Journal of Chemical Science and Engineering
JCSE, 3(2): 132-138
www.scitcentral.com

ISSN: 2642-0406

Mini Review: Open Access

Characteristic Properties and Performance of Artificial Muscles

Bidita Salahuddin[1] and Shazed Aziz[2*]

[1]*ARC Centre of Excellence for Electromaterials Science and Intelligent Polymer Research Institute, University of Wollongong, Innovation Campus, NSW 2522, Australia*

[*2]*School of Chemical Engineering, The University of Queensland, Don Nicklin Building (74), QLD 4072, Australia.*

Received January 24, 2020; Revised February 04, 2020; Accepted February 06, 2020

ABSTRACT

Artificial muscles are generally recognized as devices or materials which can mimic the movement of natural muscles by contracting, bending, or rotating when acted upon by external stimuli (such as electricity, pH, pressure, magnetic field or temperature) and exhibit shape recovery once the stimulus is withdrawn. Similar to natural muscles, fundamental engineering properties of artificial muscles are characterized in terms of force generation, response time, and actuation strain. This mini-review will provide a scientific overview of the fundamental principle of these characteristic and performance properties that are key to the feasibility and selection of potential fields of artificial muscles. The article will also demonstrate the recent characterization basics of artificial muscles as well as critical matters that need to be addressed and resolved in future.

INTRODUCTION

Artificial muscle technology has an outstanding prospect for broad future applications in industry, medicine, robotics and many other practical fields [1]. These systems generally mimic the conventional properties of natural muscles such as contraction strain, response time, force generation and tension intensity [1-3]. Biological muscles usually offer 20–40% contraction strain and 0.35 N/mm2 of tension intensity that is generated in less than one second with a power to mass ratio of 100 W/kg (specific power) [4]. However, an ultimate tensile strength of 30 MPa can be achieved by human muscles at a contraction strain of 30% [5]. Many advantages with artificial muscle technologies stem from nature's ability to fabricate complex structures which range from the molecular to the macroscopic length. Since the improvement of fabrication technology and the better understanding of nature's mechanisms, several properties that include regeneration, nano-structuring and direct chemical actuation, have become common in artificial muscle actuators.

Several artificial muscles are popular due to matching or exceeding natural muscle in strain, stress and specific power. Most of the technologies presented, for instance, feature peak stresses that can at least match natural muscle, with the peak forces per cross-sectional area in shape memory alloys exceeding those of the natural muscle by a factor of 500. Unlike mammalian skeletal muscle, some of the technologies have a 'catch-state' feature, which enables the position to be locked against a fixed load without power expenditure [6]. Nevertheless, artificial muscles suffer performance limitations such as low cycle life and low efficiency and these deficiencies limit their applications in many practical fields.

Based on the established limitations of artificial muscles, it is possible to optimize their performance in terms of their combine's characteristic properties. Here, we demonstrate the key characteristic properties of artificial muscles that are crucial to consider before integrating them into biomimetic systems. Actuating principles, along with key performance indicators, are considered in a general perspective of commonly used artificial muscles.

ACTUATING PRINCIPLES

There are several characteristic properties of artificial muscle that are defined by how the muscle is stimulated. The first approach of preparing artificial muscles, namely, McKibben pneumatic muscles (PAM) [7] is cheap and useful, but they pose limitations in use because of their bulky external pump control and driving mechanisms [8]. To solve this problem, artificial muscles including piezoelectric [9-11] or dielectric elastomer (DEA) [12,13] were produced having actuating composites where the mechanism of actuation is inherent in the properties and structure of the

---

Corresponding author: Shazed Aziz, School of Chemical Engineering, The University of Queensland, Don Nicklin Building (74), QLD 4072, Australia, E-mail: shazed.aziz@uq.edu.au

Citation: Salahuddin B & Aziz S. (2020) Characteristic Properties and Performance of Artificial Muscles. J Chem Sci Eng, 3(2): 132-138.

