, because the sheath, positioned on the surface, enables more efficient stimulus response and mechanical energy transfer than embedded guest materials⁴¹.

Tensile actuation

Fiber muscles are artificial muscle systems that generate linear contraction or extension forces in response to mechanical, thermal, chemical, electrical,

or moisture-related stimuli. Unlike traditional actuators, fiber muscles exploit their anisotropic properties and high aspect ratio to convert torsional or tensile forces into linear motion. This motion is enabled through coiling, twisting, or by leveraging specific material properties that respond to external stimuli, resulting in volume changes, thermal expansion, or other deformation mechanisms. Table 2.

The volume expansion-induced length changes in a twisted fiber using a helix model can be described by the normalized twist number as

$$\frac{n}{n_0} = \left(\frac{V_0 \lambda L_0 L_s^2 - \lambda^3 L_0^3}{V L_0 L_s^2 - L_0^3} \right)^{1/2} \quad (6)$$

where V_0 , L_0 , and n_0 denote the fiber volume, length, and number of inserted twists in the initial state, respectively, and V , L , and n denote the corresponding values in the actuated, deformed state, respectively. More specifically, L_s is the helical fiber length wrapped with yarn bias angle in a cylindrical fiber having a length of L , and $\lambda = L/L_0$ represents the ratio of the actuated to the initial fiber length⁵⁰.

Some fiber-type artificial muscles leverage the intrinsic contraction and relaxation properties of the material itself for actuation. For example, shape deformation induced by the percolation of graphene and liquid crystal elastomer (LCE) composites demonstrates reversible linear contraction–expansion behavior under photothermal stimuli, as illustrated in Fig. 3A, B¹⁴. Sodium alginate-based fibers that exhibit moisture-induced elongation have also been reported as shown in Fig. 3C^{32,51}. However, most fiber-type artificial muscles achieve high-performance actuation through twist engineering. One example is shown in Fig. 3C, which illustrates the actuation mechanism of a moisture-powered artificial muscle based on a graphene oxide and CNT composite⁵². Compared to nontwisted yarns, which exhibit only diameter expansion in response to moisture stimuli, the twisting and coiling processes significantly enhance longitudinal actuation. Electrochemical

Table 2 | Actuation mechanism and performance of fiber type, tensile artificial muscles

Stimuli	Structure	Material	Strain (%)	Work capacity (J/kg)	Ref
<i>Non-twist induced</i>					
Thermal	Fiber	MXene composite	21	1.03	30
	Mandrel	PE/COCe	50		33
Photo-thermal	Fiber	LCE/CNT	49.1	179	57
<i>Twist induced</i>					
Electro-chemical	Coil	CNT/rGO	8.1	236	53
		CNT/GO	21	4100	45
		CNT/PSS	5.8	730	45
		CNT/PDDA	4.5		45
	Coiled ply	CNT	15.1	3780	84
	Plied coil	CNT/ carbon nanoscroll	20.11	2260	44
		CNT	1.3		42
Electro-thermal	Coil	CNT/LCE	59.9	1207.1	72
		CNT/Elastomer	30.5	850	27
	Mandrel coil	Nylon/Silver	55.3		54
	Plied coil	CNT/PDMS	29.3	1450	12
Glucose	Helical	Hydrogel/Nylon	2.3		23
Moisture	Plied coil	Wool	42	320	82
		Lotus	33.3	392	39
Solvent vapor	Coil	PEO-SO ₃ /CNT	15	2000	41
	Plied coil	CNT	13.3	847.2	81
Thermal	Coil	Nylon 6,6	21	2480	28
	Plied coil	CNT/wax	7.3	1360	31
RF magnetic heating	Coil	Nylon/ GO/PDMS	30	3500	73
<i>Helical structure based twist induced</i>					
Thermal	Spiral	Nylon	8600		29
Moisture	Plied helical	Silk	6000		40
Photo-chemical	Mandrel	LCE/ Azobenzene	60		21

