Length estimation of pneumatic artificial muscles for stretch reflex of musculoskeletal robots

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***Abstract*—This paper introduces an experimental model designed to estimate the length of a pneumatic artificial muscle (PAM) by measuring pressure and force. We model the PAM as a nonlinear spring with a spring constant that is a function of deformation and pressure. The model structure has physical bases in prior research, and its coefficients are derived from static experiments that measure pressure, force, and length. We apply this model to estimate the length of four distinct PAMs, each varying in materials and shapes using data from pressure and force sensors. This approach is advantageous for controlling musculoskeletal robots offering a practical alternative for length estimation of the muscles.**

***Index Terms*—length estimation, pneumatic artificial muscle, reflex, musculoskeletal robot**

I. INTRODUCTION

Soft robots are expected to achieve adaptability to environments like living organisms [1]. Soft robots that coexist with humans have been already realized [2], [3] and have been used to understand biological intelligence through a constructive methodology [4], [5]. As actuators in musculoskeletal robots, pneumatic artificial muscles (PAMs) are often used [6]. PAMs have several advantages over conventional actuators, such as a superior power-to-mass ratio [7], high compliance [8], and low cost and ease of production [9]. However, PAMs have nonlinearity because they consist of elastic materials, which places heavy computational demands on a central control system.

To overcome this hurdle, it is proposed to integrate reflex mechanisms found in living organisms into musculoskeletal robots [10]. Reflex mechanisms enable local control systems to swiftly respond to environmental changes without commands from a central control system, thereby reducing its computational load.

One of the reflex mechanisms, the stretch reflex, requires muscle length information [11], but directly measuring PAM length with a sensor poses several challenges [12]. Firstly, as a reflex action occurs instantaneously, it might lead to significant problems such as slackness in a wire encoder and light screen in a laser sensor, which could prevent accurate measurement of the PAM's length. Secondly, because a length sensor needs to be posed at both PAM's ends, it could limit robot design. Thirdly, sensor stiffness might reduce the PAM's flexibility.

This paper presents a method to estimate the PAM length from its pressure and force instead of directly measuring it with the goal of incorporating the stretch reflex into musculoskeletal robots. The proposed model views a PAM as a nonlinear spring, with the spring constant dependent on its pressure. We determine the degrees of the spring constant based on prior models and calculate its coefficients experimentally. The effectiveness of the model is demonstrated by evaluating the error in length estimation when pressure varies sinusoidally. Applying our model allows the sensors to gather at one end of a PAM, simplifying the musculoskeletal robot design. While theoretical models of the PAM cannot accurately reflect individual differences in properties because they require almost immeasurable parameters such as fiber length and the braiding angle of the sleeve [13], our experimental approach calculates coefficients for each PAM, gaining comprehensive applicability to PAMs of various materials and shapes.

II. MODEL PROPOSAL FOR LENGTH ESTIMATION

Regarding a PAM as a spring [14], its length is expressed as the sum of a natural length and a deformation

$$l = l_n(p) + d \tag{1}$$

where l is the PAM length, $l_n(p)$ is the natural length, defined as the length without external force at pressure p, and d is the deformation from the natural length, respectively.

Assuming that $l_n(p)$ is a linear function of p within a certain pressure range, it can be given as

$$l_n(p) = mp + k \tag{2}$$

where m and k can be determined by a static loading experiment.

Introducing the PAM's nonlinearity into the spring and assuming that the spring constant is the function of p [14], the force f is given by

$$f = (a_3pd + a_2p + a_1d + a_0)d \tag{3}$$

The terms pd^2 and d^2 can be found in Chou et al.'s fundamental model [15], which capture the essential dynamic properties of the PAM. The term pd comes from Tondu et al.'s model [16]

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to more accurately reflect differences in the shape of the PAM. The term d is added based on Ferraresi et al.'s model [17] to account for differences in material. The constants $a_0 \sim a_3$ in Eq. (3) are determined by the static loading experiment. Based on the $a_0 \sim a_3$, d can be calculated from the measured p and f by solving Eq. (3).

III. EXPERIMENTAL METHOD

A. PARAMETER IDENTIFICATION EXPERIMENT

Fig. 1 is an outline diagram of the static loading experiment to identify the parameters m, k, and a_i . Table I shows the shapes and materials of the used four PAMs. The experimental procedure was as follows. First, the pressure p was adjusted to a constant level. Taking into account the strength of the materials, the pressure of PAM-A, PAM-B, or PAM-C was adjusted to 0.4MPa, 0.5MPa, 0.6MPa, 0.7MPa or 0.8MPa, while the pressure of PAM-D was 0.2MPa, 0.3MPa, 0.4MPa, 0.5MPa, or 0.6MPa. Next, the PAM was gradually stretched from the natural length by approximately 2.5mm increments and the deformation d, the force f, and the pressure p were measured at each point. Each value was stabilized by waiting for at least 2 seconds after deformation. Once d reached its maximum value predetermined based on each PAM's strength, it was contracted to the natural length l_n by approximately 2.5mm decrements, and d, p, and f were measured again at each point. Finally, the parameters m, k, and a_i were calculated by the least squares method.