composite. However, high voltages are required for this type of artificial muscle, which limits application outside research laboratories [14]. Artificial muscles have also been prepared with conducting polymers (CP) [15-22] and ionic polymer metal composites (IPMC) [23-31], these improved upon previous generations of actuators by decreasing the voltages required for actuation. These actuators produce bending motions through the movement of ions in an electrolyte but need the packaging of integrated electrodes to prevent leakage or evaporation of volatile solvent [32]. Subsequently, artificial muscles such as nanocarbon yarns [33-36], twisted-coiled polymer fibre [3,37,38], shape memory alloys (SMA) [39-46] and stimuli-responsive polymers [47-48] solved most of the issues of the previous devices by creating actuating materials. As reported, these actuating materials can produce artificial muscles of high power to weight ratios, giant stroke and large force. Nonetheless, each of these materials also has some limitations which have restricted full realization of their application.

CHARACTERISTIC PROPERTIES

Artificial muscles either exhibit a single actuation characteristic or a combination of performance based on the applied stimuli and field of application. Typical property interests are stress generation, magnitude and rate of actuation strain, materials creep, and hysteresis. The following sections demonstrate the basic understanding of these properties and the factors that determines the ultimate output of the artificial muscles.

Actuation stress and strain

Above all, actuation stress and strain are the two crucial characteristics of the artificial muscle. Stress is the applied force per unit cross-sectional area of the actuator materials; while blocking stress is the maximum blocking force per unit cross-sectional area in a single stroke that produces maximum work output [49]. Generated force scales linearly with the cross-sectional area in actuator systems where the direction of actuation is normal to the surface [50]. Blocked force provides good insight into the muscle’s actuation ability under external forces. Linear actuators typically can contract/expand when the externally applied force is smaller than the blocked force. Strain, typically referred as actuation strain, describes the displacement that is normalized by the original material length towards the direction of actuation [51,52]. **Figure 1** shows a comparison of actuation stress as a function of actuation strain achieved by several kinds of artificial muscle. Strain is regularly used in working devices; however, it is not possible to obtain the peak strain while operating at peak stress [53]. Strain rate is another strain-related property that entails the average change in strain per unit time throughout an actuator stroke. The maximum strain rate is typically experienced at high frequencies and small strains. Quicker responses can frequently be gained by optimizing geometry and processing and consequently, the numbers are often not ultimate limits but rather signify the present state of the art [54,55].

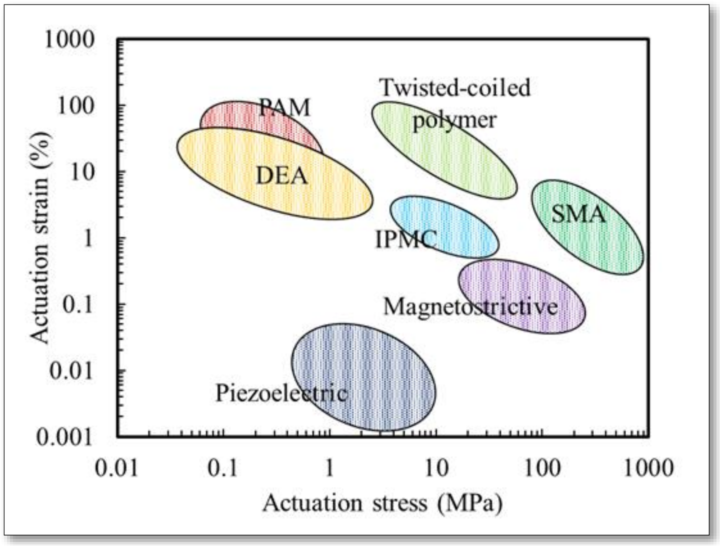

Figure 1. Comparison of optimum actuation stress as a function of actuation strain of different actuators.