actuation based on twisted, coiled or plied CNT yarn is another example of high-performance tensile actuation as illustrated in Fig. 3D⁵³. In addition to twist engineering, structural modifications such as yarn writhe further contribute to increased stroke, highlighting the importance of structural design in optimizing artificial muscle performance. By applying chirality modulation, homochiral structures and heterochiral structures can be devised, which show opposite directional actuation. (Fig. 3D)^{26,28} When a secondary twisted structure is applied, moisture-responsive plied helical fiber muscles achieve up to 6000% tensile strain, while spiral twisted coiled yarn-based muscles reach up to 8600%, exhibiting giant stroke capabilities^{28,29,54}. Chemical modification and electrochemical engineering, such as unipolar coating or material composite, is also a strategy for high-performance actuation^{44,45}.

Bending Actuation

Bending actuation is a vital component in the field of fiber-type artificial muscles, offering broad potential for biomimetic and robotic applications, particularly in replicating natural muscle movements. It plays a key role in tasks such as the bending of the human arm, which involves the coordinated

contraction of muscles like the biceps and triceps. Replicating this motion is crucial for developing biomimetic robotic systems, soft actuators, and medical devices⁵⁵. Effective bending actuation depends on bending angle, curvature, and force, which collectively determine displacement, bending sharpness, and load-bearing capacity.

Fiber-type artificial muscle bending mechanisms can be categorized into four main types based on structure and actuation type. The first mechanism involves direct bending induced by asymmetric structures or asymmetric responses to external stimuli. This mechanism is particularly effective for snap-through actuations and rapid-response systems. A representative example includes shape memory polymers or alloys configured into bistable structures, which undergo bending when triggered by thermal or electrical stimuli²⁴. In addition to bending actuation achieved through the formation of simple bilayer structures, phototropic bending can also be induced by one-sided illumination. In Fig. 4A, under controlled NIR light illumination, the CNT and LCE composite fiber exhibits photo-induced phototropic bending actuation⁵⁶. Figure 4B shows a bilayer structure on graphene-based fiber where a graphene-graphene/GO bilayer structure was induced by laser for moisture powered bending muscle fiber¹⁹.

The second mechanism is twist-to-tensile induced bending, where Fig. 4C shows a light-responsive coiled artificial muscle fiber, fabricated from a bio-based polyamide copolymer. The fiber adopts a twist-mandrel coiled configuration, enabling high DOF in multidirectional bending. The muscle exhibits twist-induced bending actuation in response to varying laser intensities⁵⁷.