TABLE I: The Characteristics of the experimented PAMs

PAM	Length [cm]	Diameter [mm]	bladder Material
A	21.6	19.9	Rubber
B	21.1	13.4	Rubber
C	14.1	13.4	Rubber
D	21.2	19.0	Silicon

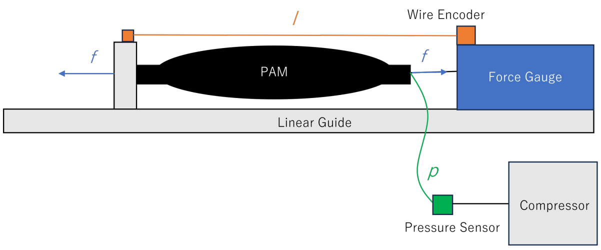

Fig. 1: Outline diagram of the static loading experiment

B. ERROR EVALUATION EXPERIMENT

We dynamically estimated the length of the four different PAMs to verify the general applicability of the model. The jig holding the left end of the PAM in Fig. 1 was removed and a pulley was installed in its place. A proportional control valve was installed between the pressure sensor and the compressor. The experiment procedure was as follows. First, a weight of either 5kg or 10kg was connected to the PAM via the pulley to apply a constant force f. Next, considering the strength of each PAM, the pressure $p[\text{MPa}]$ was varied over time $t[\text{s}]$ by the proportional control valve according to

$$p = 0.2 \sin\left(\frac{2\pi t}{5}\right) + 0.6 \tag{4}$$

for PAM-A, PAM-B, and PAM-C, and

$$p = 0.2 \sin\left(\frac{2\pi t}{5}\right) + 0.4 \tag{5}$$

for PAM-D. At each time, f, p, and the length l were measured. Finally, the errors were calculated between the measured and estimated l.

IV. LENGTH ESTIMATION RESULT

A. PARAMETER IDENTIFICATION

Fig. 2 shows the relationship between the pressure p and the natural length $l_n(p)$ of the PAMs. As assumed, there is a tendency for $l_n(p)$ to decrease linearly with p within the range of the tested pressure. The dashed lines in Fig. 2 represent the fitted lines using the least squares method, expressed by Eq. (2).

Fig. 3 shows the result of the static loading experiment for PAM-B. The red and blue points represent the data during expansion and contraction respectively, and the green dashed lines represent the solutions d to Eq. (3), which is given by substituting the acquired parameters a_i and the measured f and p. Generally, PAMs exhibit hysteresis due to friction, so the data differ between expansion and contraction processes. We only present the static loading experimental result for PAM-B because of the space constraint, but similar results were obtained for the other PAMs.

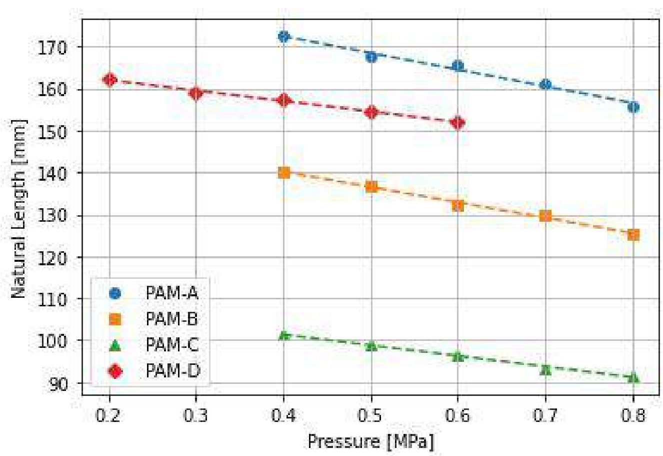

Fig. 2: Relationship between pressure and natural length

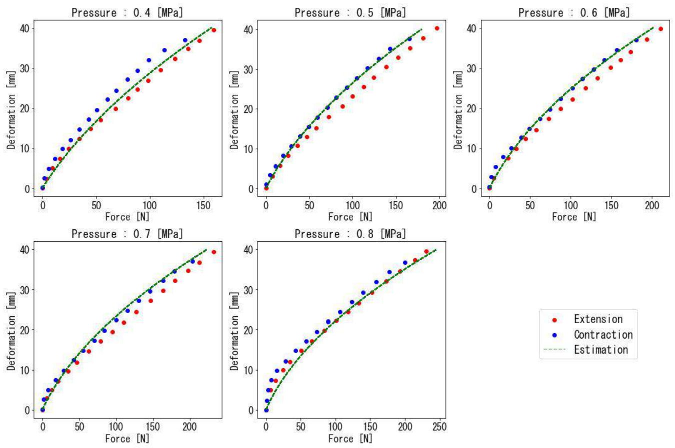

Fig. 3: Relationship between force and deformation at each pressure (PAM-B)

B. ERROR EVALUATION

Fig. 4 and Fig. 5 show the dynamic length estimation result for PAM-B and PAM-D, respectively. With the proposed method, the length estimation was achieved with maximum errors of 1.72% for PAM-A, 1.19% for PAM-B, 1.18% for PAM-B, and 1.65% for PAM-D respectively, and with mean squared errors of 0.861% for PAM-A, 0.653% for PAM-B, 0.683% for PAM-C, and 0.846% for PAM-D respectively.