Stiffness

Stiffness, another key characteristic of the actuator, is described by the resistance of an elastic material to the deformation by the given force and is a function of both material and geometry [56]. Stiffness depends on the modulus of elasticity or Young’s Modulus, which is theoretically constant for a specific material under specified environmental conditions [57]. Stiffness is related to the thickness and shape of the formed part of the material [58]. In general, stiffness describes the deforming nature of the material under applied load although the material tends to return to its original shape once the load is removed. In the case when the dimension of the material does not change after the removal of the load, stiffness is associated with elastic deformation [59]. **Figure 2** shows the typical stress-strain curve of a material which is divided into elastic and plastic regions. The initial slope of the curve also provides the material's modulus [60]. It is significant as it governs the actuator's passive capacity to respond to load changes as well as disturbances and in conjunction with the density and mass controls the frequency beyond which inertial effects become significant. The stiffness of several actuating materials changes when activated. In the case of mammalian skeletal muscle, the stiffness can be changed by a factor of 50 to assist in control [61].

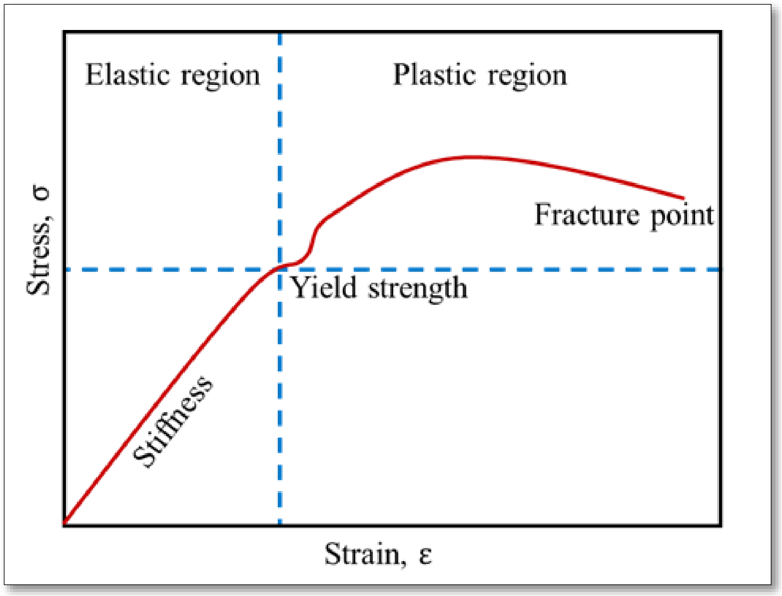

Figure 2. The typical stress-strain curve of a material representing the stiffnesses.

Creep and stress relaxation

Creep and stress (force) relaxation are another two important characteristics for some materials. Creep defines the slow continuous deformation of material at constant stress. Creep is the phenomenon where when a persistent and constant force is applied, it results in deformation which increases curvilinearly over time **(Figure 3a)** [62]. Once a viscoelastic material is subjected to constant strain, the stress originally induced by it decays in a time-dependent manner, and this phenomenon is known as stress relaxation. The force needed to perform a given elongation decreases over time in a predictable curvilinear force-relaxation pattern as shown in **Figure 3b** [62]. The loop produced by force-elongation (or stress-strain) plots throughout loading and subsequent unloading of the specimen **(Figure 3c)** has been demonstrated by mechanical hysteresis. In fact, hysteresis has a close relation with fatigue life and crack propagation because of energy dissipation during cycles of transformation [62].