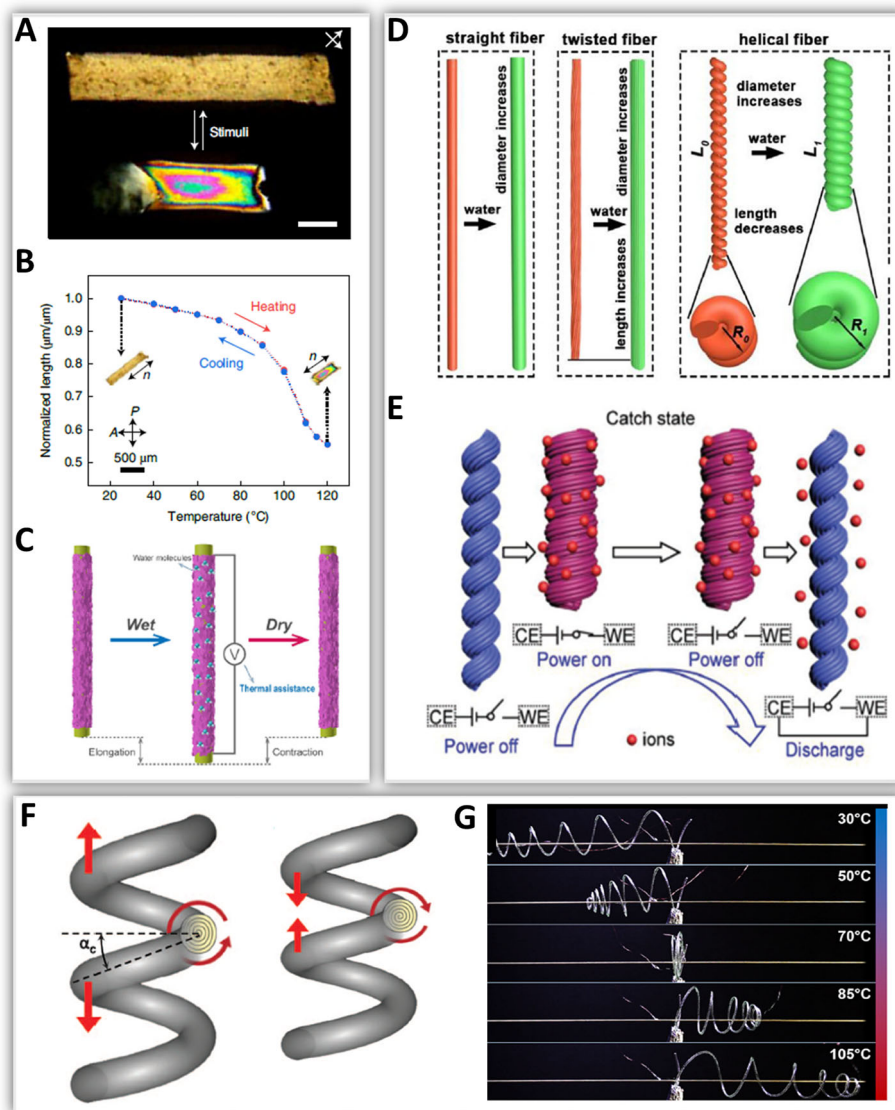
The third mechanism is shape-programmed bending actuation. High DOF graphene fiber powered by moisture in predetermined movement can be realized by selectively forming bilayer structures using laser patterning. (Fig. 4D)¹⁹ A shape-programmable, high DOF artificial muscle driven by laser demonstrates multiple and multidirectional bending by adjusting the laser irradiation direction and position. PDA-coated tubular LCE combined with a low melting point alloy (LMPA) rod forms joints under light irradiation, enabling rapid and reversible shape programming. (Fig. 4E)⁵⁸ Additionally, multi-modal and reprogrammable actuation, performing complex and multiple bending, is achieved using a PNIPAM/PCL fiber artificial muscle under low-temperature conditions⁵⁹.

The fourth mechanism is tensile-induced bending, which involves applying tensile forces directly to the artificial muscle to generate bending. The fibers are structured or arranged in such a way that tensile stress causes a controlled bending response⁶⁰. Tensile-induced bending actuation exhibiting an arm-like structure was demonstrated by Kanik et al.³³ and other research groups through the implementation of Humerus-Joint-Radius and Ulna configurations^{30,61}, which mimic the natural bending of biological limbs, such as the human arm, where bending occurs owing to the contraction of the bicep muscles. Artificial muscles designed to replicate this motion apply tensile forces along specific structural geometries to achieve controlled bending.

Isometric actuation

Isometric actuation in fiber-type artificial muscles involves generating force without changing length, making it crucial for applications needing static load maintenance or consistent pressure. Actuation stress, like tensile or compressive stress, is assessed through isometric force. The ability to produce substantial isometric force is essential in applications such as robotic grippers, biomedical devices, and soft robotics, for example, in situations involving load-bearing during bending while maintaining a fixed posture⁶². Moreover, isometric force generation can be considered as a useful parameter for evaluating the efficiency, strength, and reliability of these artificial muscles, precise control over tasks requiring steady force output. Electrochemical isometric actuation^{51,63–66} has been reported in various studies, for example, a mussel-inspired fiber demonstrated high performance with a maximum isometric contraction stress of 17.7 MPa⁶⁷. A nylon-based artificial muscle exhibited a 28.4 MPa, achieving over 100 times the isometric actuation stress of mammalian skeletal muscles (≈ 0.35 MPa)⁶⁸. A moisture-powered fiber actuator generated a maximum isometric stress of 24 MPa,

