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SMA-based bionic integration design of self-sensor–actuator-structure for artificial skeletal muscle

Jianjun Zhang, Yuehong Yin*

State Key Laboratory of Mechanism System and Vibration, Institute of Robotics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

This paper presents a novel shape memory alloy (SMA)-based artificial skeletal muscle (AM) with functions of actuating, energy-storing and self-sensing. The design is based on the comparison of skeletal muscle and SMA wire mechanical properties that are described by force–velocity and force–length relationships. Experimental results have shown that SMA wires can initially imitate force–velocity properties of skeletal muscles, but cannot imitate their force–length properties, which is improved by adding an anti-overstretching flexible body. Besides, a simple but effective artificial tendon is utilized to achieve energy storage like human tendon. In order to realize the self-sensing function of the AM, self-sensing properties of SMA wires are explored and modeled based on the experimental study of resistivity variations. The AM self-sensing capability is further demonstrated by its application to a 1 degree of freedom (DOF) robotic ankle-foot.

1. Introduction

Skeletal muscles are multi-functional actuators of human motor system with functions of actuating, energy-storing and self-sensing. For decades, many scholars have conducted and are still conducting research on imitating the form and function of skeletal muscles. Many actuator devices (such as electric motors, hydraulics and pneumatics) and smart materials (such as EAP and SMA) have been put forth as “artificial muscles”. Conventional actuator devices, such as DC motor [1–3] and hydraulics [4] are hard to imitate skeletal muscles because of their low power density and large volume. Pneumatic artificial muscles [5], such as the “McKibben Muscles”, can imitate the performance of natural muscle, but they are noisy and require a separate pump to provide the energy. In addition, the actuators mentioned above cannot imitate the self-sensing capability of skeletal muscles without additional sensors. EAP-based artificial muscle has been developed recently [6]. EAP has self-sensing capability, but the generated force is small and the operating voltage is too high (>1000 V) to be of practical use. SMA wires have not only unidirectional actuating but also self-sensing capabilities similar to skeletal muscles. Further, there are many other common features between SMA wires and skeletal muscles, such as high energy density, flexibility and silent operation. Besides, SMA wires can be driven directly by low-voltage. Thus, it is feasible to realize SMA-based artificial skeletal muscle with self-sensing and actuating abilities. SMA wire was not only used for micro-applications, such as gripper [7] and dynamic splint [8], but also used for large output force applications [9]. Besides, Lan et al. [10,11] developed several SMA actuated flexural manipulators using the inherent self-sensing capacity.

In the development of the AM, mechanical properties of skeletal muscles are used to describe the performance that the AM is expected to achieve. We use parallel SMA wires as contractile element. Experimental results have shown that the force–velocity properties of SMA wires are muscle-like, but the force–length properties are not. An anti-overstretching flexible body is added in parallel with SMA wires to improve the force–length properties. Skeletal muscles attach to bones through tendons. Hill [12] shows that tendons represent a spring-like elastic components. One advantage of incorporating elastic tendon elements is to allow for energy storage in locomotor systems. In the AM design, a simple but effective artificial tendon is proposed to achieve the energy storage and minimize heating power of SMA wires. As with skeletal muscles, SMA wires also have self-sensing abilities, which mainly refer to the use of resistance as a sensor to detect the length change of SMA wires [14,15]. However, the self-sensing capability has not yet been entirely explored and few self-sensing model is proposed in literature. Lan and Fan [11] developed an accurate self-sensing model based on the SMA strain to resistance curves by polynomial fitting, which is proved to be effective. In this paper, we propose a self-sensing model to establish resistance to length (R–L) relation based on deeply exploring inherent resistivity properties of SMA wires.

The motivation of this paper is to develop a novel SMA-based artificial skeletal muscle with actuating, energy-storing and self-sensing functions. The AM presents preliminary simulation of

* Corresponding author. Tel.: +86 21 34206310.
E-mail address: yhyin@sjtu.edu.cn (Y. Yin).

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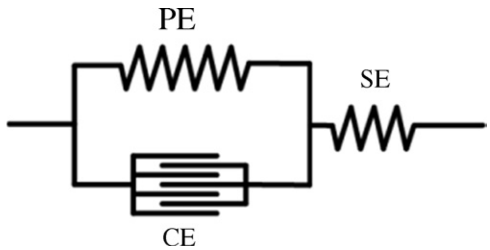

Fig. 1. Schematic of the three-element muscle model.

mechanics and energy storage properties of skeletal muscles. Furthermore, the self-sensing capability is achieved by modeling SMA resistance–length relationship. Finally, we present a robotic ankle-foot prototype actuated and sensed by the AM. The experimental results demonstrate that the AM is robust to external load variations and accurate angle control using self-sensing method is achieved within SMA bandwidth.