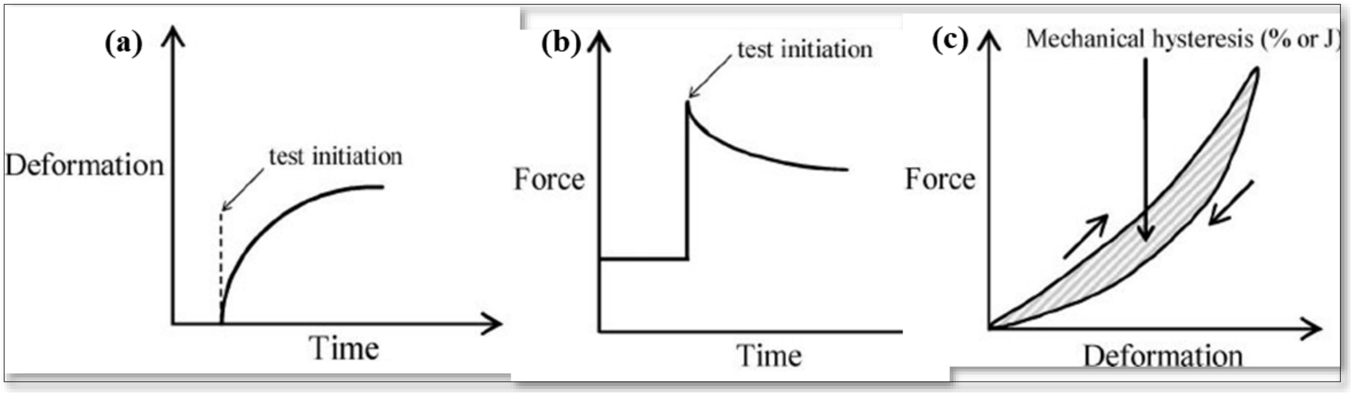

Figure 3. (a) Typical creep behavior. (b) Force-relaxation curve. (c) Mechanical hysteresis tests-the small arrows at the bottom graph indicate loading and unloading directions [62].

Response time

In addition to the above-mentioned properties, response time plays a significant role in the field of actuator technologies. Some actuators respond quickly while others require high response time. For example, pneumatic actuators can provide very fast response while most of the SMAs need a long response time to actuate [63]. Hydrogel-based actuators are still struggling to obtain a fast response when stimulated [64]. Because the response time of the hydrogel is nearly proportional to the square of the thickness, different shapes and sizes of the hydrogel are of research interest. Together with fast response, it is also crucial for the actuators to provide a long cycle life. Cycle life refers to the number of valuable strokes that the material is able to undergo and is generally highly reliant on strain as well as stress. A repeating pattern of loading and unloading is usually performed during the cyclic test; an ideal mechanical actuator is expected to provide unlimited cycle life without any deformation [65]. Other properties are often necessary to describe actuating materials including, temperature dependence of the response, coefficient of thermal expansion, thermal diffusivity, ionic diffusion coefficients, resistivity, minimum displacement, positioning resolution and gauge factor. Also, environmental resistance can be a substantial factor in many applications. Unfortunately, these characteristics are often not known.

Performance Representation

Performance of an actuator is often explained as the work density, this describes the amount of work produced in one actuator cycle normalized by actuator volume (or mass). The volume occupied by electrolytes, counter electrodes, power supplies etc. are usually excluded in the determination of work density, because these additional contributions to actuator volume cannot scale linearly with work output [66]. Also, the product of maximum stress and maximum strain is not considered as work density. Therefore, specific power is now often used to define the power output per unit mass of the actuator material. The maximum product of stress and strain rate divided by density is used to estimate peak power density. Usually peak power is lower than the product of peak stress and peak strain rate standardized by density due to the interdependence of load and rate [67].

Power to weight ratio as a function of different actuators' mass, for example, SMA, pneumatic motor, hydraulic actuators etc. is shown in **Figure 4a** [68]. The performance of the actuators can be represented as efficiency, defined as the ratio of work produced to input energy. Stored electrical energy and sometimes thermal energy can be recovered to enhance efficiency. **Figure 4b** shows the efficiency plotted as a function of the actuation strain for most of the existing actuation methods, including materials such as SMA piezoelectric materials and hydraulic and pneumatic setups. It can be seen that actuation methods demonstrating high actuation strain (approximately 100%) along with high efficiency are developed on all of the hydraulic or pneumatic devices [69].

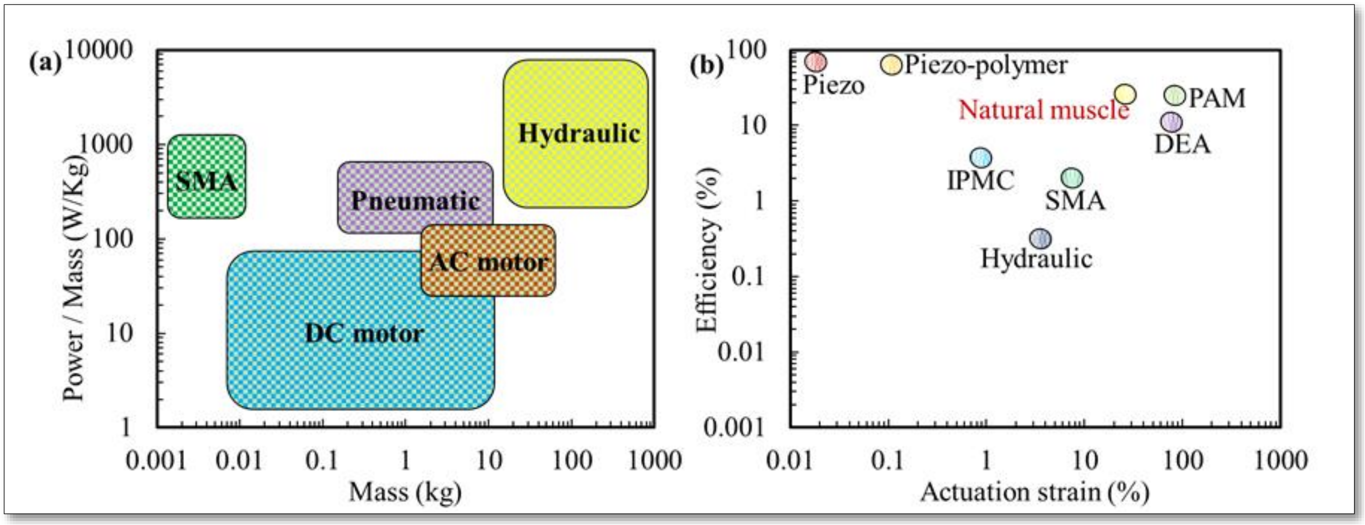

Figure 4. (a) Comparison of specific power obtained from different actuators [68]. (b) Maximum efficiency plotted versus actuation strain for various actuating methods (SMA-shape memory alloy, IPMC-ionic polymer metal composite, DEA-dielectric elastomer actuator, PAM-pneumatic artificial muscle, FEA-ferroelectric actuator) [69].

CONCLUSIONS AND RECOMMENDATION

In this mini-review, we highlighted the current characterization basics of artificial muscles that are being globally utilized for evaluating the performance. Many different approaches have been used for characterizing artificial muscles to evaluate the contraction strain, blocking force, work density, or power-to-weight ratio. Acceptance of the concept that natural muscles can be the most effective in terms of actuation response has meant that efforts to create artificial muscles have gained significant attention in recent times. However, mimicking the full mix of properties of mammalian skeletal muscles has never yet been achieved by any artificial muscle characterization techniques. Although it is understood that the gap between the lab-based experiments and practical application is still substantial, more research works are required to narrow the gap and the future development of practical applications for artificial muscles. One recommendation is to establish integrated characterization methods that can address many challenges in a one-step experimental technique. It is also important to introduce new characteristic terminology that can define the overall performance of artificial muscle compared to those skeletal.

CONFLICTS OF INTEREST

There are no conflicts to declare.