Fig. 3 | Tensile actuation of fiber-type artificial muscle. Tensile actuation of graphene and LCE composite fiber in response to an external stimulus, as visualized through thermal imaging (A) and actuation trend of LCE as a function of temperature, showing distinct heating and cooling responses (B). Reproduced with permission under Creative Commons CC BY license from ref. 14, copyright 2022, Springer Nature. C Scheme of moisture-induced elongation actuation of sodium alginate-based fiber. Reproduced with permission from ref. 32, copyright 2024 Royal Society of Chemistry. D Scheme of volume expansion and the resulting dimensional alterations in GO/CNT composite fibers that are straight, twisted, and excessively twisted into a coiled form. Reproduced with permission⁵². Copyright 2018, Elsevier. E Electrochemical actuation behavior of coiled CNT/rGO yarn in response to electrochemical ion insertion changes, demonstrating contraction upon charging and expansion upon discharging. Reproduced with permission⁵³. Copyright 2018, Elsevier. F Actuation mechanism of helical-structured nylon artificial muscles, illustrating the effect of chirality on actuation direction in homochiral and heterochiral structures. Reproduced with permission²⁸. Copyright 2014, The American Association for the Advancement of Science. G Maximization of tensile actuation through structural engineering of helical artificial muscles by varying helical diameter across different temperatures. Reproduced with permission²⁹. Copyright 2016, National Academy of Sciences.



approximately 68 times that of skeletal muscles, and was utilized for its lengthwise shrinkage properties in biomedical applications by maintaining isometric stress at both ends of an open wound, which gradually converted into contractile actuation, enabling effective wound closure³².

Application of fiber-type artificial muscles

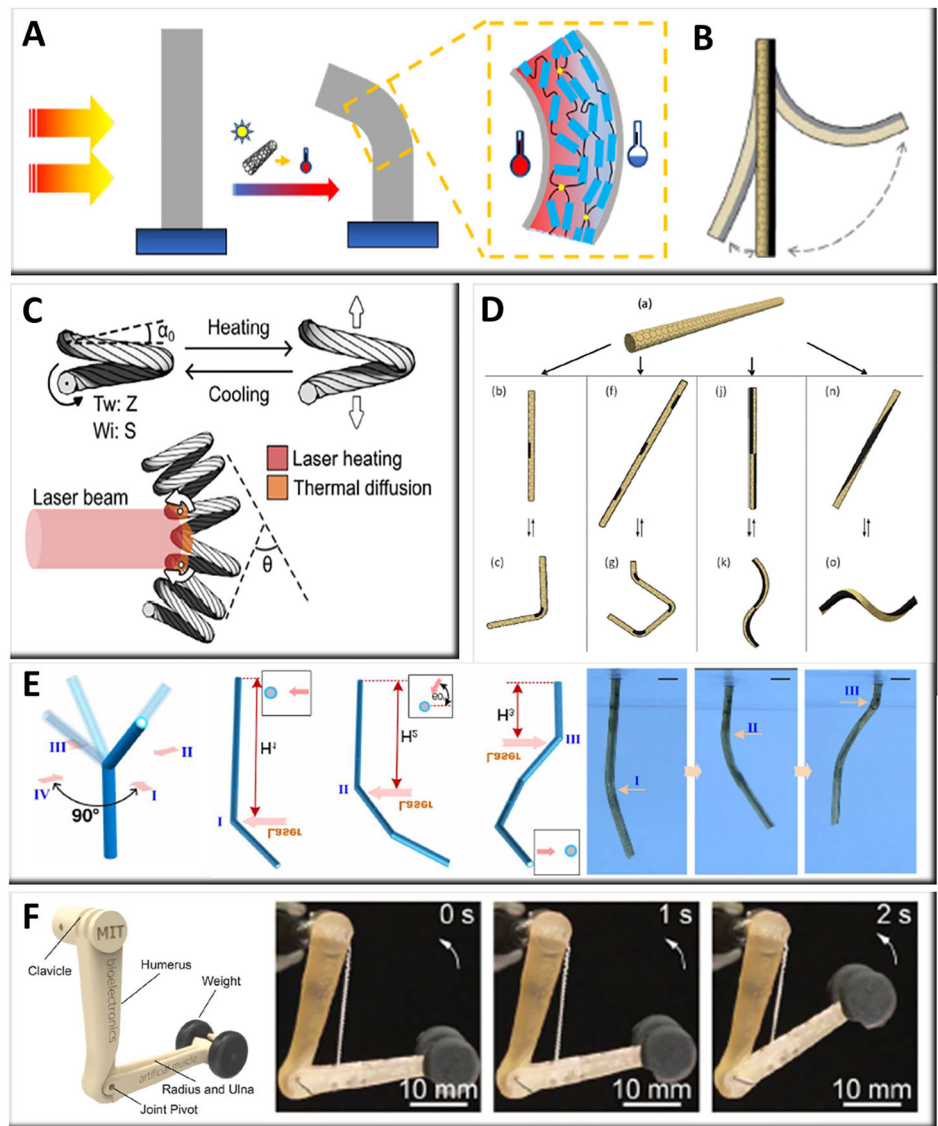
Figure 5 shows the diverse applications of fiber-type artificial muscles across domains such as wearable robots, locomotion robots, biomimetic robots and small-scaled robots. In wearable robotic application, fiber-type artificial muscle performs various and practical applications such as smart clothes, healthcare, and assistive suit robots^{13,61,69}. Figure 5A shows a smart wearable, tensile actuating muscles based on nontoxic viscose fibers exemplified by a humidity- and temperature-responsive sleeve that rolls up autonomously under elevated environmental conditions⁹. Fiber type artificial muscle also supports human motion as exoskeleton and exosuit, for instance, a low-temperature-operating polyethylene (PE) fiber muscle aids finger movement, demonstrating potential in assistive devices. (Fig. 5B)⁷⁰ Fig. 5C presents a light-responsive hemostatic bandage used in an isometric pressure application to reduce fluid flow in a simulated arm, illustrating both the physical constriction of the infusion tube and the real-time visualization of liquid flow⁶². Practical biomedical application such as wound closure and healing by moisture-adaptive contraction of sodium alginate-based fiber

