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Fabrication and control of miniature McKibben actuators

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ABSTRACT

This paper investigates the development of miniature McKibben actuators. Due to their compliancy, high actuation force, and precision, these actuators are on the one hand interesting for medical applications such as prostheses and instruments for surgery and on the other hand for industrial applications such as for assembly robots. During this research, pneumatic McKibben actuators have been miniaturized to an outside diameter of 1.5 mm and a length ranging from 22 mm to 62 mm. These actuators are able to achieve forces of 6 N and strains up to about 15% at a supply pressure of 1 MPa. The maximal actuation speed of the actuators measured during this research is more than 350 mm/s. Further, positioning experiments with a laser interferometer and a PI controller revealed that these actuators are able to achieve sub-micron positioning resolution.

1. Introduction

New industrial and medical applications require inexpensive microactuators with a high force and power density. While microsystems technology focused on the development of actuators with sub-millimeter outer dimensions and traditional actuators have outer dimensions of several millimetres, there is a lack of systems that bridge both approaches. Nonetheless, there is a strong demand for such actuators on the one hand for medical applications such as prostheses and advanced instruments for surgery and on the other hand for industrial applications such as for human–machine interaction and inspection robots [1–5]. These applications typically require high forces (1–10 N), speed (10–100 mm/s) and large strokes (1–10 mm) to be generated in a confined volume (10–100 mm^3). High output forces in are particularly difficult to achieve at microscale. Interestingly, recent studies showed that pneumatic and hydraulic microactuators are excellent candidates for combining high actuation force and strokes [1,2,6,7]. In this paper, we discuss the miniaturized pneumatic actuator which fits in the specifications sketched above.

Two types of pneumatic actuators can be distinguished: piston–cylinder systems on the one hand and elastic actuators on the other hand [1,2]. Piston–cylinder actuators consist of a rod that slides upon pressurization in a cylinder. These are the most commonly used hydraulic actuators in large scale systems. Elastic actuators on the other hand consist of one or more elastic parts that expand upon pressurization, and are commonly used in microsystems. Piston–cylinder actuators have shown to achieve high forces and large strokes at small scale, but are difficult to seal. Elastic actuators on the other hand are more difficult to integrate in a mechanical design and have non-linear force-stroke characteristics. However, elastic actuators usually have the advantage of being leak-tight, compliant and cheaper to fabricate. Therefore, this paper focuses on the miniaturization of a particular type of elastic actuators: McKibben actuators. For a more elaborate overview of miniature pneumatic and hydraulic actuators we refer to [1,2]. McKibben actuators were developed in the 1950s by J.L. McKibben and Gaylord [8] are well-known within the field of humanoid robotics because they are unequalled in terms of actuation force per actuator weight [8–18]. In addition, McKibben actuators are soft and compliant, which makes them interesting for all applications where machines interact directly with human beings such as instruments for surgery [1,2,13], prostheses [14,15], human–machine interfaces and other robots [9,16]. Despite this compliancy, we show in this paper that these actuators can achieve very high positioning accuracies and high actuation forces. During this research, pneumatic McKibben actuators have been miniaturized to an outside diameter of 1.5 mm and lengths of 22 mm, which are probably the smallest actuators of this type.

Basically McKibben actuators consist of an expandable tube which is reinforced by a woven structure as illustrated in Fig. 1a. Upon pressurization, the elastic tube will maximize its volume, resulting in an expansion of the actuator diameter. Due to geometrical constraints of the woven structure, this results at the same time in a contraction of the actuator length as illustrated in Fig. 1b. It is the latter property that is used to generate the actuation stroke. The fact that these actuators can only generate pulling forces can be a disadvantage in some applications, however, prior research on large scale McKibben actuators presented various methods to integrate these artificial muscles in mechanical systems [19].