REFERENCES

1. Mirvakili SM, Pazukha A, Sikkema W, Sinclair CW, Spinks GM, et al. (2013) Niobium nanowire yarns and their application as artificial muscles. Adv Funct Mater 23: 4311-4316.
2. Bar-Cohen Y (2001) Electroactive polymer (EAP) actuators as artificial muscles: Reality, potential and challenges (SPIE Press, 2001).
3. Haines CS, Lima MD, Li N, Spinks GM, Foroughi J, et al. (2014) Artificial muscles from fishing line and sewing thread. Science 343: 868-872.
4. Sangian D, Naficy S, Spinks GM, Tondu B (2015) The effect of geometry and material properties on the performance of a small hydraulic McKibben muscle system. Sens Actuators Phys 234: 150-157.
5. Jarvis JC, Kwende MMN, Shortland A, Eloakley RM, Gilroy SJ, et al. (1997) Relation between muscle contraction speed and hydraulic performance in skeletal muscle ventricles. Circulation 96: 2368-2375.
6. Huck WTS (2008) Responsive polymers for nano scale actuation. Mater Today 11: 24-32.
7. Aschenbeck KS, Kern NI, Bachmann RJ, Quinn RD (2006) Design of a quadruped robot driven by air muscles. 1st IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 875-880.
8. Chou CP, Hannaford B (1996) Measurement and modeling of McKibben pneumatic artificial muscles. IEEE Trans Robot Autom 12: 90-102.
9. Kim HS, Kim JH, Kim J (2011) A review of piezoelectric energy harvesting based on vibration. Int J Precis Eng Manuf 12: 1129-1141.
10. Chaillet N, Regnier S (2013) Microrobotics for micromanipulation. Wiley.
11. Qing FY, Jikui L, Andrew F, William M (2012) MEMS for Biomedical Applications. Woodhead Publishing, pp: 291-336.
12. Kornbluh RD, Pelrine R, Pei Q, Heydt R, Stanfordet S, et al. (2002) Electroelastomers: Applications of dielectric elastomer transducers for actuation, generation, and smart structures.
13. Jun K, Kim D, Ryu S, Oh IK (2017) Surface modification of anisotropic dielectric elastomer actuators with uni- and bi-axially wrinkled carbon electrodes for wettability control. Sci Rep 7: 6091.
14. Tian L, Tevet-Deree L, de Botton G, Bhattacharya K (2012) Dielectric elastomer composites. J Mech Phys Solids 60: 181-198.
15. Otero TF, Sanchez JJ, Martinez JG (2012) Biomimetic dual sensing-Actuators based on conducting polymers. Galvanostatic theoretical model for actuators sensing temperature. J Phys Chem B 116: 5279-5290.
16. Baughman RH (1996) Conducting polymer artificial muscles. Synth Met 78: 339-353.
17. Pei Q, Inganaes O (1992) Electrochemical applications of the bending beam method. 1. Mass transport and volume changes in polypyrrole during redox. J Phys Chem 96: 10507-10514.
18. Madden JD, Vandesteeg N, Anquetil PA, Madden PG, Takshi A, et al. (2004) Artificial muscle technology: Physical principles and naval prospects. IEEE J Ocean Eng 29: 706-728.
19. Baughman RH, Shacklette LW, Elsenbaumer RL, Plichta EJ, Becht C (1991) Micro electromechanical actuators based on conducting polymers.
20. Naseri M, Fotouhi L, Ehsani A (2018) Recent progress in the development of conducting polymer-based nanocomposites for electrochemical biosensors applications: A mini-review. Chem Rec 18: 599-618.
21. Das TK, Prusty S (2012) Review on conducting polymers and their applications. Polym Plast Technol Eng 51: 1487-1500.
22. Madden JD, Madden PG, Hunter IW (2002) Conducting polymer actuators as engineering materials.
23. Shahinpoor M, Bar-Cohen Y, Xue T, Simpson JO, Smith J (1998) Ionic polymer-metal composites (IPMCs) as biomimetic sensors, actuators and artificial muscles - A review. Smart Mater Struct 7: R15-R30.
24. Ahn KK, Truong DQ, Nam DNC, Yoon JI, Yokota S (2010) Position control of ionic polymer metal composite actuator using quantitative feedback theory. Sens Actuators Phys 159: 204-212.
25. Truong DQ, Ahn KK, Nam DNC, Yoon JI (2010) Identification of a nonlinear black-box model for a self-sensing polymer metal composite actuator. Smart Mater Struct 19: 085015.