was also performed. (Fig. 5D)^{32,51} Shape memory alloy-based wearable artificial muscles are applied in ankle, which provides antagonistic force to restore the ankle's position post-actuation which working as a walking assistance robot. (Fig. 5E)⁷¹

Locomotion robot applications of fiber-type artificial muscle include a crawling robot, a swimming robot, a jumping and flying robot⁵⁶. Biomimetic inchworm-like robots are enabled by CNT and LCE double-network fiber actuators, which facilitate crawling motion by applying an origami structure (Fig. 5G)⁷². Direct worm-like crawling was enabled by a multilinked coiled muscle system composed of two bars and four coiled muscles connected via linkers, exhibiting magnetically programmed bending under torque and contraction under RF magnetic heating. (Fig. 5H)⁷³ Fig. 5I shows a crawling robot driven by electrothermally activated CNT/PDMS coiled yarn muscles and equipped with ratchet wheels, demonstrated sequential crawling motion, achieving an 80 mm displacement at a speed of $2.67 \text{ mm} \cdot \text{s}^{-1}$ ¹². Crawling in pipe environment and free-standing locomotion of light-powered artificial muscle were performed. (Fig. 5J)^{21,74} Swimming actuation of miniaturized boat by a two-end tethered, electrochemically driven torsional muscle and flying actuation by biomimetic jumping actuation based on tensile actuation were performed. (Fig. 5K, L)^{43,75}

For biomimetic based robotic actuation, winding and color-changing motion of an artificial tendril made from a long, string-shaped anisotropic

