

Characteristic Properties and Performance of Artificial Muscles

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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(such as electricity, pH, pressure, magnetic field or temperature) and exhibit shape recovery once the stimulus is withdrawn.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

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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].

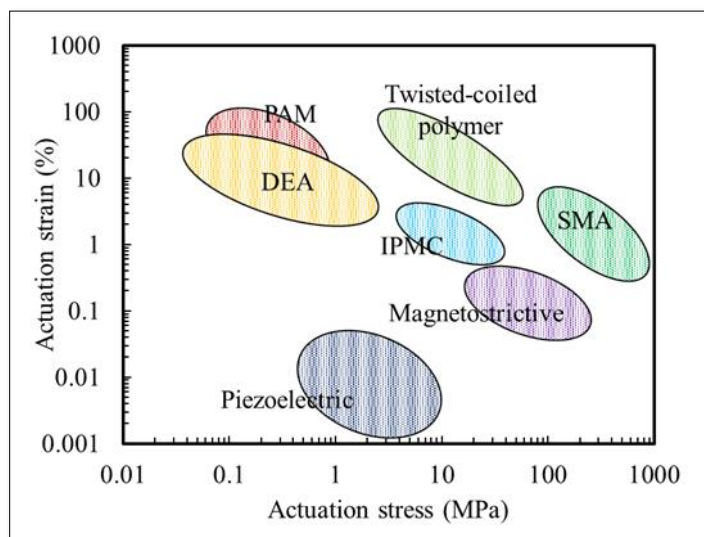


Figure 1. Comparison of optimum actuation stress as a function of actuation strain of different actuators.

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].

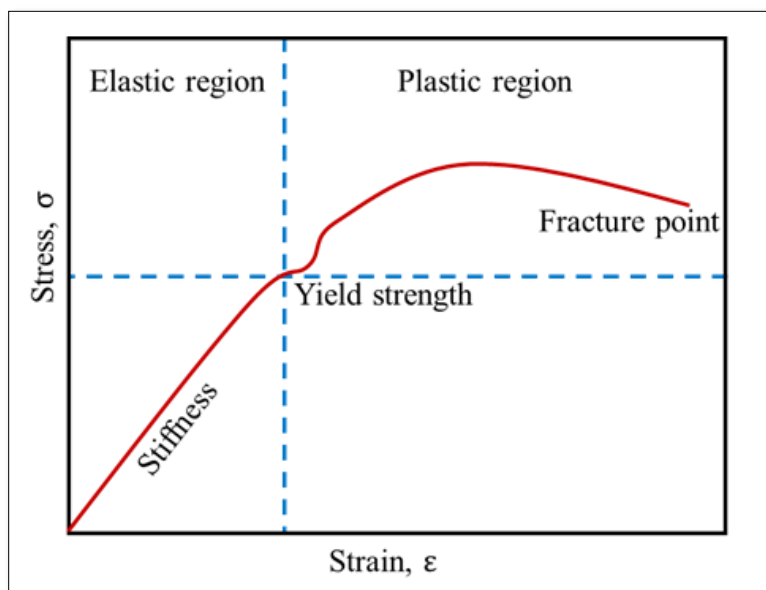


Figure 2. The typical stress-strain curve of a material representing the stiffnesses.

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].

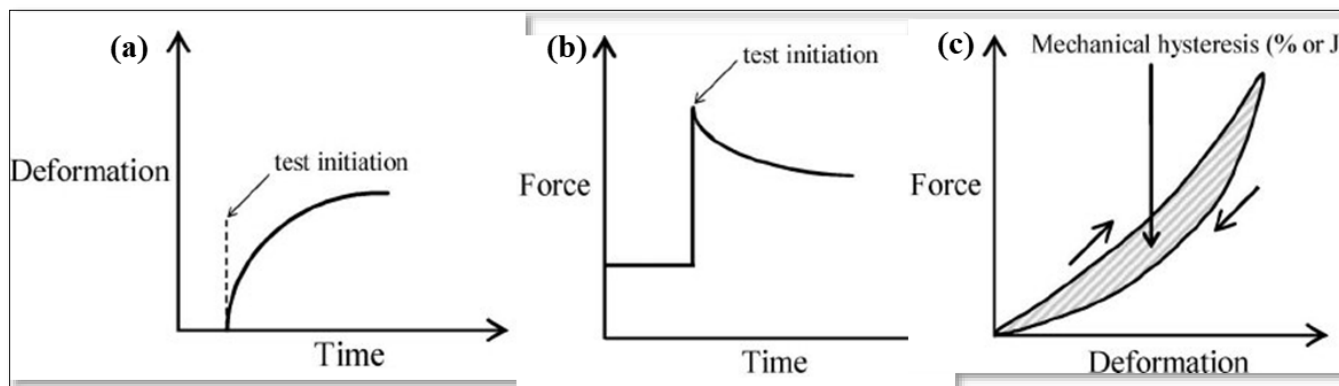


Figure 3. (a) Typical creep behavior. (b) Force-relaxation curve. (c) Mechanical hysteresis tests-the small arrows at the bottom graph indicate loading and unloading directions [62].

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

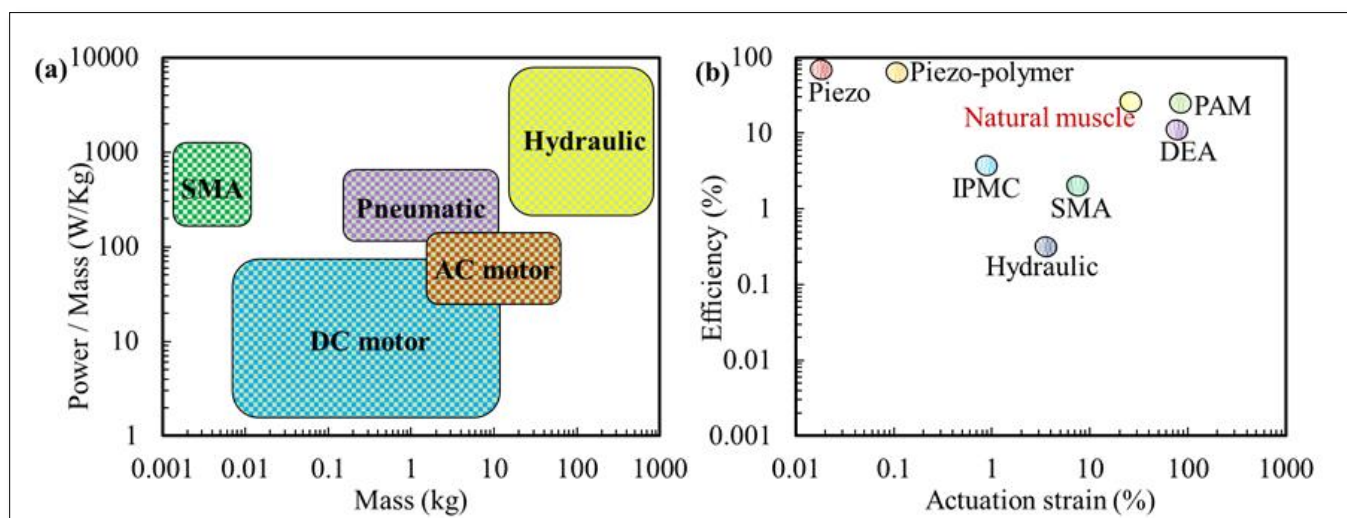


Figure 4. (a) Comparison of specific power obtained from different actuators [68]. (b) Maximum efficiency plotted versus actuation strain for various actuating methods (SMA-shape memory alloy, IPMC-ionic polymer metal composite, DEA-dielectric elastomer actuator, PAM-pneumatic artificial muscle, FEA-ferroelectric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

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].

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.

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