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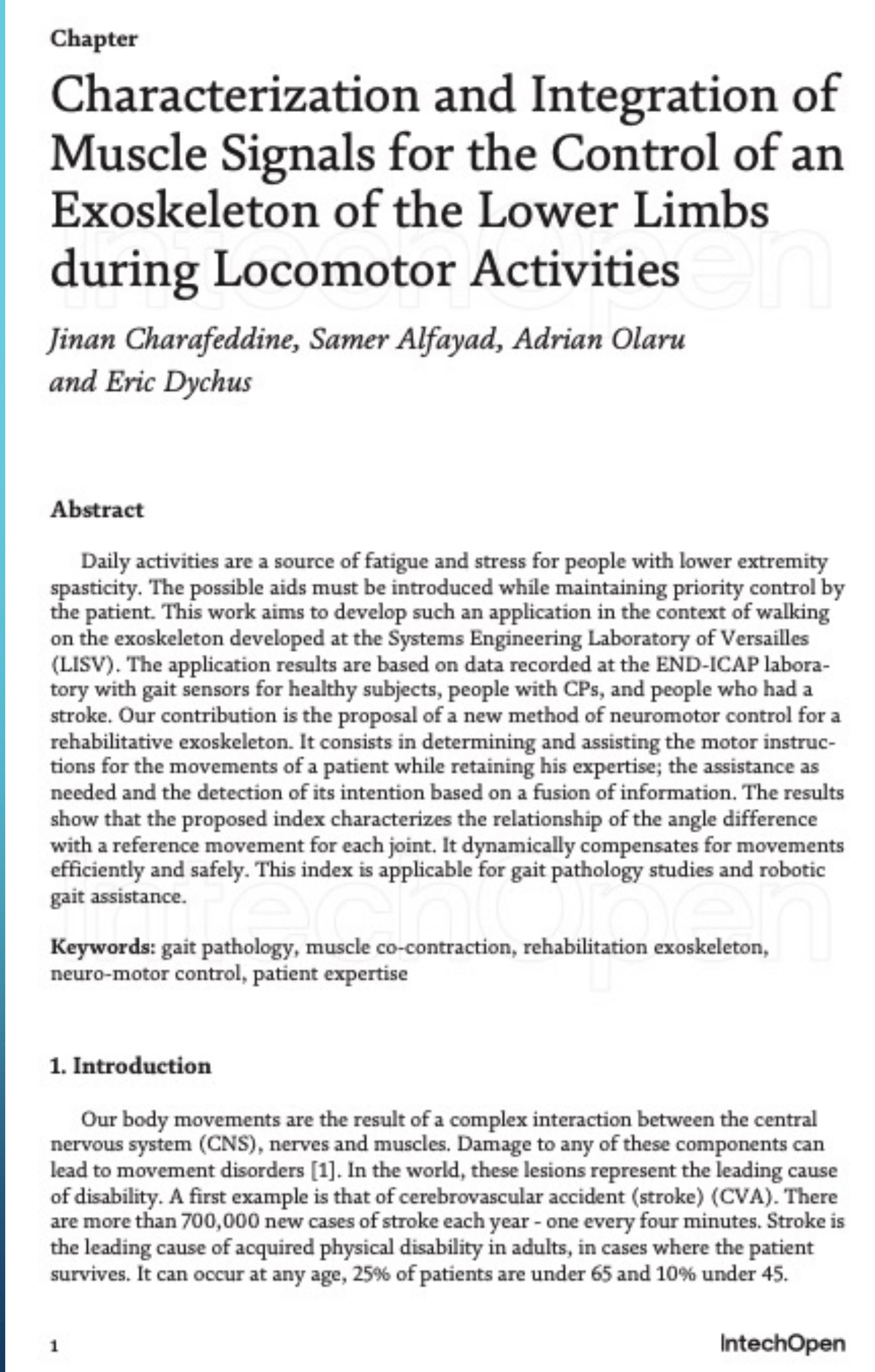

Chapter

Characterization and Integration of Muscle Signals for the Control of an Exoskeleton of the Lower Limbs during Locomotor Activities

Jinan Charafeddine, Samer Alfayad, Adrian Olaru and Eric Dychus

Abstract

Daily activities are a source of fatigue and stress for people with lower extremity spasticity. The possible aids must be introduced while maintaining priority control by the patient. This work aims to develop such an application in the context of walking on the exoskeleton developed at the Systems Engineering Laboratory of Versailles (LISV). The application results are based on data recorded at the END-ICAP laboratory with gait sensors for healthy subjects, people with CPs, and people who had a stroke. Our contribution is the proposal of a new method of neuromotor control for a rehabilitative exoskeleton. It consists in determining and assisting the motor instructions for the movements of a patient while retaining his expertise; the assistance as needed and the detection of its intention based on a fusion of information. The results show that the proposed index characterizes the relationship of the angle difference with a reference movement for each joint. It dynamically compensates for movements efficiently and safely. This index is applicable for gait pathology studies and robotic gait assistance.

Keywords: gait pathology, muscle co-contraction, rehabilitation exoskeleton, neuro-motor control, patient expertise

1. Introduction

Our body movements are the result of a complex interaction between the central nervous system (CNS), nerves and muscles. Damage to any of these components can lead to movement disorders [1]. In the world, these lesions represent the leading cause of disability. A first example is that of cerebrovascular accident (stroke) (CVA). There are more than 700,000 new cases of stroke each year - one every four minutes. Stroke is the leading cause of acquired physical disability in adults, in cases where the patient survives. It can occur at any age, 25% of patients are under 65 and 10% under 45.

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29 JUNE – 3 JULY

ARTIFICIAL MUSCLE FOR EXOSCHELETONS AND HUMAN ROBOTS- OVERVUE

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ACRONIMES

- shape memory alloys (SMA)
- dielectric elastomer actuators (DEAs)
- electroactive polymer (EAP)
- ionic polymer-metal composites (IPMC)
- shape memory polymer (SMP)
- soft fluidic actuator (SFA)
- twisted string actuators (TSAs)
- super-coiled polymer (SCP)

1.INTRODUCTION

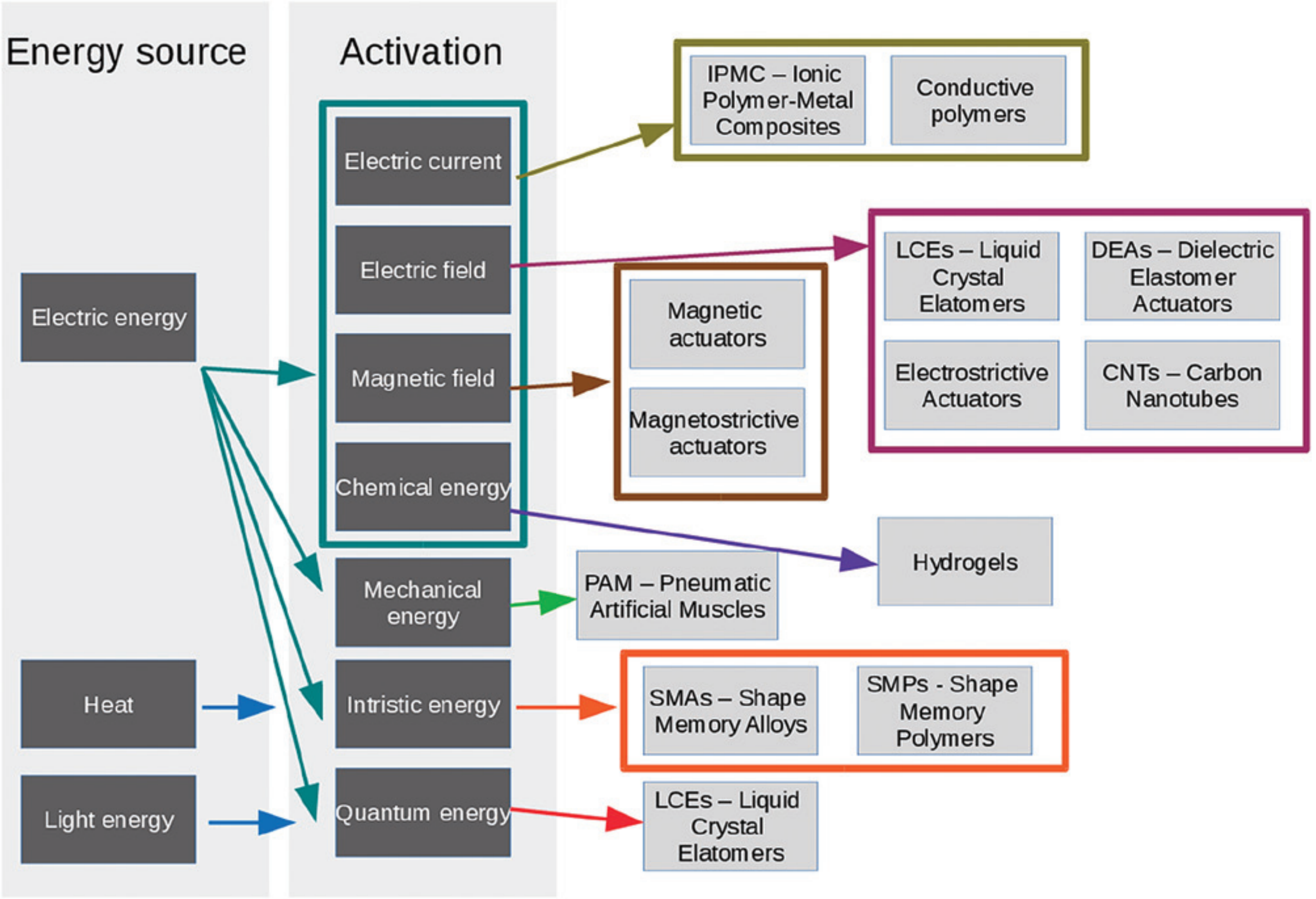
- Artificial muscles are broadly defined as the materials and devices that can change their shapes under external chemical or physical stimuli [1]–[3]. A subset of artificial muscles, defined as robotic artificial muscles, are actuators that conform to biologically inspired manners to generate work.
- These actuators, ranging from shape memory alloys (SMA) to dielectric elastomers, offer many advantages over conventional rigid actuators (e.g., electric motors) – i.e.,

➢high power-to-weight ratio,

➢high force-to-weight ratio,

➢inherent compliance, and all without complex linkages [4]–[9].

Robotic artificial muscles have shown strong potential as driving mechanisms for novel robotic applications such as robot manipulators and grippers, biomimetic robots, robotic prosthetics and exoskeletons, medical robots, soft robots, and many others [10]–[16].