Fig. 4 | Bending actuation of fiber-type artificial muscle. **A** Phototropic bending actuation of the CNT and LCE composite fiber actuated by near-infrared light. Reproduced with permission⁵⁶. Copyright 2021 Elsevier. **B** Bending actuation induced by humidity change of bilayered fiber structure by laser scan-induced reduction of graphene. Reproduced with permission¹⁹. Copyright 2013 WILEY-VCH Verlag GmbH & Co. KGaA. **C** Thermal untwisting of light-responsive multidirectional bending coiled artificial muscle fiber. Reproduced with permission under Creative Commons CC BY license from ref. 57, copyright 2024, Wiley-VCH GmbH. **D** Predetermined complex movements of graphene/GO fibers powered by moisture, which is achieved by selectively creating bilayer structures through laser patterning of the fiber. Reproduced with permission¹⁹. Copyright 2013 WILEY-VCH Verlag GmbH & Co. KGaA. **E** A laser-driven, shape-programmable artificial muscle based on LCE showing multidirectional bending by controlling the direction and position of laser exposure. Reproduced with permission under License 4.0 (CC BY-NC) from ref. 58. Copyright 2022, The American Association for the Advancement of Science. **F** Tensile induced, load lifting, bending, actuating fiber-based artificial muscle applying Humerus–Joint–Radius and Ulna. Reproduced with permission³³. Copyright 2016, National Academy of Sciences.



soft actuator, utilizing low-density polyethylene and a silver nanowire percolation network. (Fig. 5N)⁷⁶ For bionic-based robotic actuation, the untethered spatiotemporal control of an underwater soft robotic gripper, assembled using hetero spring (tensile actuation) and homo ring actuators (isometric actuation after catching an object) made from LCE was introduced. (Fig. 5O)²¹ A bionic arm utilizing a dual-tendon coiled actuator (DTCA) system features a tendon-driven hand and a hinge joint, each powered by separate DTCA bundles; the bundles enable grasping and flexion by forearm retraction, while integrated springs assist with payload handling. (Fig. 5P)²⁵.

The importance of small-scale robots for diagnosis, treatment, and surgery in the medical field is growing⁷⁷. Accordingly, microfluidic mixer which mix fluids by rotating paddle inside the microfluidic device, actuated by torsional electrochemically powered CNT muscle. (Fig. 5Q)⁵⁰ A shape-engineered elastomeric microtube-based micro-tentacle is capable of conformal wrapping around and securely grasping a *Mallotus villosus* egg was also introduced. (Fig. 5R)⁷⁸ In Fig. 5S and Fig. 5T, a medical application was demonstrated, highlighting the benefits of miniature artificial muscles. Figure 5S shows supercoiled muscle for high stroke, high work capacity for microtool as medical scissor, which converts tensile actuation to rotational movements of miniature scissors⁷⁹. Figure 5T shows leveraging the advantages of fiber-type wireless medical scissors is demonstrated through a

schematic illustrating a cutting device comprising 3D-printed magnetic components and cutting blades, where cutting is activated through RF magnetic heating⁷³. A wireless medical driller device was also demonstrated, showing practical performance of drilling agarose gel by about ~ 1.2 mN·m of torque generated by the coiled artificial muscle⁷³.

Conclusions and perspective

Fiber-type artificial muscles have emerged as a promising solution for robotic actuation, offering advantages such as high flexibility, lightweight nature, and adaptability to various surfaces, including textiles and curved structures. By classifying actuation into tensile, bending, torsional, and isometric modes, this review provides a structured understanding of biological muscle-inspired structures and mechanisms. The combination of advanced materials, structural modifications, and multifunctional capabilities has driven considerable progress in this field, thereby enhancing performance and applicability.