26. Jeon JH, Kang SP, Lee S, Oh IK (2009) Novel biomimetic actuator based on SPEEK and PVDF. Sens Actuators B Chem 143: 357-364.
27. Shahinpoor M, Kim KJ (2001) Ionic polymer-metal composites: I. Fundamentals. Smart Mater Struct 10: 819-833.
28. Shahinpoor M, Kim KJ (2004) Ionic polymer-metal composites: IV. Industrial and medical applications. Smart Mater Struct 14: 197-214.
29. The Royal Society of Chemistry (2016) Ionic polymer metal composites (IPMCs): Smart multi-functional materials and artificial muscles, Volume 2.
30. Kim KJ, Tadokoro S (2007) Electroactive polymers for robotic applications: Artificial muscles and sensors. Springer London.
31. Wu F, Chen N, Chen R, Zhu Q, Qian J, et al. (2016) “Liquid-in-solid” and “solid-in-liquid” electrolytes with high rate capacity and long cycling life for lithium-ion batteries. Chem Mater 28: 848-856.
32. Kim KJ, Shahinpoor M (2003) Ionic polymer metal composites: II. Manufacturing techniques. Smart Mater Struct 12: 65-79.
33. Baughman RH, Cui C, Zakhidov AA, Iqbal Z, Barisci JN, et al. (1999) Carbon nanotube actuators. Science 284: 1340-1344.
34. Aliev AE, Oh J, Kozlov ME, Kuznetsov AA, Fang S, et al. (2009) Giant-stroke, superelastic carbon nanotube aerogel muscles. Science 323: 1575-1578.
35. Foroughi J, Spinks GM, Wallace GG, Oh J, Kozlov ME, et al. (2011) Torsional carbon nanotube artificial muscles. Science 334: 494-497.
36. Lima MD, Li N, Jung de Andrade M, Fang S, Oh J, et al. (2012) Electrically, chemically and photonically powered torsional and tensile actuation of hybrid carbon nanotube yarn muscles. Science 338: 928-932.
37. Aziz S, Naficy S, Foroughi J, Brown HR, Spinks GM (2015) Characterization of torsional actuation in highly twisted yarns and fibres. Polym Test 46: 88-97.
38. Aziz S, Naficy S, Foroughi J, Brown HR, Spinks GM (2016) Controlled and scalable torsional actuation of twisted nylon 6 fiber. J Polym Sci Part B Polym Phys 54: 1278-1286.
39. Bergamasco M, Dario P, Salsedo F (1990) Shape memory alloy micro actuators. Sens Actuators Phys 21: 253-257.
40. Rossiter J, Takashima K, Mukai T (2014) Thermal response of novel shape memory polymer-shape memory alloy hybrids. SPIE Smart Structures and Materials Nondestructive Evaluation and Health Monitoring 2014.
41. An SM, Ryu J, Cho M, Cho KJ (2012) Engineering design framework for a shape memory alloy coil spring actuator using a static two-state model. Smart Mater Struct 21: 5.
42. Koh JS (2018) Design of shape memory alloy coil spring actuator for improving performance in cyclic actuation. Mater Basel Switz 11: 2324.
43. Jani JM, Leary M, Subic A, Gibson MA (2014) A review of shape memory alloy research, applications and opportunities. Mater Des 56: 1078-1113.
44. Alagirusamy R, Das A (2010) Technical Textile Yarns. Elsevier Science.
45. Meng H, Li G (2013) A review of stimuli-responsive shape memory polymer composites. Polymer 54: 2199-2221.
46. Liu C, Chun SB, Mather PT, Zheng L, Haley EH, et al. (2002) Chemically cross-linked polycyclooctene: Synthesis, characterization and shape memory behavior. Macromolecules 35:27.
47. Wei M, Gao Y, Li X, Serpe MJ (2017) Stimuli-responsive polymers and their applications. Polym Chem 8: 127-143.
48. Pilate F, Toncheva A, Dubois P, Raquez JM (2016) Shape-memory polymers for multiple applications in the materials world. Eur Polym J 80: 268-294.
49. Huber JE, Fleck NA, Ashby MF (1997) The selection of mechanical actuators based on performance indices. Proc R Soc Math Phys Eng Sci 453: 2185-2205.
50. Kazerounian KSM (2000) American Society of Mechanical Engineers. Design Engineering Division. 26th Biennial Mechanisms and Robotics Conference.
51. Acosta M (2016) Strain mechanisms in lead-free ferroelectrics for actuators. Springer International Publishing.
52. Darvishvand A, Zajkani A (2019) A new model for permanent flexural deflection of cantilever MEMS actuator by conventional mechanism-based strain gradient plasticity framework. Microsyst Technol 25: 4277-4289.
53. Lang J, Ding B, Zhu T, Su H, Luo H, et al. (2016) Cycling of a lithium-ion battery with a silicon anode drives large mechanical actuation. Adv Mater 28: 10236-10243.
54. Skinner SN, Zare-Behtash H (2018) State-of-the-art in aerodynamic shape optimization methods. Appl Soft Comput 62: 933-962.
55. Tawfick S, Tang Y (2019) Stronger artificial muscles, with a twist. Science 365: 125-126.
56. Armanios EA (1997) Fibers AC. D-30 on HM & Composites T. Composite Materials: Fatigue and Fracture. ASTM international.
57. Furnémont R, Mathijssen G, Verstraten T, Lefeber D, Vanderborght B (2016) Bi-directional series-parallel elastic actuator and overlap of the actuation layers. Bioinspir Biomim 11: 016005.
58. Hu JW (2016) Advanced materials and structural engineering. Proceedings of the International