2. Bionic design of artificial skeletal muscle

The first step in designing an AM is to identify the properties to be imitated. Skeletal muscles perform both dynamic and static work. Dynamic work permits locomotion of the body segments in space. Static work maintains body posture or position [13]. Since the last century, a wide variety of models have been proposed to describe the mechanical properties of skeletal muscles [16–20]. The most representative model was developed by Hill [16]. According to Hill-model, the skeletal muscle architecture can be simplified as three major components as shown in Fig. 1: the contractile element (CE), the parallel element (PE) and the series element (SE). CE represents muscle fibers that generate active contraction force. PE comprises the passive elastic connective tissue surrounding muscle fibers that prevents the overstretching of CE and lessen the danger of the muscle injury. SE is represented by tendons. Mechanical properties of skeletal muscles can be described by examining the force–velocity and force–length relationships of the skeletal muscle architecture.

2.1. Mechanical properties of skeletal muscles

When a fully activated muscle is clamped isometrically and then suddenly released to allow shortening against external loads, the force–velocity relationship can be determined by measuring the velocity of the muscle at various external loads [16]. When there is no load on the muscle, the velocity of shortening is greatest. As the external load increases, the velocity of shortening decreases. When the external load equals to the maximal force that the muscle can exert, the velocity of shortening becomes zero. The general form of force–velocity relationship is expressed as:

$$(F + a)(V + b) = (F_0 + a)b \tag{1}$$

where F is the muscle force, V is the muscle contraction velocity, F_0 is the maximal muscle force. a and b are constants. The dimensionless force–velocity relationship of skeletal muscle reveals a hyperbolic shape (see Fig. 2(a)).

When the skeletal muscle contracts isometrically and tetanically, the force–length relationships can be determined by measuring the force output against the length of the skeletal muscle. For the whole skeletal muscle, the force is produced by both active components and passive components. The general form of force–length relationship is expressed as follows [18]:

$$F = F_a^m + F_p^m \tag{2a}$$

$$F_a^m = \beta f(L) \tag{2b}$$

$$F_p^m = \begin{cases} 0 & \text{for } L < L_0 \\ g(L) & \text{for } L > L_0 \end{cases} \tag{2c}$$

where F is the total force generated by the whole muscle, F_a^m is the active force developed by CE, F_p^m is the passive force developed by PE and SE, L_0 is the resting length of the muscle, and β is the activation degree of the muscle, which is equal to 1 when the muscle contracts tetanically. $f(L)$ and $g(L)$ represent the active force–length and passive force–length relationships respectively. The detail expressions of $f(L)$ and $g(L)$ are listed in Ref. [18]. The dimensionless force–length relationships (see Fig. 2(b)) comprise the active (dashed), passive (dotted) and total (solid) force generated by the muscle against its length. Note that, the active force–length reveals a parabolic shape, and F_0 is the maximum isometric force generated by CE when the muscle is at the resting length L_0. Besides, the passive force is 0 when the muscle length is less than the resting length. When the muscle is stretched beyond the resting length, the passive force rises and the active force decreases, thereby protecting the muscle from overstretching. The passive curve varies depending on how much connective issue the muscle contains, but the parabolic shape of active curve is generally the same in different muscle [13].

2.2. SMA based artificial contractile element

SMA mainly has two phases, namely martensite (M), austenite (A). When being activated by heating, a SMA wire shortens its length from M to A. Subsequent cooling returns the wire to its longest length (equal to non-activated "resting" length) from A to M under enough applied load. The SMA wire can serve as the artificial contractile element because of its active contractile function, which is similar to muscle fibers. In order to imitate mechanical properties of skeletal muscles, we conducted a series of force–velocity and force–length experiments on a single SMA wire.

A fully heated SMA wire with temperature higher than austenite finish temperature is clamped isometrically and then suddenly released to allow shortening against external loads. The force–velocity curve is obtained by plotting the contraction velocity at various external loads, as shown in Fig. 3(a). Where F_0 is the maximal force that the SMA wire can exert, and v_0 is the maximal contraction velocity of the SMA wire. The force–velocity curve presents the same trend as that of skeletal muscles, which reveals that the SMA wire is a reasonable approximation to skeletal muscles for force–velocity properties.

When the fully heated SMA wire contracts over a range of lengths ($0.9L_0 < L < L_0$), the force–length relationship can be determined by measuring the force output against the length of the SMA wire, as shown in Fig. 3(b). The force increases from zero at the SMA wire's minimum length to the maximum value F_0 when the SMA wire is at resting length L_0. The dimensionless force–length curve has a similar parabolic shape to the active force–length curve of skeletal muscles when the SMA wire length is less than the resting length, which is caused by SMA phase transformation. However, unlike skeletal muscles, the SMA wire cannot be stretched beyond the resting length. Otherwise plastic deformation will occur and shape memory effect will be destroyed [21]. Furthermore, the SMA wire cannot imitate the passive force–length properties either. Thus the force–length performance of SMA wires must be improved.

2.3. SMA actuated artificial skeletal muscle design

The main design principle of the AM is to imitate mechanical properties of skeletal muscles while maintaining simplicity. Similar to skeletal muscles, the AM also mainly comprises three elements: