# Dynamic length estimation of pneumatic artificial muscles using pressure and deformation dependent spring model for robot reflex mechanism

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***Abstract*—This paper presents an experimental model to estimate the length of pneumatic artificial muscles (PAMs) from its pressure and tension with the goal of incorporating a reflex mechanism into musculoskeletal robots. Our model treats a PAM as a non-linear spring with the spring constant dependent on pressure and deformation. The order of the model equation is determined based on the previous studies and the coefficients, which reflect individual differences in characteristics, are determined experimentally using the least squares method. As a result, when the pressure was varied in the triangular waveform, the length estimations of four PAMs with the different materials and shapes were achieved with the maximum error of 1.72% and the root mean squared percentage errors within 0.861%.**

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

## I. INTRODUCTION

Soft robots are expected to achieve adaptability to environment like living organisms. As actuators in a musculoskeletal robot, pneumatic artificial muscles (PAMs) are often used. However, their inherent nonlinearity places heavy computational demands on a center control system. To overcome this hurdle, it is proposed to integrate reflex mechanisms found in living organisms into musculoskeletal robots [1]. Reflex mechanisms enable local control systems to swiftly respond to environmental changes without commands from a center control system, thereby reducing its computational load. One of the reflex mechanisms, stretch reflex, requires muscle length information, but directly measuring PAM length with a sensor poses several challenges. Firstly, as a reflex action occurs instantaneously, it might lead to significant measurement 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 need tp 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 in order to incorporate the stretch reflex into PAM-actuated robots. The proposed model views a PAM as a nonlinear spring, with the spring constant dependent on its pressure and deformation from natural length. We determine the degree of the spring constant based on prior models and acquire its coefficients through experiments. Then, we measure the error in length estimation when pressure varies trigonometrically, showing the effectiveness of the proposed model in the actual driving mode. Applying our model allows the sensors to gather at one end of a PAM, simplifying musculoskeletal robot structure. 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, our experimental approach calculates coefficients for each PAM. This approach gains comprehensive adaptability to PAMs of various materials and shapes.

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## II. MODEL PROPOSAL FOR LENGTH ESTIMATION

Regarding a PAM as a nonlinear spring [2], its length is expressed as the sum of a natural length and a deformation from natural length:

$$L = L_n + L_d \tag{1}$$

where $L$ is the PAM length, $L_n$ is the natural length, defined as the length without external force at pressure $P$, and $L_d$ is the deformation from the natural length.

Assuming that $L_n$ is a linear function of $P$ within a certain pressure range, it can be expressed as:

$$L_n = mP + k \tag{2}$$

where the constants $m$ and $k$ are calculated by applying the least squares method to length data measured while supplying compressed air to the PAM.

Furthermore, assuming that the spring constant of the PAM is the function of $P$ and $L_d$ [2], the force $F$ is given by:

$$F = (a_3 P L_d + a_2 P + a_1 L_d + a_0) L_d \tag{3}$$

Here, the terms $PL_d^2$ and $L_d^2$ are derived from Chou et al.'s fundamental model [3] to capture the essential dynamic properties of the PAM. The $PL_d$ term is based on Tondu et al.'s model [4] to more accurately reflect differences in the shape of the PAM, while the $L_d$ term is added based on Ferraresi et al.'s model [5] to account for differences in material. The constants $a_0 \sim a_3$ in Equation (3) are determined by applying the least squares method to data obtained from the load experiment, and $L_d$ is calculated as a solution to Equation (3).

## III. EXPERIMENTAL METHOD

### A. PARAMETER IDENTIFICATION EXPERIMENT

Figure 1 is an outline diagram of the experiment conducted to determine the parameters necessary for length estimation. Table I shows the shapes and the materials of the sacs of the four PAMs used in the experiment. The experimental procedure is as follows: first, the pressure $P$ was adjusted to a constant level. Taking into account the strength of the materials of the sacs, the pressure of PAM-A, PAM-B, or PAM-C was adjusted to $0.4\mathrm{MPa}$, $0.5\mathrm{MPa}$, $0.6\mathrm{MPa}$, $0.7\mathrm{MPa}$ or $0.8\mathrm{MPa}$, while the pressure of PAM-D was adjusted to $0.2\mathrm{MPa}$, $0.3\mathrm{MPa}$, $0.4\mathrm{MPa}$, $0.5\mathrm{MPa}$, or $0.6\mathrm{MPa}$. Next, the PAM was gradually stretched from the natural length by approximately $2.5\mathrm{mm}$ increments and the deformation from the natural length $L_d$, the force $F$, and the pressure $P$ were measured at each point. During this process, each value was stablized by waiting for at least 2 seconds after deformation. Once $L_d$ reached its maximum value predetermined based on each PAM's strength, then it was contracted by approximately $2.5\mathrm{mm}$ decrements until reaching the natural length $L_n$, and $L_d$, $P$, and $F$ were measured at each point. Finally, the estimation parameters $m$, $k$, and $a_i$ were calculated for each PAM using the least squares method.