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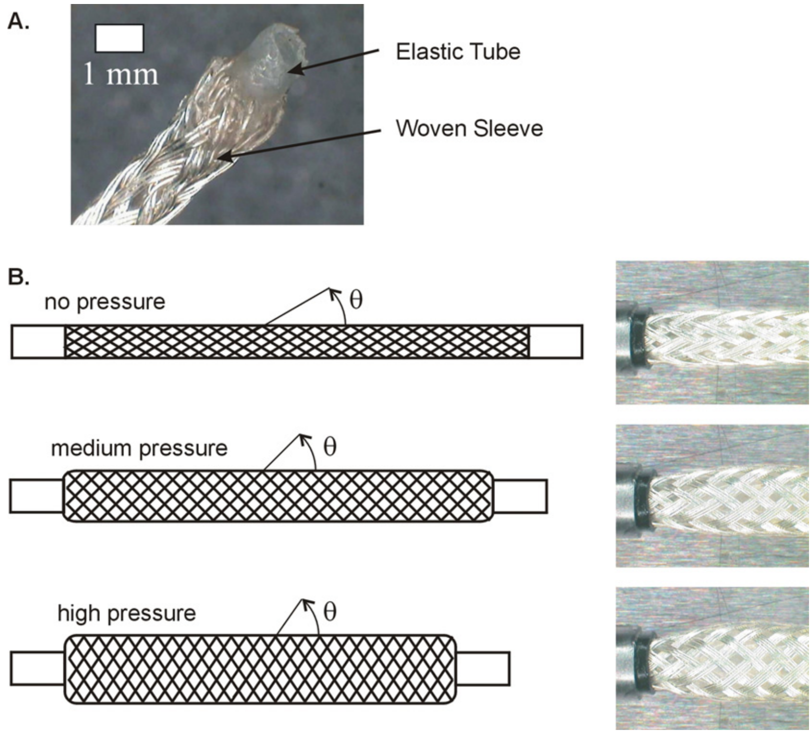

Fig. 1. (a) Example of a McKibben actuator developed during this research. (b) Operation principle of McKibben actuators.

The scope of this research is to miniaturize McKibben actuators to the dimensions sketched above, which fit in between typical MEMS and traditional actuators. We first introduce a model that describes the behaviour of McKibben actuators, followed by a low cost method to fabricate them. Next, measurements are performed to quantify the force, stroke speed, and positioning accuracy of these actuators. At present, these actuators are being implemented in instruments for keyhole surgery with actuated degrees of freedom inside the human body as will be discussed further on.

2. Numerical model

McKibben actuators were first modelled numerically by Gaylord [8]. In his model, the relation between the fluid pressure in the actuator and the actuation force is given by Eq. (1). As shown by this equation the actuation force scales as D^2, which is similar to other microactuators based on an active surface such as piston–cylinder pneumatic actuators and electrostatic actuators [21]. Interestingly, however, our measurements showed that the force output of McKibben actuators at this scale is higher than that of piston–cylinder actuators with the same dimentsions at the cost of lower strokes (see further) [1,6,7].

$$F = \frac{P\pi D_{45^\circ}^2}{2}(3\cos^2\theta - 1) \tag{1}$$

D_{45°. is the diameter of the woven structure for an angle θ equal 45°. The length L of the actuator is given by Eq. (2).

$$L = S\cos\theta \tag{2}$$

S is the effective length of the strands in the woven structure. Maximal contraction occurs at zero load on the actuator. From Eqs. (1) and (2), the maximal contraction can be derived as given in Eq. (3).

$$L = S\frac{1}{\sqrt{3}} = 0.577S \tag{3}$$

For ϕ equal to 45° it can be verified that the output force of the actuator equals the output force of a hydraulic piston with a diameter equal to D_{45°.

Alternatively, the behaviour of McKibben actuators has been modelled numerically by Colbrunn et al. [11]: Consider a McKibben actuator with a length L and a diameter D. These variables can be expressed as a function of following geometrical constants: the thread length b, the number of turns n of a single thread, and the interweave angle θ as illustrated in Fig. 1. The relation between the actuation force F, the length L, and the pressure P is determined by Eq. (4) [11]:

$$F = \frac{P \cdot b^2}{4\pi n^2}\left(\frac{3L^2}{b^2} - 1\right) \tag{4}$$

This relationship gives a basic insight in the relationship between the actuation pressure, stroke and force. Nevertheless, Eq. (4) has limitations since it omits forces due to the elastic deformation of the bladder and the friction between the bladder and the woven structure. Better results were obtained by an ad hoc adaptation of Eq. (4). The latter approach resulted in Eq. (5):

$$F = \max\left[(F_{\min}), \frac{(P - P_{Corr})\cdot b^2}{4\pi n^2}\left(\frac{3(L - L_{Corr})^2}{b^2} - 1\right)\right] + \max[0, k_b \cdot (L - L_{b_0})] \tag{5}$$

This new model is a simple extension of Eq. (4), that introduces a number of extra parameters such as L_{Corr} that takes into account that the extremities of actuator that are not functional due to the practical connection of the actuator to the outside world, P_{Corr} takes into account that when a certain strain is imposed on the actuator a corresponding pressure must be applied to the actuator before the actuation is started, the minimum actuation force $F_{\min}$ takes into account that McKibben actuators cannot generate pushing forces. Finally, two parameters that allow to take into account the strain