Recent advancements in fiber-type artificial muscles can be broadly classified into key domains such as material engineering, performance enhancement, and functional diversification. In the realm of material engineering, the development of composite systems has significantly increased actuation stress and responsiveness. On the structural front, innovations such as mandrel-based fabrication techniques and untethered,

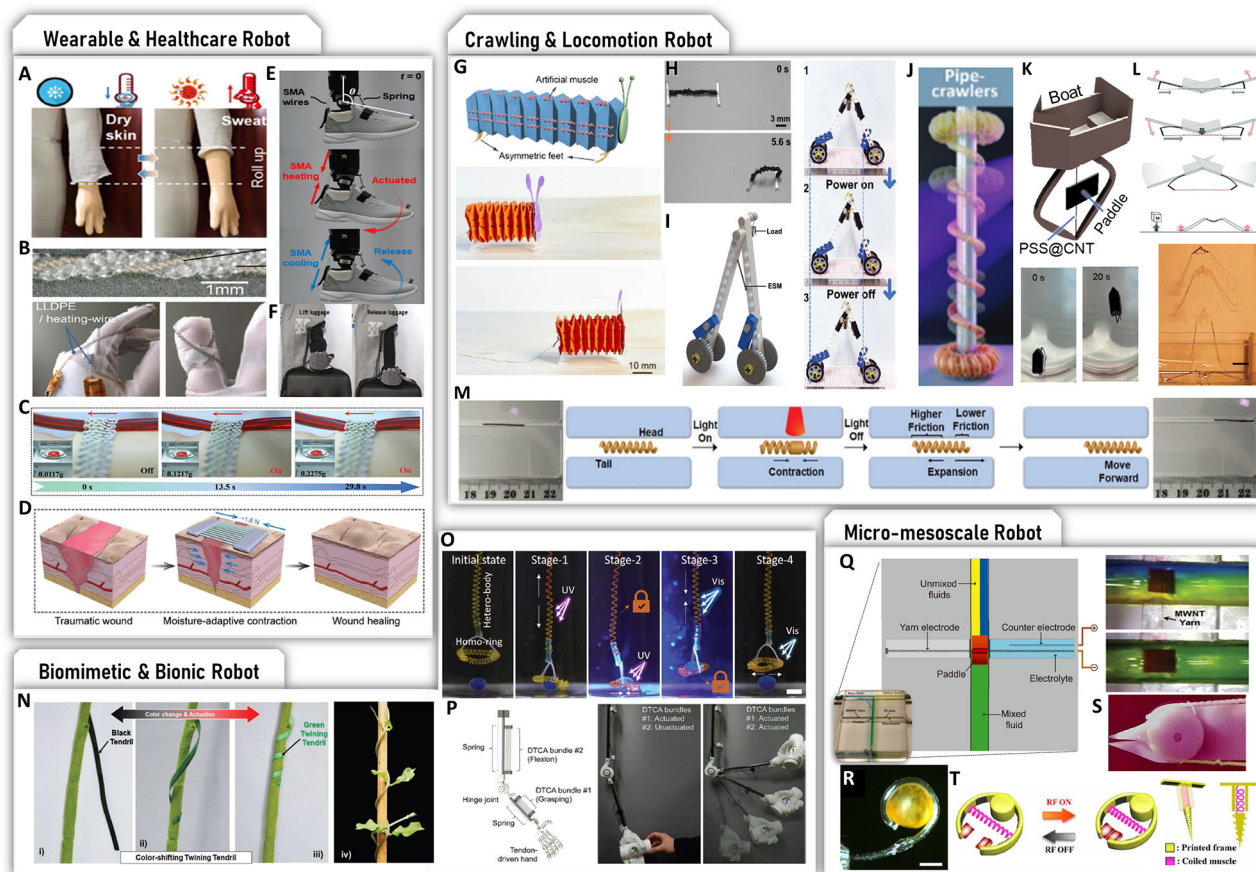


Fig. 5 | Various applications of fiber-type artificial muscles. Applications of fiber-type artificial muscles in wearable robotics (A–E), locomotion robots (F–L), biomimetic and bionic robots (M–P), and micro and mesoscale robots (Q–T). **A** Reprinted with permission from¹⁰¹ Copyright 2021 American Chemical Society. **B** Reproduced with permission under Creative Commons CC BY license from⁷⁰, Copyright © 2016, The Author(s) **C** Reproduced with permission under Creative Commons CC BY license from⁶², copyright 2024, Wiley-VCH GmbH. **D** Reproduced with permission under Creative Commons CC BY license from³², copyright 2023, Wiley-VCH GmbH. **E** Reproduced with permission under CC BY 4.0 license from⁷¹. **F** Reproduced with permission⁹ copyright 2022 Wiley-VCH GmbH. **G** Reprinted with permission from⁷². Copyright 2024 American Chemical Society. **H** Reproduced with permission under Creative Commons CC BY license from⁷³, Copyright © 2022, The American Association for the Advancement of Science. **I** Reproduced with permission¹². Copyright 2025 Wiley-VCH GmbH. **J** Reproduced with permission²¹. Copyright 2024 Wiley-VCH GmbH. **K** Reprinted

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freestanding artificial muscle configurations have enhanced applicability under diverse operating conditions^{26,80}. Self-supported system is also the structural progress being faced and addressed, including self-plied structure^{64,81,82}. To enhance various performance factors, a structural approach to artificial muscles, beyond simple twisting and coiling, is expected to be necessary, including the fabrication of higher-order coils such as hierarchically arranged structure^{83,84} and supercoil^{54,79,85}. The fiber bundle-type structure broadens the scope of future applications. Beyond simply scaling up through multifilament bundles or braided structures, fiber bundles can also be designed for multifunctional applications by integrating actuating fibers with sensory fibers⁸⁶. In addition, braid-shaped multifilament layers have been explored to construct one-body yarn-type artificial muscles, where the bundle serves as integrated anode and cathode layers⁸⁷.

Moreover, the development of multifunctional artificial muscles capable of self-healing, self-sensing, perceptive sensing, and energy harvesting opens new opportunities for intelligent and adaptive robotic systems^{88–91}. In particular, perceptive sensing of artificial muscle, which can sense length or