TABLE I
THE CHARACTERISTICS OF THE EXPERIMENTED PAMS

| PAM | Length [cm] | Diameter [mm] | Sac 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 |

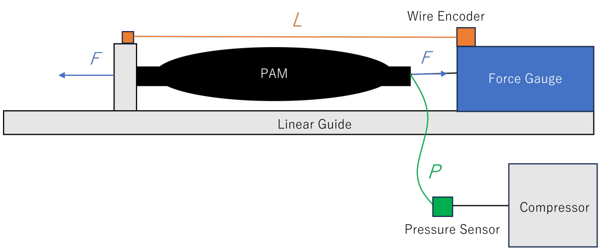


Fig. 1. OUTLINE DIAGRAM OF THE PARAMETER IDENTIFICATION EXPERIMENT

### B. DYNAMIC ESTIMATION EXPERIMENT

Figure 2 is an outline diagram of the experiment to verify the effectiveness of the proposed model by measuring the error when dynamically estimating the length of the PAMs using the acquired parameters. The experimental procedure is as follows: first, a weight of either $5\mathrm{kg}$ or $10\mathrm{kg}$ was connected to the PAMs via a pulley to apply a constant force $F$. Next, considering the strength of each PAM, the pressure $P[\mathrm{MPa}]$ was trigonometrically varied over time $t[\mathrm{s}]$ by a proportional control valve (PCV) 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 $L$ of the PAMs were measured. Finally, the errors were calculated between the measured and estimated $L$.

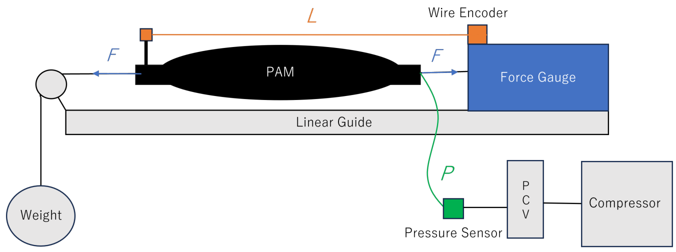


Fig. 2. OUTLINE DIAGRAM OF THE DYNAMIC ESTIMATION EXPERIMENT

## IV. LENGTH ESTIMATION RESULT

### A. ESTIMATION PARAMETER IDENTIFICATION

Figure 3 shows the relationship between the pressure $P$ and the natural length $L_n$ of the four PAMs. As assumed, there is a tendency for $L_n$ to decrease linearly with $P$ within the range of the pressures tested. The dashed lines in figure 3 represent the straight lines fitted to each data set using the least squares method, expressed by Equation (2).

On the other hand, Figure 4 shows the result of the parameter identification experiment for PAM-B. The red points represent the data during expansion, the blue points represent the data during contraction, and the green dashed lines represent the solutions $L_d$ to Equation 3,which is obtained by substituting the gained parameters $a_i$ and the sensor values $F$ and $P$. Generally, PAMs exhibit hysteresis due to friction, so the data differs between expansion and contraction process. In this paper, we only present the experimental result for PAM-B because of the space constraint, but the similar results were obtained for the other PAMs.