V. DISCUSSION

To improve length estimation accuracy, we expanded Eq. (3) by adding the terms p^2 and d^2 and increasing the parameters as follows

$$F = (b_5p^2 + b_4pd + b_3d^2 + b_2p + b_1d + b_0)d \qquad (6)$$

As a result, the dynamic length estimation was achieved with the maximum errors of 1.12% for PAM-A, 0.773% for PAM-B, 1.01% for PAM-B, and 0.755% for PAM-D respectively, and with the root mean squared errors of 0.633% for PAM-A, 0.353% for PAM-B, 0.548% for PAM-C, and 0.435% for PAM-D respectively. The errors were reduced as expected for all PAMs.

We also tried another approach by introducing a cubic polynomial model and increasing the parameters as follows

$$F = (c_4p^3 + c_3p^2d + c_2pd^2 + c_1d^2 + c_0)d \qquad (7)$$

As predicted, the root mean squared errors decreased to 0.516% for PAM-A, 0.484% for PAM-B, 0.500% for PAM-C, and 0.606% for PAM-D respectively. However, even though the maximum errors decreased to 1.22% for PAM-A and 0.951% for PAM-C respectively, they actually increased to 1.41% for PAM-B and 1.99% for PAM-D respectively. This result suggests that, even if the coefficients of the model equation are determined experimentally, the degrees must be carefully determined based on previous studies so as to express intrinsic characteristics of the PAM. For example, the newly added term p^3 may have amplified the error of the pressure sensor. When applying our model to a reflex mechanism, it will also be necessary to carefully consider the contribution of each term to the accuracy of the length estimation based on the reliability of the force and pressure sensors used.

Wickramatunge et al. proposed separating the parameters a_i into contraction ones a_i^c and extension ones a_i^e to reflect the hysteresis of the PAM [14]. They also suggested using different parameters for low-pressure and high-pressure ranges to further improve the accuracy [14]. However, our model ignores these suggestions and simplifies the length estimation method by using the same parameters across the entire pressure range, regardless of contraction or expansion. This is because our model is supposed to be applied to the reflex mechanism. If it is necessary to switch the parameters depending on the situation, it would be difficult for the reflex mechanism to respond quickly to disturbances. Musculoskeletal robots often carry microcomputers on their structures, so the employed length estimation method is desired to be simple for efficient operation given the limited computational resources.

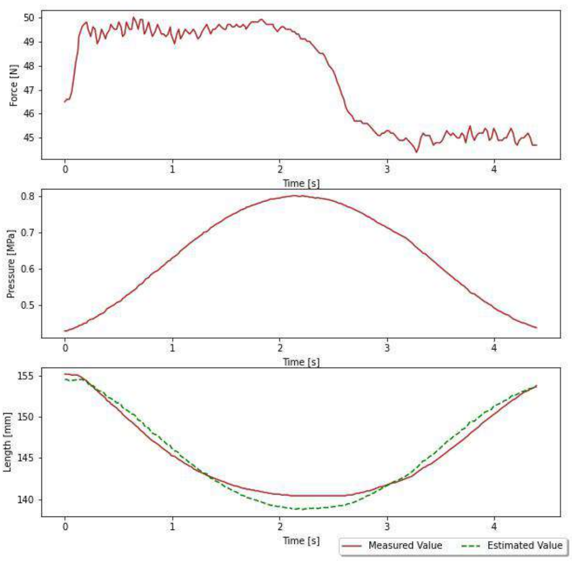

Fig. 4: Dynamic length estimation (PAM-B, Rubber)

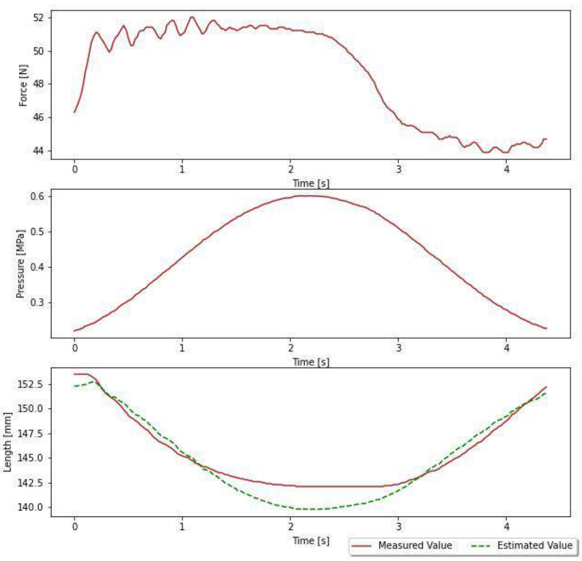

Fig. 5: Dynamic length estimation (PAM-D, Silicon)

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