loads by integrated perception and actuation, is important because it enables real-time response to external environmental changes and allows precise, intelligent actuation in various real-world application^{86,92–94}. Meanwhile, the integration of bio-driven actuation systems has improved biocompatibility, paving the way for broader biomedical applications^{95,96}. Color-changing or transparent functionalities for robotic applications, such as camouflage, are promising features that can be integrated into fiber-type artificial muscles^{97,98}. Multifunctional artificial muscles that respond to multiple stimuli simultaneously are increasingly vital for wearable and robotic systems due to their enhanced programmability, remote controllability, for instance, the twisted GO/SA fiber-based actuator, which uses both infrared light and moisture to actuate smart nets and elevating bridges was reported 17.

Despite these advancements, several challenges remain, particularly in mass production, commercialization, and sustainability. Implementing fiber-type artificial muscles in textile form is a crucial starting point for the practical scale-up of this technology^{30,33}. Also, the fabrication of assistive garments using commercial artificial muscle yarns is one of the attempts

toward the commercialization of fiber-type artificial muscles⁶⁵. Developing scalable manufacturing methods and incorporating eco-friendly materials, such as cotton and lotus fibers, are crucial steps toward sustainable and practical applications^{18,39,76}. For a sustainable system for power supplying of artificial muscle, for example, a zinc-air powered carbon nanotube muscle was actuated by chemical energy without an external power supply⁹⁹. Addressing these challenges will require ongoing interdisciplinary research that integrates fiber fabrication techniques with scalable, sustainable, and cost-effective production strategies.

Looking forward, the future of fiber-type artificial muscles lies in leveraging novel materials and actuation techniques to bridge the gap between biological and synthetic motion systems. With ongoing technological progress, next-generation artificial muscles are expected to achieve unprecedented levels of efficiency, responsiveness, and versatility, paving the way for enhanced robotic capabilities and human augmentation.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

J.H.M. wrote the manuscript. J.H.M., S. H. Ko, and S.J.K. conceptualized and conceived the study and edited the manuscript. J.H.M., J.S.H., H.K., and S. H. Kim investigated and analyzed the data. S. H. Ko and S.J.K. supervised the research.

Competing interests

The authors declare no competing interests.

Additional information

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