Energy source
Activation
Electric energy
Heat
Light energy
Electric current
Electric field
Magnetic field
Chemical energy
Mechanical energy
Intristic energy
Quantum energy
IPMC – Ionic Polymer-Metal Composites
Conductive polymers
LCEs – Liquid Crystal Elatomers
DEAs – Dielectric Elastomer Actuators
Electrostrictive Actuators
CNTs – Carbon Nanotubes
Magnetic actuators
Magnetostrictive actuators
Hydrogels
PAM – Pneumatic Artificial Muscles
SMAs – Shape Memory Alloys
SMPs - Shape Memory Polymers
LCEs – Liquid Crystal Elatomers

Artificial muscles are made from electroactive polymers (EAPs), which are simple, lightweight strips of highly flexible plastic.

EAPs can be stimulated to change shape or size through activation mechanisms via chemical, thermal, pneumatic, optical, electric, or magnetic means.

EAPs are divided into two major categories based on their activation mechnism:

- electronic (driven by electric field) and
- ionic (driven by diffusion of ions) types.

Electronic EAP and Ionic EAP:

Dielectric EAP; Electrostrictive Graft Elastomers; Electrostrictive Paper; Electro-Viscoelastic Elastomers; Ferroelectric Polymers; Carbon Nanotubes (CNT); Conductive Polymers (CP); ElectroRheological Fluids (ERF); Ionic Polymer Gels (IPG); Ionic Polymer Metallic Composite (IPMC)

- **Electronic EAPs** *are driven by Coulomb forces and they can be made to hold the induced displacement while activated under a DC voltage*. These EAP materials have high mechanical energy density and they can be operated in air with no major constraints. They require a high activation field (>30 MV/m) that can cause uncomfortable electric shocks. The advantages of electronic EAPs are fast reactivity and delivery of strong mechanical forces. They do not need a protective coating and require almost no current to hold a position.
- **Ionic EAPs** *are driven by the mobility or diffusion of ions and they require two electrodes and an electrolyte for activation*. They require as low as 1-2 volts to induce a bending displacement. The disadvantages of using ionic EAP materials are the need to maintain wetness and the difficulties in sustaining constant displacement under activation of a DC voltage. The other major shortcoming is that if the voltage is above a certain level, electrolysis occurs, which causes irreversible damgage to the material.

EAP type Advantages Disadvantages

Electronic EAP:

- Exhibit rapid response (milliseconds)
- Can hold strain under DC activation
- Induces relatively large actuation forces
- Exhibits high mechanical energy density
- Can operate for a long time in room conditions
- Requires high voltages (~100 MV/meter)
- Independent of the voltage polarity, it produces mostly monopolar actuation due to associated electrostriction effect

Ionic EAP:

- Natural bi-directional actuation that depends on the voltage polarity
- Requires low voltage
- Some ionic EAP like conducting polymers have a unique capability of bi-stability
- Requires using an electrolyte
- Requires encapsulation or protective layer in order to operate in open air conditions
- Low electromechanical coupling efficiency
- Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage

- Slow response (fraction of a second)
- Bending EAPs induce a relatively low actuation force
- Electrolysis occurs in aqueous systems at >1.23 V

The background of the work is that Danfoss A/S, a major Danish industrial company, has developed a new actuator technology based on the Electro Active Polymer (EAP) materials. Danfoss started its work on EAP in 1998 in a Z. Fan, K. Raun, L. Hein and H.-E. Kiil collaboration project **ArtMus** together with the Danish Polymer Centre at Resø, and the Department of Chemistry at DTU [4].

In spring 2006, a venture project called **PolyPower** was initiated at Danfoss to investigate the possibilities of scaling up production and design new actuators and applications based on EAP. Up to now, Danfoss has accomplished manufacturing actuators in an up-scaled laboratory level and is looking into larger-scale manufacturing and application possibilities.

There are three main types of artificial muscles.

SMA – Shape Memory Alloys
EAC – Electro Active Ceramics
EAP – Electro Active Polymers

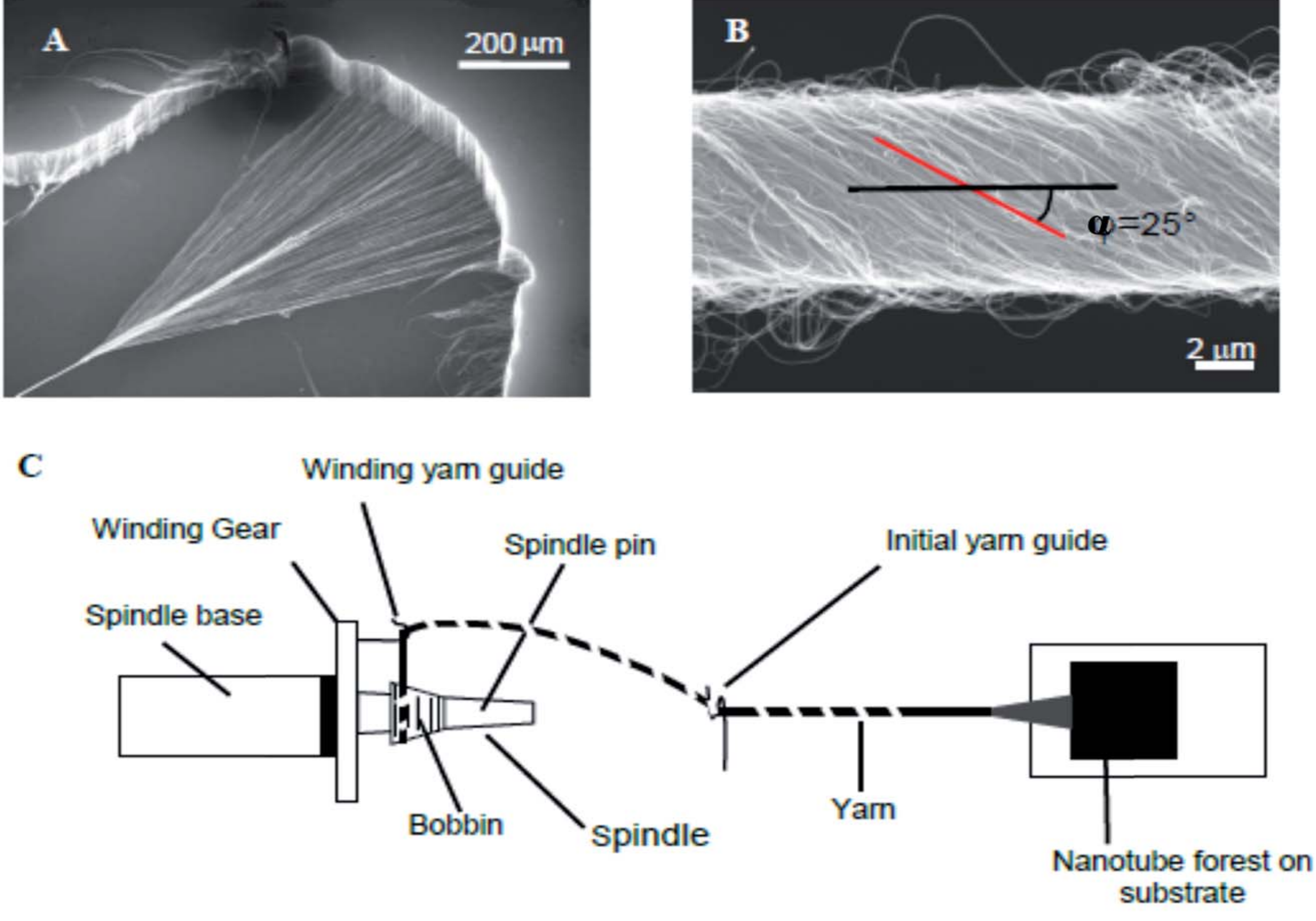
Property	Human muscle	SMA	EAC	EAP
Actuation strain [%]	20% (max. 40%)	< 8%	Max. 0.3%	> 300%
Force [MPa]	0.1	200	40	25
Reaction speed	msec	msec to min	µsec to sec	µsec to min
Density [kg/m^3]	1037			960-1100
Power to mass [$W \cdot kg^{-1}$]	50 (max.200)	3500		Up to 3500
Drive voltage	-	5V	50-800V	Ionic:1-7 V, Electronic: 10-150V/µm
Consumed power	-	Watts	Watts	Milli-watts
Fracture toughness	High and can self repair	Resilient, elastic	Fragile	Resilient, elastic

2.CARBON NANOTUBE AND GRAPHENE FIBER ARTIFICIAL MUSCLES

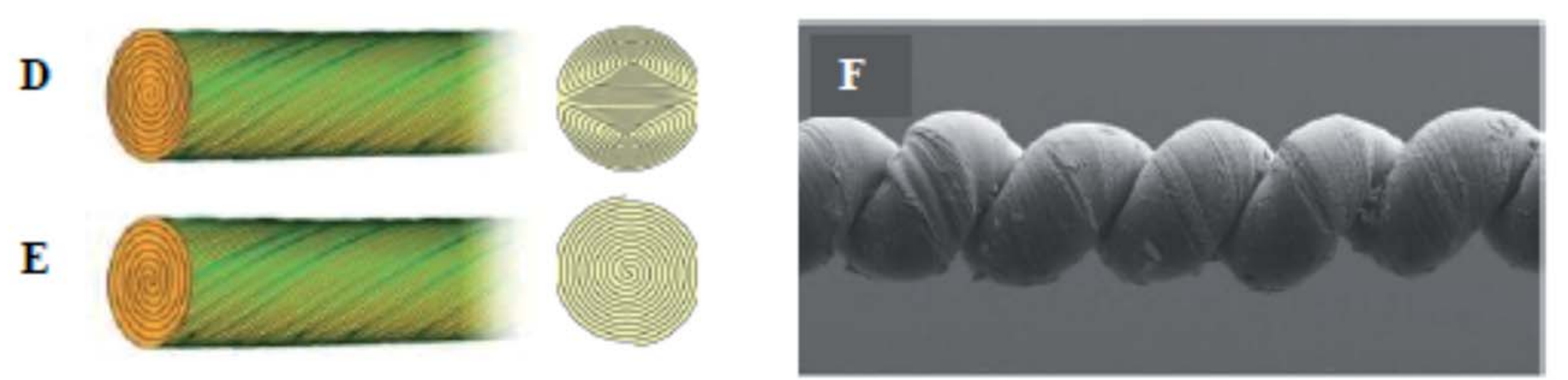
Actuator materials capable of producing a rotational or tensile motion are rare and, yet, rotary systems are extensively utilized in mechanical systems like electric motors, pumps, turbines and compressors.

Rotating elements of such machines can be rather complex and, therefore, difficult to miniaturize. Rotating action at the microscale, or even nanoscale, would benefit from the direct generation of torsion from an actuator material.

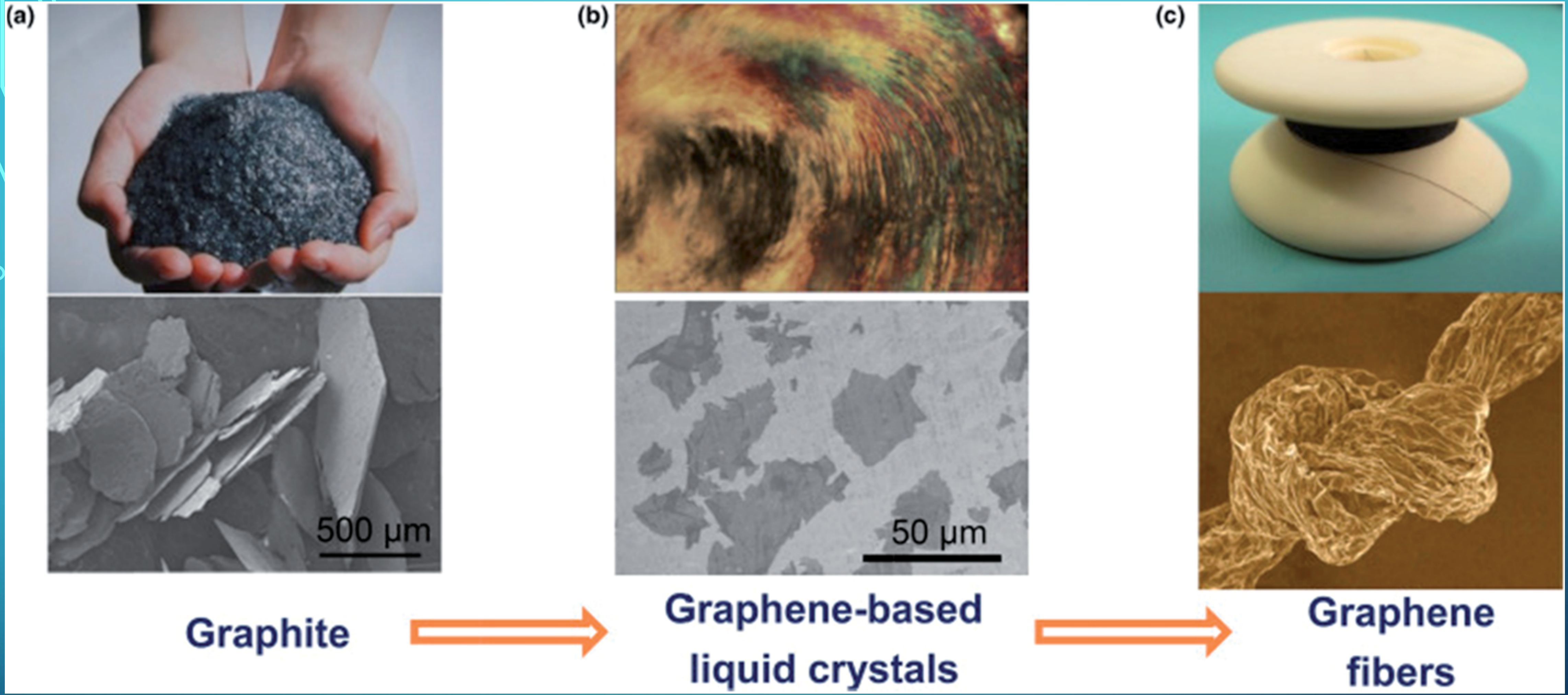
Herein we discuss the advantages of using **carbon nanotube (CNT)** yarns and/or **graphene (G) fibers** as novel artificial muscles that have the ability to be driven by the electrochemical charging of helically wound multiwall carbon nanotubes or graphene fibers as well as elements in the ambient environment such as moisture to generate such rotational action.



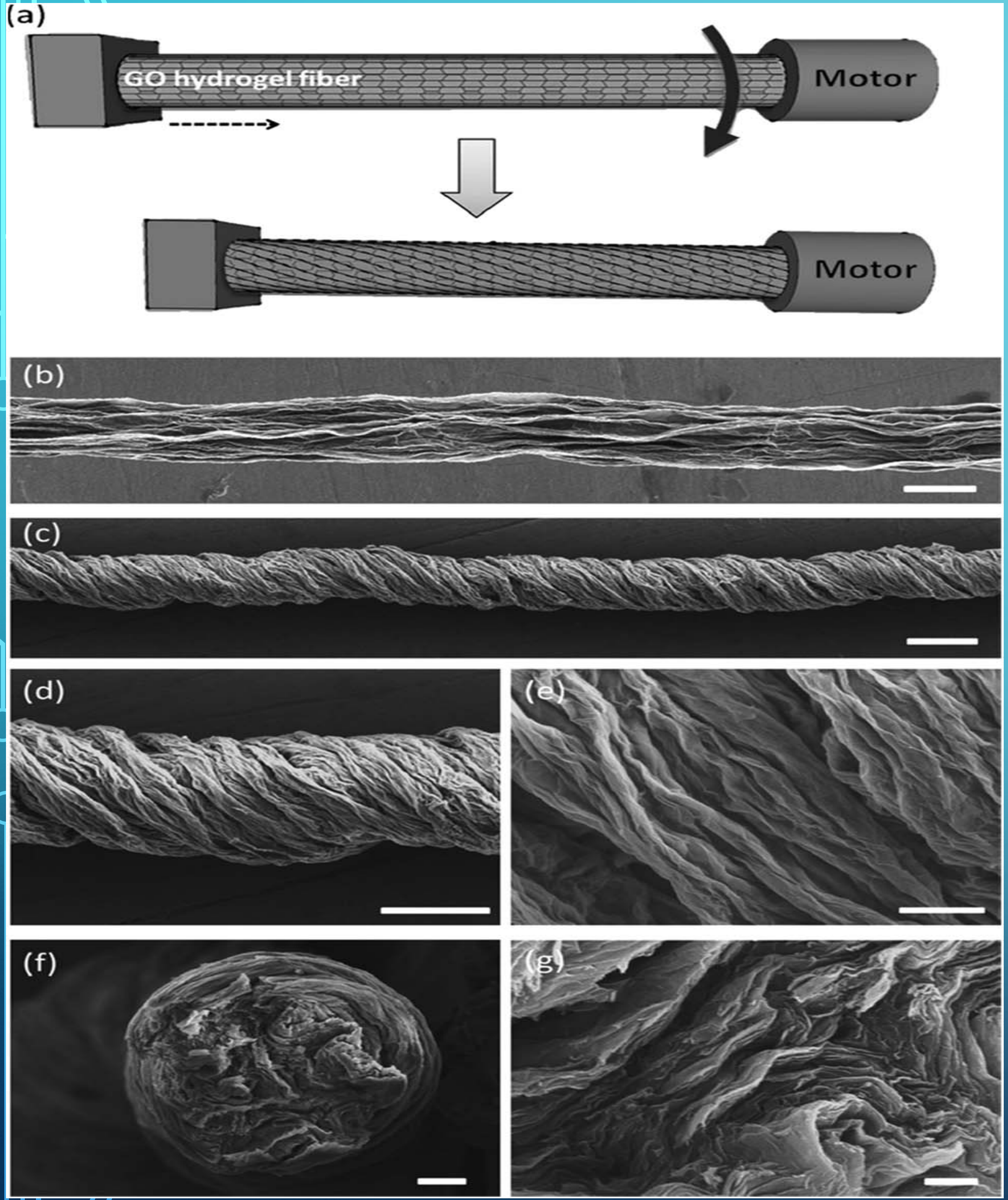
(A) SEM micrograph of a MWNT forest and (B) SEM micrograph of a carbon nanotube yarn that was symmetrically twist spun from a MWNT forest. Schematic diagram of spinning of a MWNT yarn from a multi-walled carbon nanotube forest (C)



Idealized cross-sections for Fermat (D) and dual-Archimedean (E) scroll structures spun symmetrically and highly asymmetrically, respectively, from a carbon nanotube forest. (F) SEM micrograph of a coiled, wax-infiltrated hybrid MWNT yarn.



The road from graphite to graphene fibers. In the first step, graphite crystals (a) are exfoliated into individual graphene sheets, usually by chemical modification. The modified graphene sheets form liquid crystals in solvents with orientational or positional order (b). In the second step, wet-spinning assembly is employed to make continuous graphene fibers (c) from these graphene-based liquid crystals, which transform order from the fluid state to order in the solid state. This figure has been reproduced from ref. 36 with permission from Elsevier.



Fabrication and characterization of graphene fibber artificial muscles,

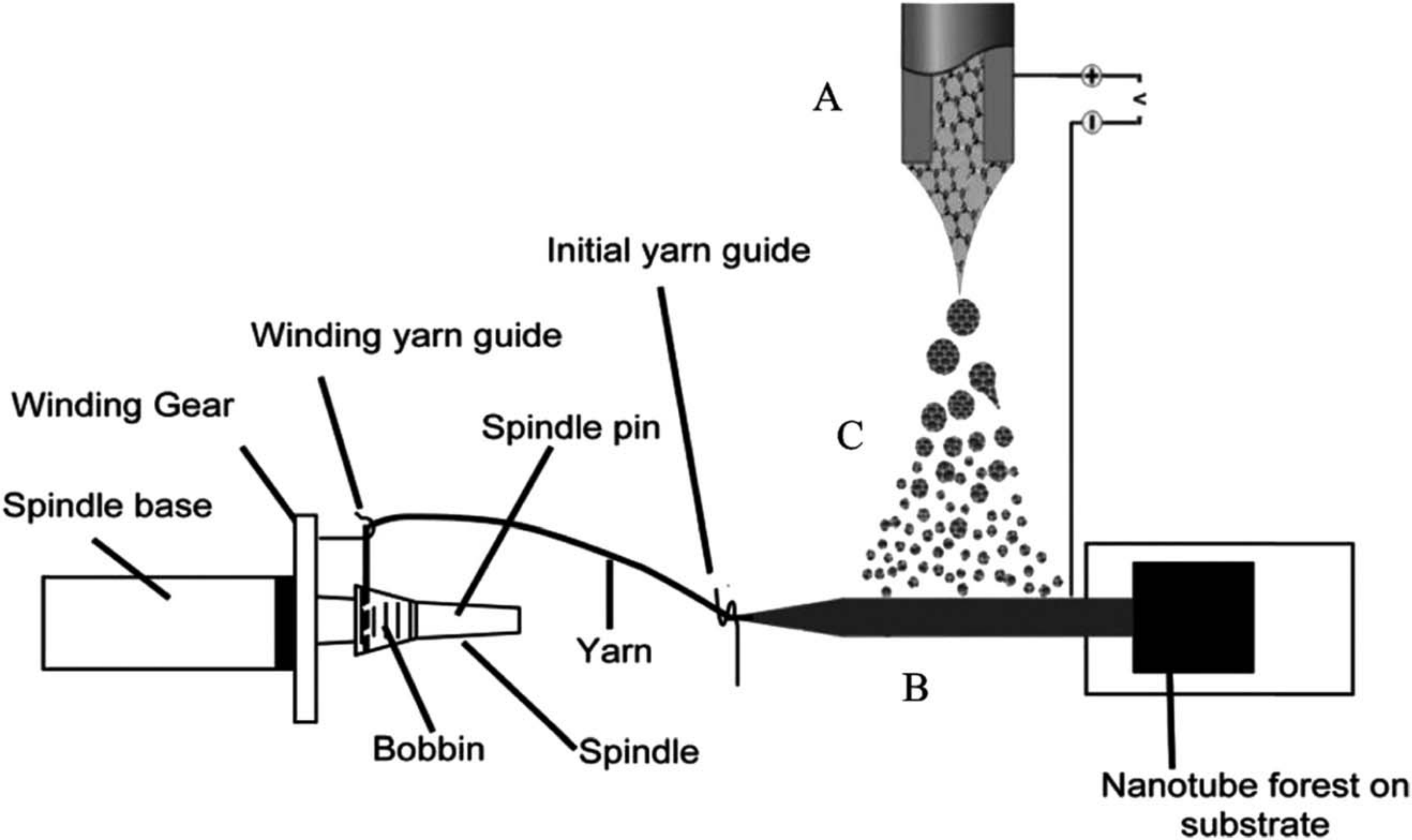
(a) scheme of the graphene fibber fabrication; the arrow indicates the direction of rotation;