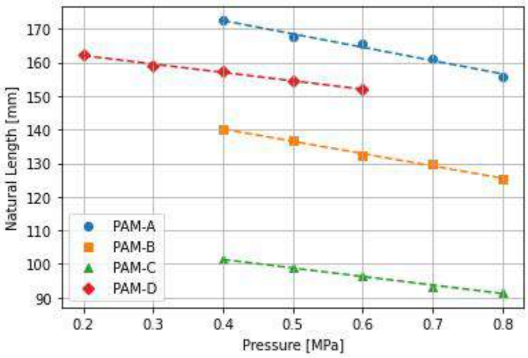


Fig. 3. RELATIONSHIP BETWEEN PRESSURE AND NATURAL LENGTH

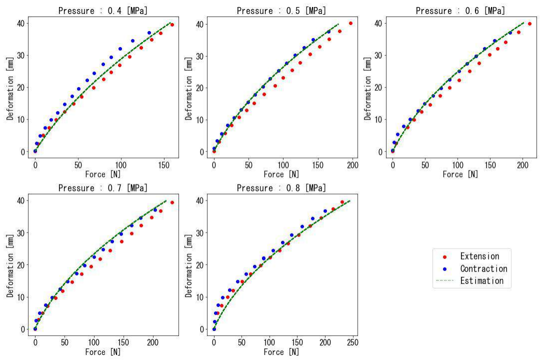


Fig. 4. RELATIONSHIP BETWEEN FORCE AND DEFORMATION AT EACH PRESSURE (PAM-B)

### B. DYNAMIC LENGTH ESTIMATION RESULT

Figure 5 shows the dynamic length estimation result using the acquired parameters for PAM-B. With the proposed method, the dynamic length estimation was achieved with maximum errors and mean squared error rates shown in the first and second columns of Table II respectively.

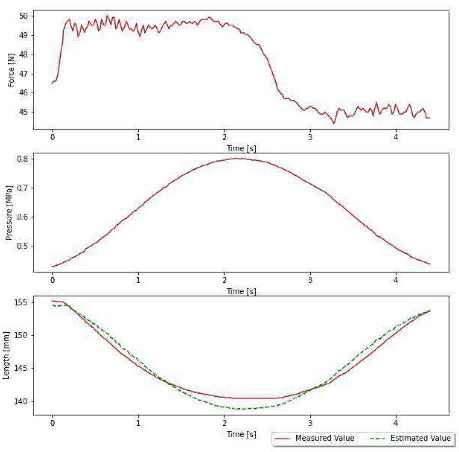


Fig. 5. RESULT OF DYNAMIC LENGTH ESTIMATION (PAM-B)

TABLE II
MAXIMUM ERROR AND ROOT MEAN SQUARED PERCENTAGE ERROR OF DYNAMIC LENGTH ESTIMATION

| PAM | Maximum Error[%] (Eq.(3)) | Root Mean Squared Error[%] (Eq.(3)) | Maximum Error[%] (Eq.(6)) | Root Mean Squared Error[%] (Eq.(6)) | Maximum Error[%] (Eq.(7)) | Root Mean Squared Error[%] (Eq.(7)) |
|---|---|---|---|---|---|---|
| A | 1.72 | 0.861 | 1.12 | 0.633 | 1.22 | 0.516 |
| B | 1.19 | 0.653 | 0.773 | 0.353 | 1.41 | 0.484 |
| C | 1.18 | 0.683 | 1.01 | 0.548 | 0.951 | 0.500 |
| D | 1.65 | 0.846 | 0.755 | 0.435 | 1.99 | 0.606 |

## V. DISCUSSION

To improve length estimation accuracy, we expanded Equation (3) by adding the terms $P^2$ and $L^2$ and increasing the number of the parameters as follows:

$$F = (b_5P^2 + b_4PL_d + b_3L_d^2 + b_2P + b_1L_d + b_0)L_d \quad (6)$$

As a result, as shown in the third and fourth columns of Table II, the errors were reduced as expected for all PAMs.

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

$$F = (c_4P^3 + c_3P^2L_d + c_2PL_d^2 + c_1L_d^2 + c_0)L_d \quad (7)$$

However, in some cases, the errors were actually increased as indicated in the fifth and sixth columns of Table II. This result suggests that, even if the coefficients of the model equation are determined experimentally, the degree must be carefully determined based on previous studies so as to express intrinsic dynamic 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 length estimation based on the reliability of the force and pressure sensors used.

## VI. SUMMARY

In this paper, we proposed the method to dynamically estimate the length of tha PAM, reflecting individual differences in material and shape by determining the degree of the model equation based on previous studies and experimentally determining its coefficients. In the future, we will develop a musculoskeletal robot equipped with a reflex mechanism and verify the effectiveness of our method in reflex actions.

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