Conference on Advanced Materials and Engineering Structural Technology (ICAMEST 2015), Qingdao, China.

59. Gauthier MM, Committee AIH, International HCA (1995) Engineered Materials Handbook, Desk Edition. ASM International.
60. Biron M (2015) Material selection for thermoplastic parts: Practical and advanced information. Elsevier Science, 2015.
61. Hunter IW, Lafontaine S (1992) A comparison of muscle with artificial actuators. Technical Digest IEEE Solid-State Sensor and Actuator Workshop. IEEE, pp: 178-185.
62. Rosso C, Valderrabano V (2010) Biomechanics of the Achilles Tendon. In Disability and Rehabilitation - DISABIL REHABIL 30.
63. Considine DM, Considine GD (2012) Standard Handbook of Industrial Automation. Springer US.
64. Tokudome Y, Kuniwaki H, Suzuki K, Carboni D, Poologasundarampillai G, et al. (2016) Thermoresponsive wrinkles on hydrogels for soft actuators. Adv Mater Interfaces 3.
65. Salaneck (2019) Science and applications of conducting polymers, papers from the sixth European industrial workshop. CRC Press.
66. Carpi F (2016) Electromechanically active polymers: A concise reference. Springer International Publishing.
67. Prechtl EF, Hall SR (1999) Design of a high efficiency, large stroke, electromechanical actuator. Smart Mater Struct 8: 13-30.
68. Nespoli A, Besseghini S, Pittaccio S, Villa E, Viscuso S (2010) The high potential of shape memory alloys in developing miniature mechanical devices: A review on shape memory alloy mini-actuators. Sens Actuators Phys 158: 149-160.
69. Miriyev A, Stack K, Lipson H (2017) Soft material for soft actuators. Nat Commun 8: 596.