(b and c) SEM images of the directly dried graphene fibber and twisted graphene fibber;

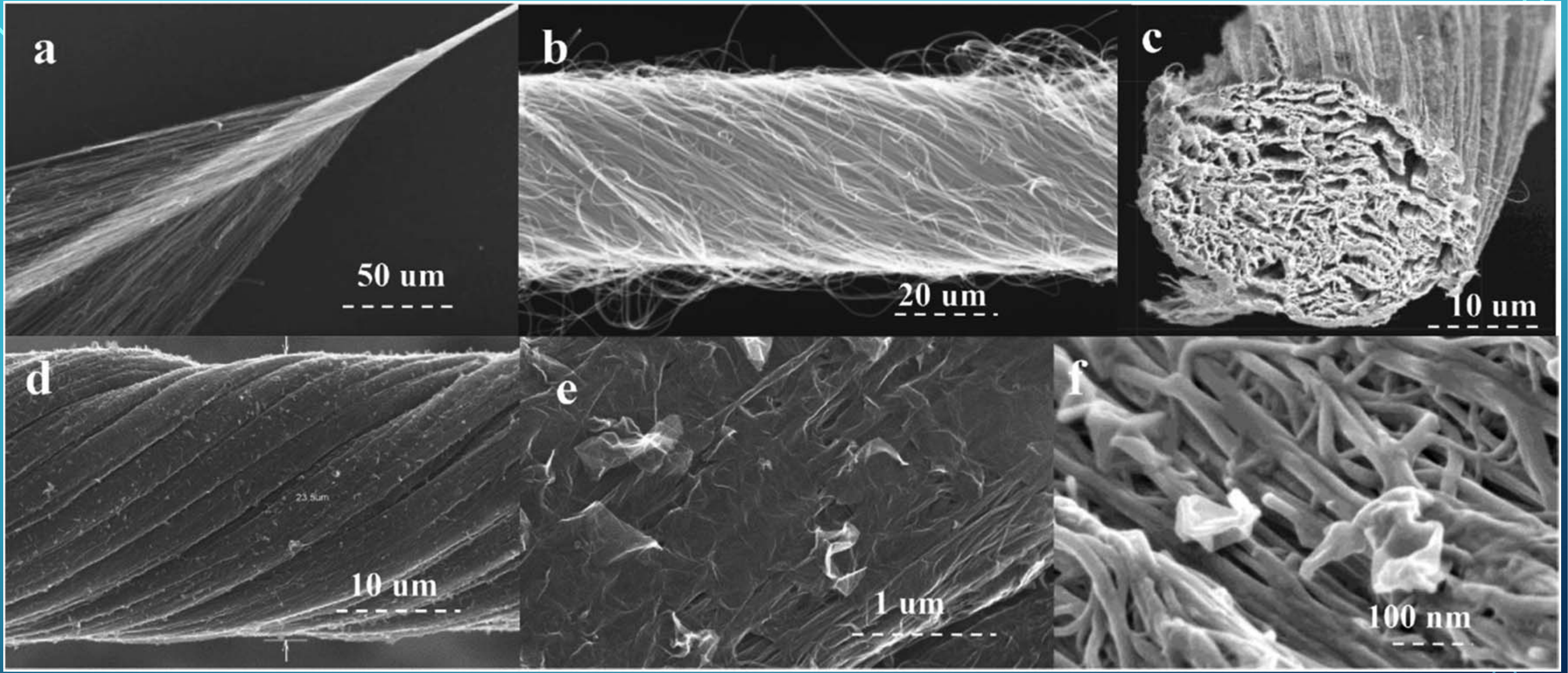
(d and e) enlarged view of the twisted graphene fibber and its surface respectively;

(f) cross-section of a graphene fibber;

(g) enlarged cross-section of the graphene fibber.



Schematic diagram of a continuously produced hybrid Carbon Nano Tube (CNT)/graphene yarn. (A) Electrospinning setup used for graphene deposition; (B) MWNT sheet drawn from a spinnable forest and employed as the graphene collector; (C) graphene dispersion (electrospray).



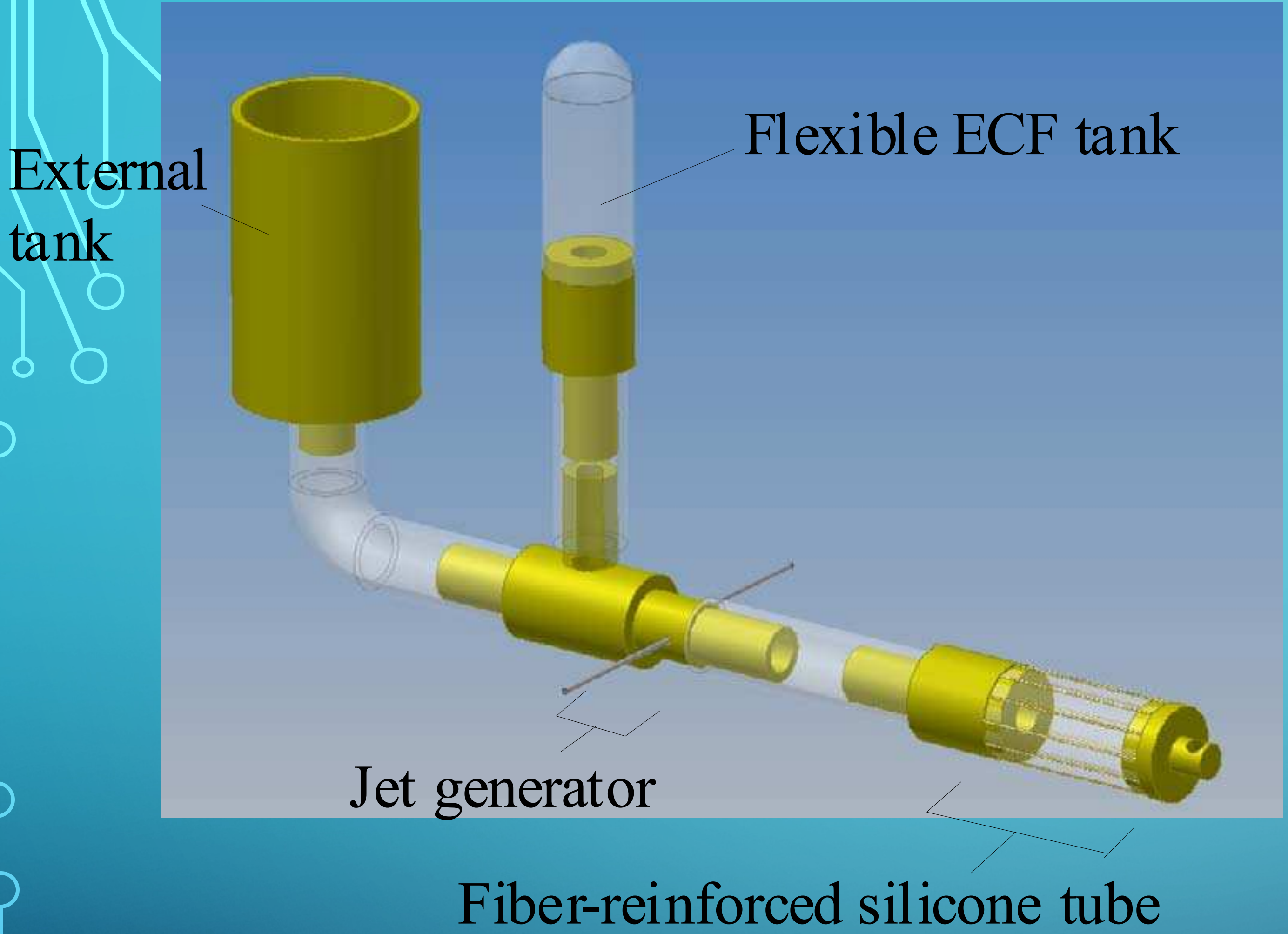
SEM images of (a) the CNT forest during twist insertion to form pristine yarns, (b) the pristine CNT yarn, and the hybrid carbon nanotube– graphene yarn: cross-section (c) at low and (f) high magnification; hybrid yarn surface (d) at low and (e) high magnification.

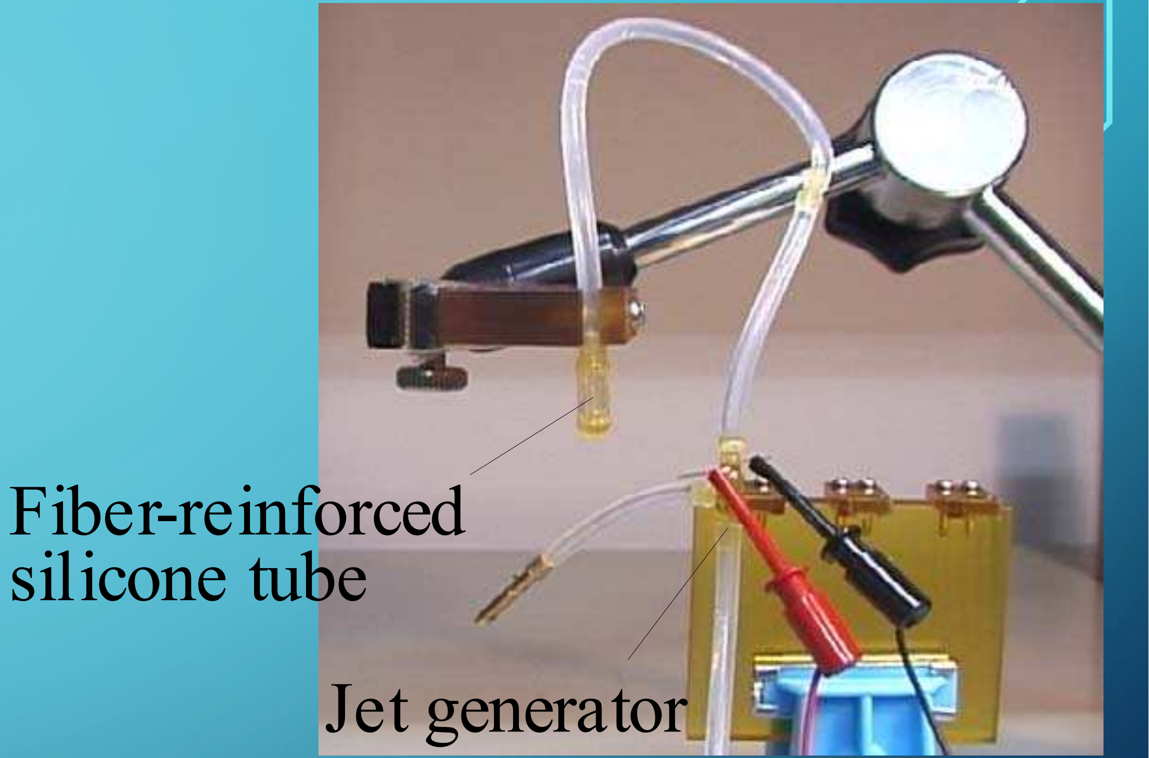
3. ELECTRO-CONJUGATE FLUID

- The electro-conjugate fluid (ECF) is a kind of dielectric fluids, which works as a smart fluid (functional fluid). Applying high voltage (several kV) between electrodes inserted into the fluid, we can observe an active jet flow between the electrodes. Although a high voltage is needed to generate the jet flow, the current consumption is quite low (several A). The qualitative phenomenon itself is known as an electro-hydrodynamics (EHD) effect [12].

A major advantage the proposed micro artificial muscle actuator is that it includes the micro pressure source inside the actuator. This enables us to construct a compact artificial muscle, and then, it is easy to apply the actuator to autonomous systems. Furthermore, we can arrange the micro artificial muscle actuators in an array to obtain larger stroke or force just like natural systems do.

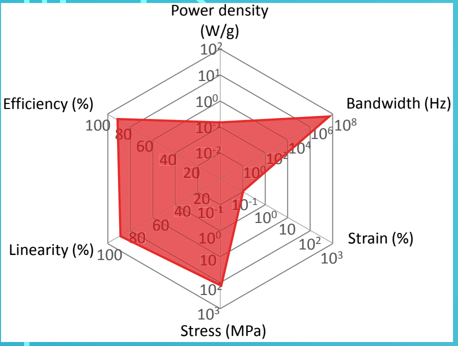
The maximum normalized contraction and normal force obtained were about 0.16 of the initial length and 0.2 N, respectively.



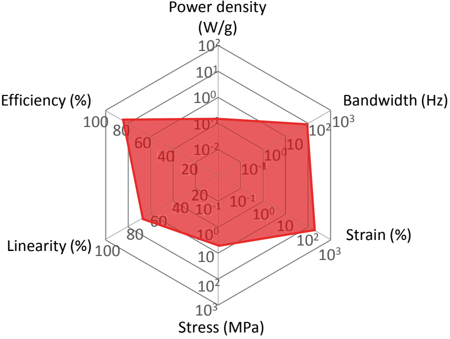


Schematic illustration of the prototype

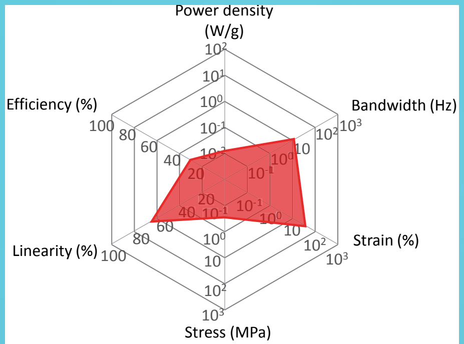
4. ROBOTIC ARTIFICIAL MUSCLES



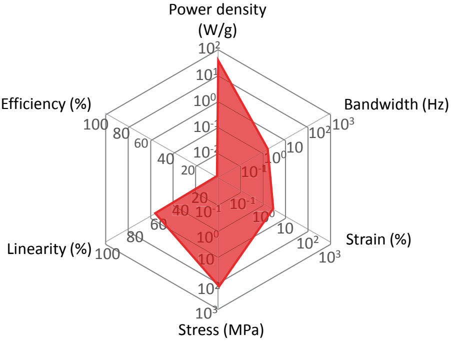
(a) Piezoelectric



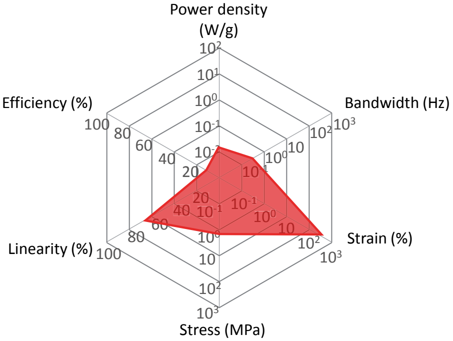
(b) Dielectric elastomer actuator (DEA)



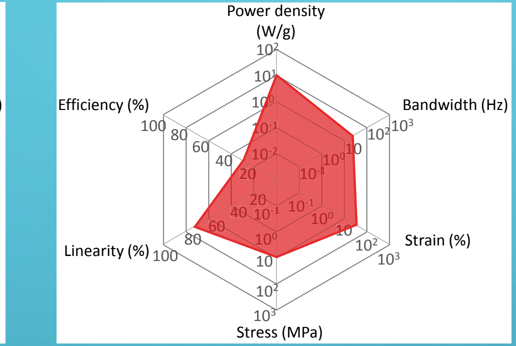
(c) Ionic polymer-metal composite (IPMC)



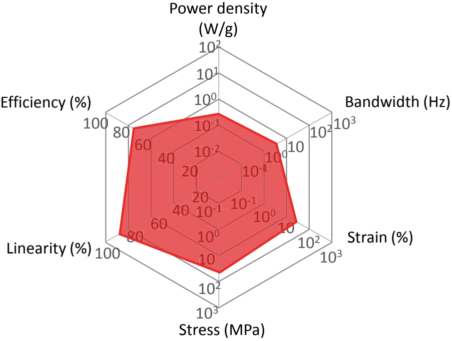
(d) Shape memory alloy (SMA)



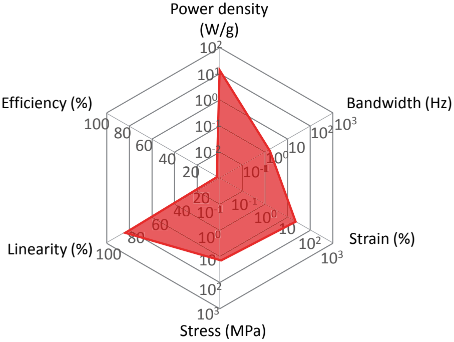
(e) Shape memory polymer (SMP)



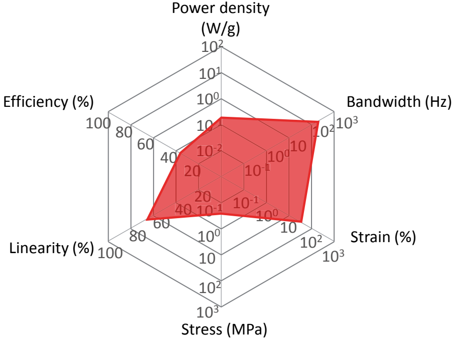
(f) Soft fluidic actuator



(g) Twisted string actuator (TSA)



(h) Super-coiled polymer (SCP)



(i) Skeletal muscle

This figure should be used as a high-level comparison between actuators, keeping in mind that variations on individual actuators may shift their characteristic charts slightly;

(a) Piezoelectric actuators, PA have the highest bandwidth and efficiency [27], but exhibit low strain and low power density [28].

(b) Dielectric elastomer actuator, DEAs produce large strain, reasonably high bandwidth, and high efficiency, but require high voltage [29].

(c) Ionic polymer metal composite, IPMC actuators require low working voltage and can work in aquatic environment, but have low power density and stress [30].

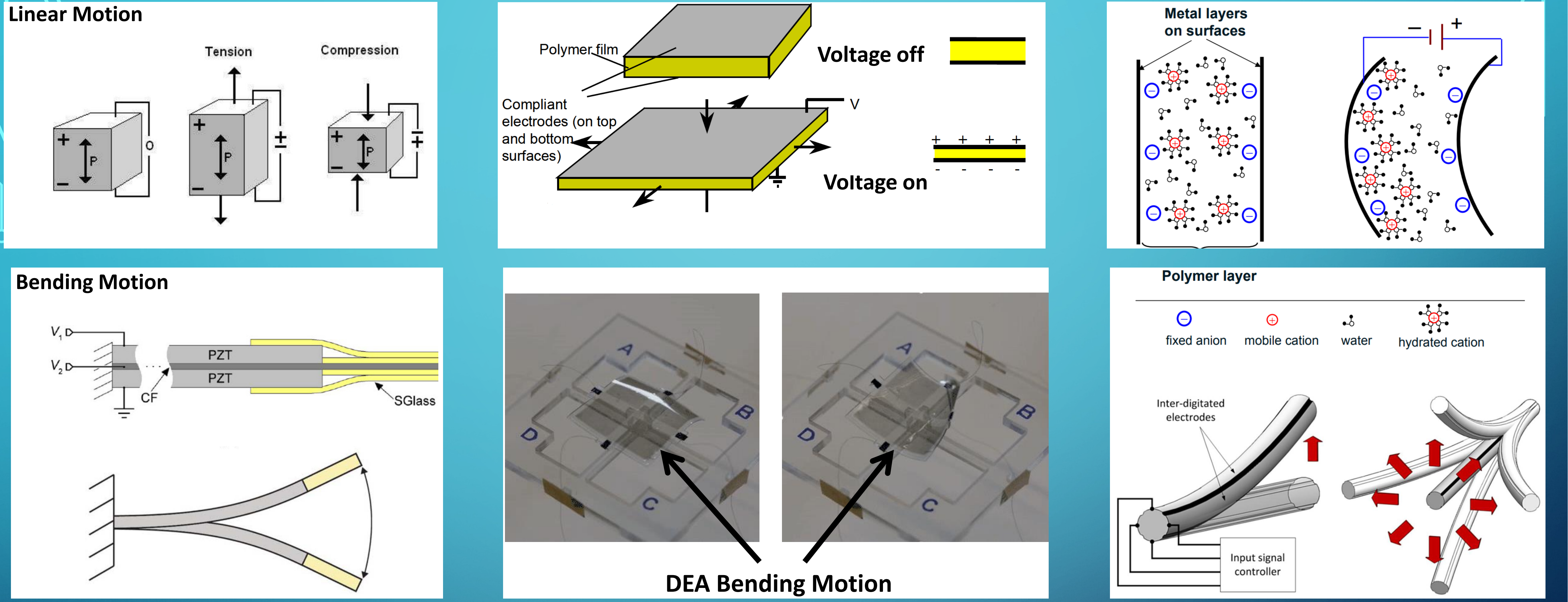
(d) Shape memory alloy, SMA actuators have the highest power density and stress [31], but also high nonlinearity and low efficiency (lower than 1.3%) [18],

(e) Shape memory polymer, SMP actuators can produce very large strain [29], but can be slow [32].

(f) Soft fluidic actuators, SFA have high power density and good bandwidth, but the required compressors or air sources reduce the effective power to weight ratio [33], [34].

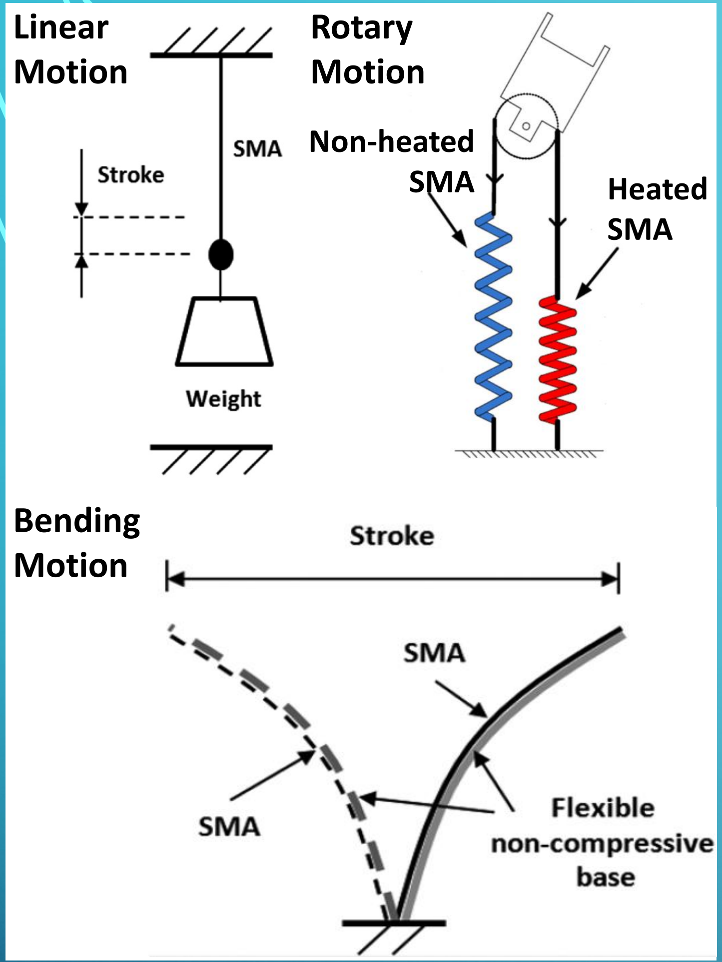
(g) Twisted string actuator, TSAs are intrinsically compliant with good efficiency, but have limited bandwidth and contraction stroke [35], [36].

(h) Super coiled polymer, SCP actuators demonstrate large actuation range and significant mechanical power, but have limited bandwidth and low efficiency which ranges from 0.71% to 1.32% [37], [38].

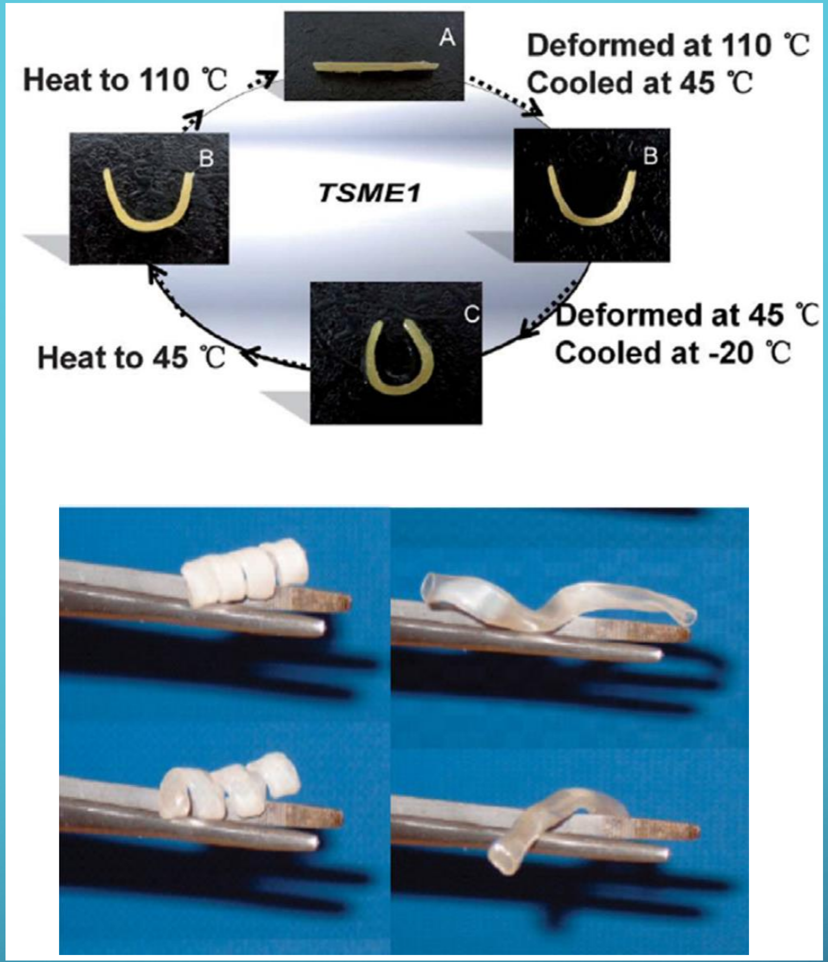


(a) Piezoelectric actuator (b) DEA (c) IPMC actuator

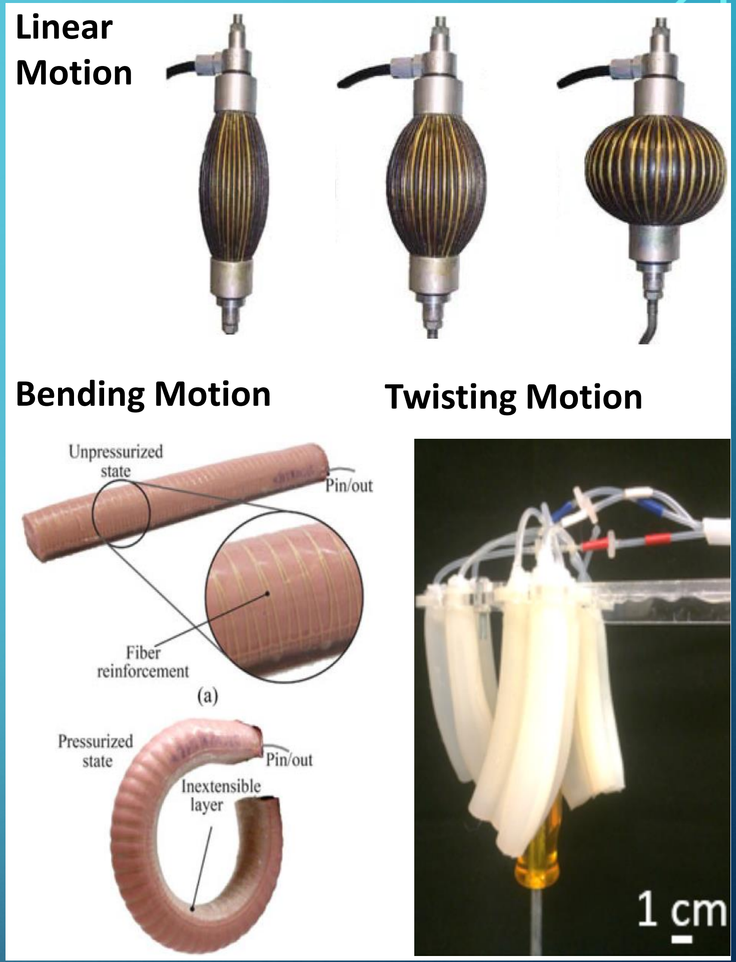
(a). Piezoelectric actuators can produce motion under electric fields due to the converse piezoelectric effect [39] (top). Bending motions can be realized [12] (bottom). (b). Dielectric elastomer actuator, DEA reduces thickness when the differential voltage is applied between the electrodes due to the Coulomb charge attraction effect [40] (top). Bending motion can be realized [9] (bottom). (c). Ionic polymer metal composite, IMPC actuator produces bending motions under an electrical field due to the the fluid-induced swelling force and the electrostatic force [41] (top). Multiple-degree-of-freedom motions can be realized [42].



(d) SMA actuator

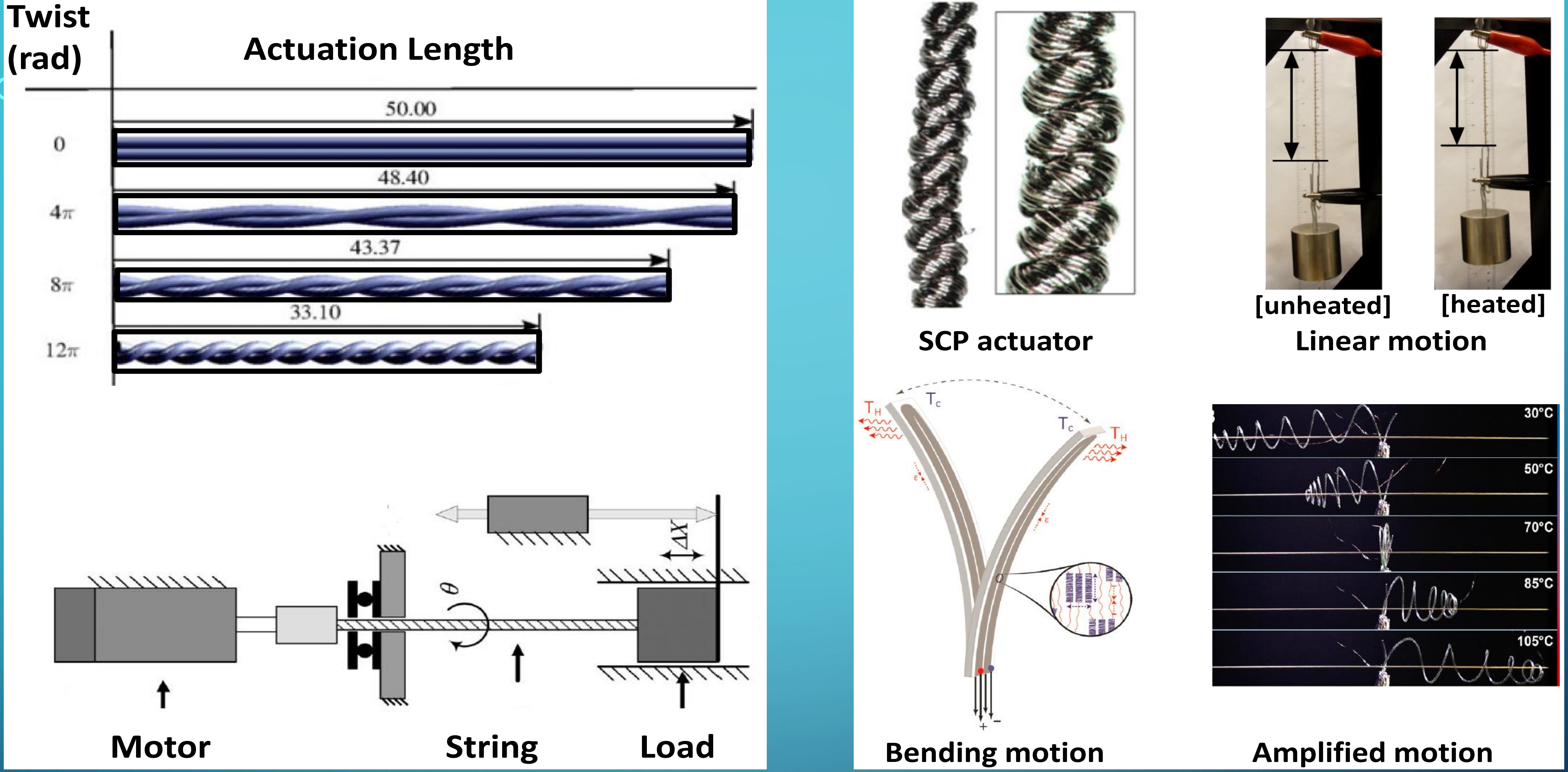


(e) SMP actuator



(f) Soft fluidic actuator

(d). Shape memory alloy, SMA actuators can produce contractions and elongations under temperature changes due to phase transition. Bending and rotary motions can be realized [11], [31]. (e). Shape memory polymer, SMP actuators can undergo a recoverable deformation and produce complex bending, twisting, folding motions due to shape memory effect [43]. (f). Soft fluidic actuators can produce linear motions under different pressure environments [44]. Bending [45] and twisting motions [46] can be realized.

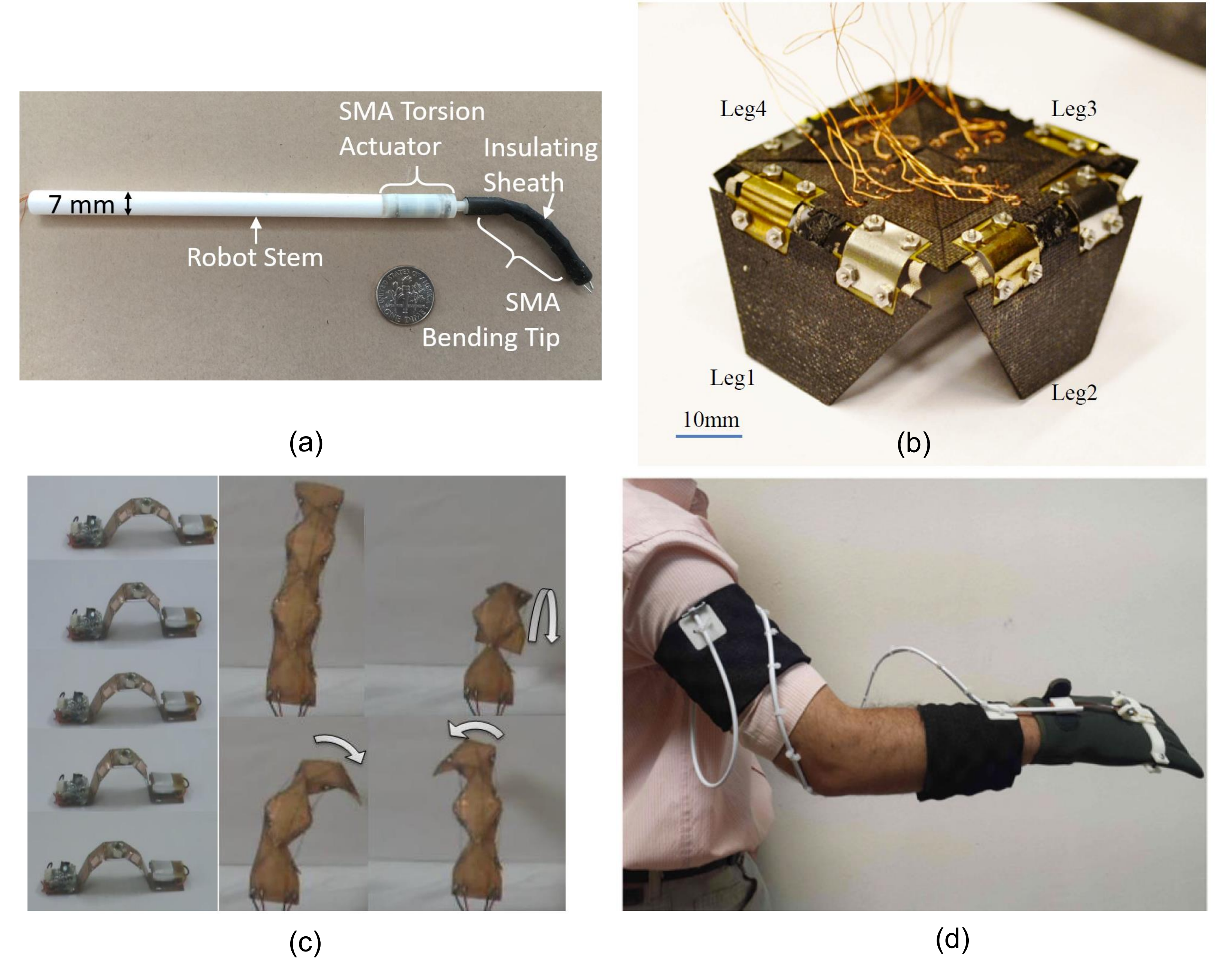


(g) TSA

(h) SCP actuator

(g). Twisted string actuator, TSA produces linear motions by converting the rotary motion into a linear tensile force [47], [48]. (h). Super coiled polymer, SCP actuators are constructed from twisting polymer fibers or filaments [38]. They can generate linear, bending, and torsional motions due to the thermal expansion property and geometric coil configuration [37], [49]–[51].

5. APPLICATIONS IN ROBOTICS



(a)

(b)

(c)

(d)

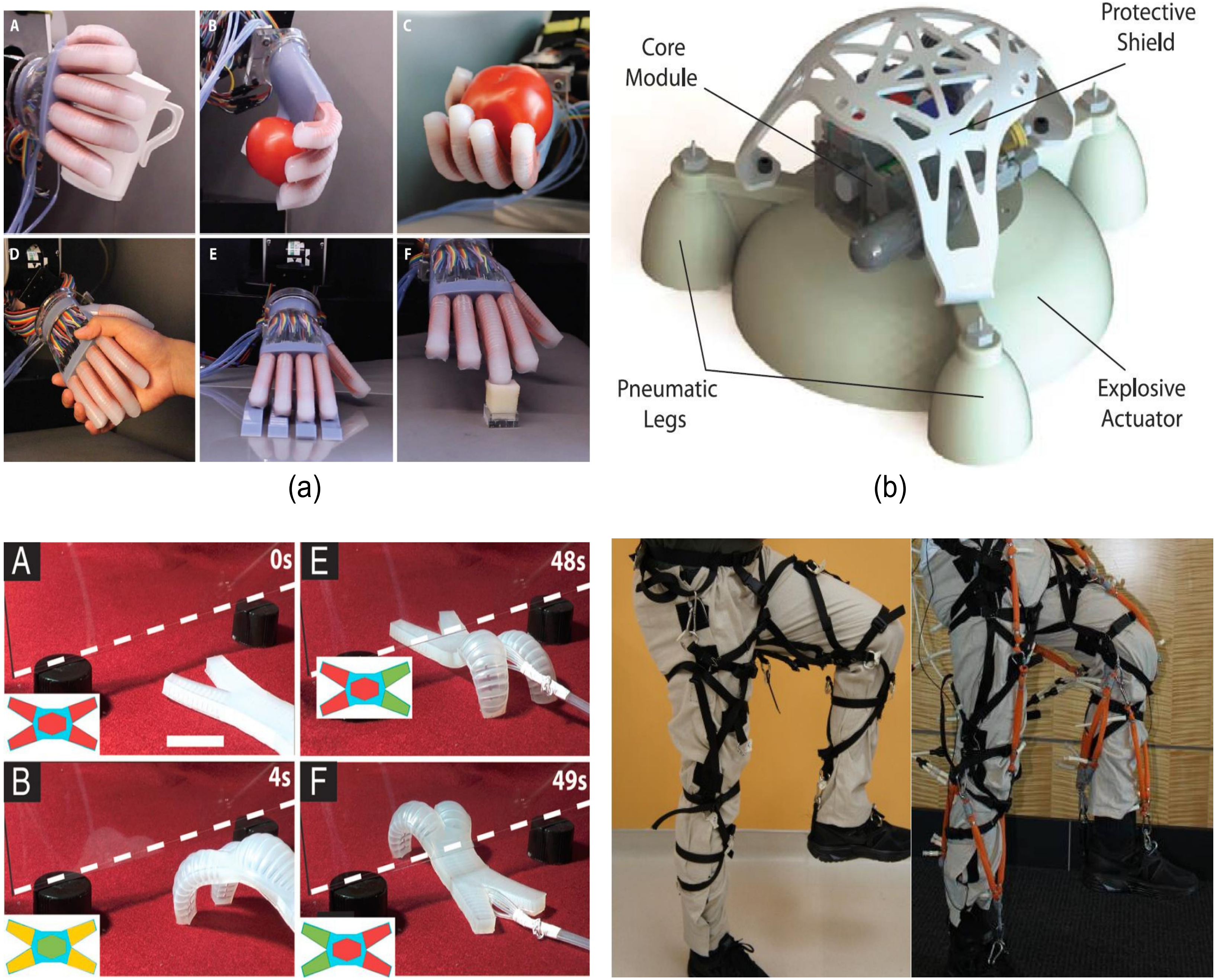
Robotic applications of Shape meory actuator, SMA and Shape memory polimer, SMP actuators:

(a) An shape memory alloys (SMA)-actuated Neurosurgical Intracerebral Haemorrhage Evacuation (NICHE) robot [125].

(b) A four-fold robotic origami with bi-directional actuators formed by antagonistic shape memory alloys SMA sheets [139].

(c) A two DOF inchworm-like crawling robot [136].

(d) A wearable wrist exoskeleton prototype [233].



(a) (b) (c) (d)

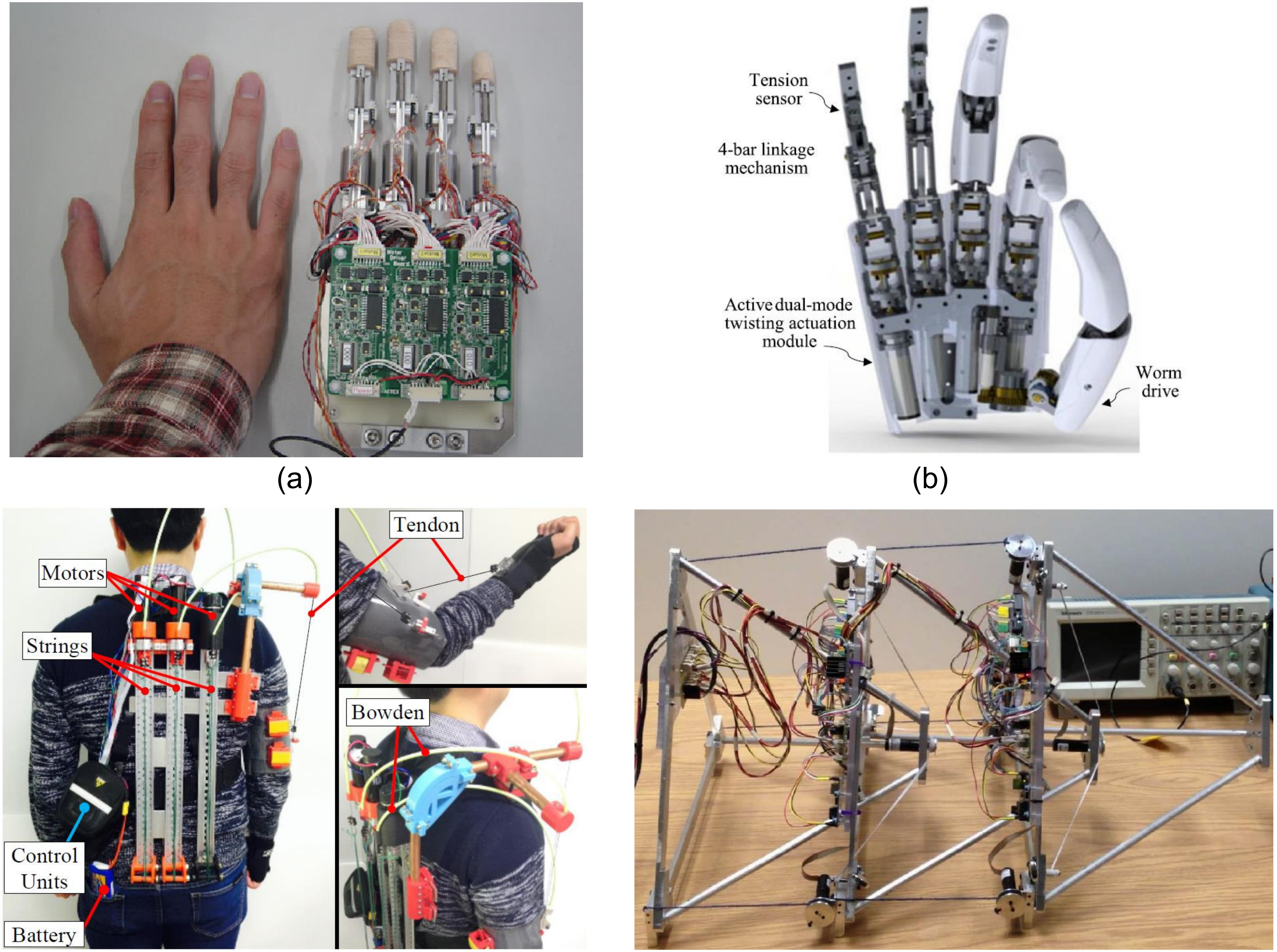
Robotic applications of soft fluidic actuators:

(a) A robotic hand driven by bending Pneu-net type actuators [239].

(b) A 3D-printed, functionally graded soft robot powered by combustion [240].

(c) A pneumatically actuated robot [241].

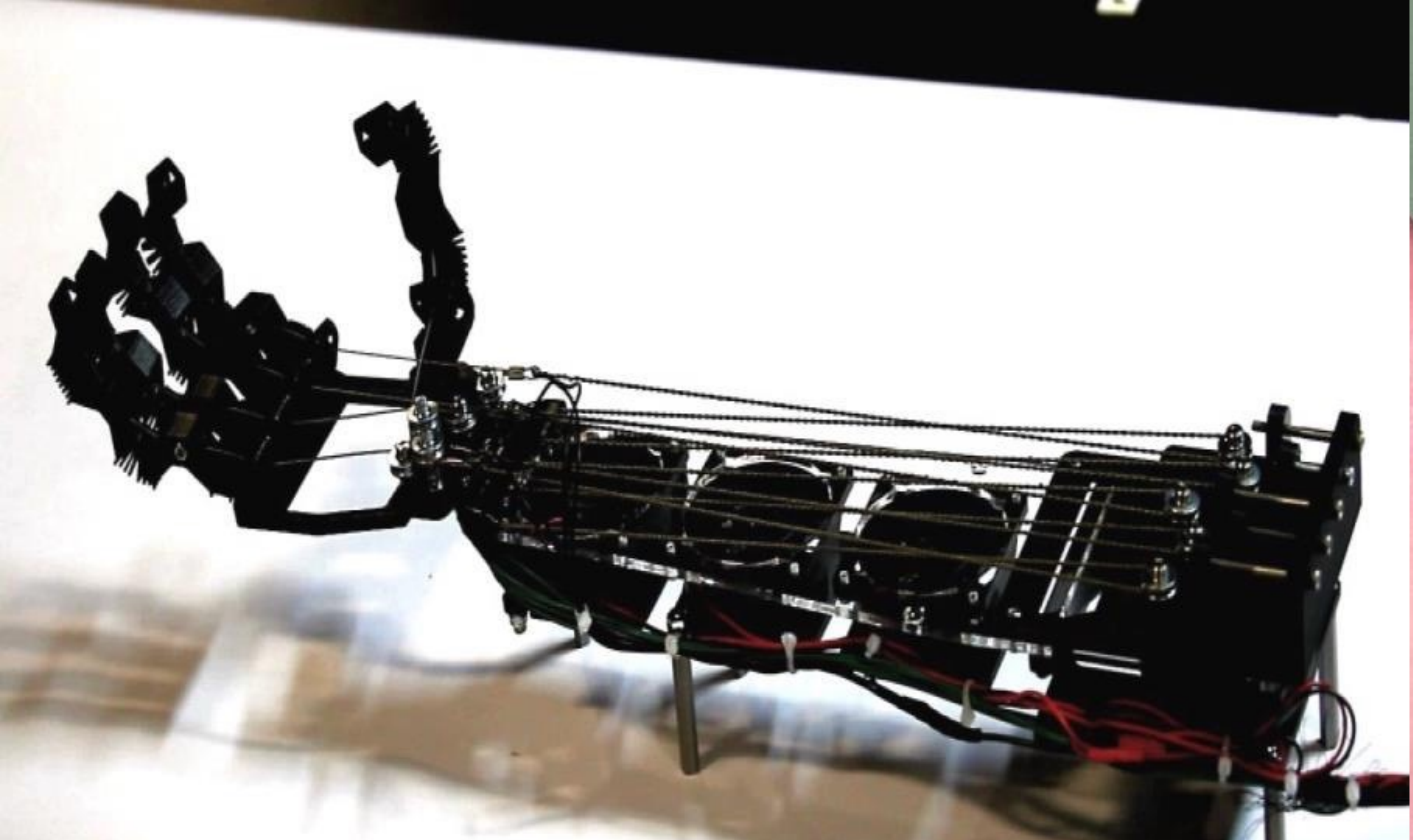
(d) Robotic soft exosuit driven by McKibben actuators for walking assistance [242].



(a) (b)

(c) (d)

Robotic applications of twisted string actuators, TSAs:
(a). Lightweight robotic hands [249].
(b). Anthropomorphic robot hand [178].
(c). Auxilio exosuit [251].
(d).A rolling tensegrity robot [252].



6. CONCLUSION

Robotic artificial muscles offer a balance of actuation performance, power-to-weight ratio, and inherent compliance in muscle-form factors, thus are strongly desirable as biomimetic actuators for various robotic applications.

The study and utilization of robotic artificial muscles have grown significantly in the last decade.

To achieve the full potential, fundamental studies are still needed to study how to fabricate, model, control, and design artificial muscles to obtain muscle-like properties and achieve muscle-like behaviours. For example, a common challenge faced by the majority of robotics artificial muscles is the fabrication, integration, and calibration of proprioceptive sensors for feedback-controlled actuation.

Soft strain sensors have been developed for robotic manipulators actuated by pneumatic artificial muscles, PAMs, but there often exists a trade off between the sensor stretchability and sensitivity. Solving these challenges has the potential of accelerating the quest for human-like and animal-like robotic behaviours and the distribution of robots into the public.