Abstract—It is important to develop the orthosis which improves the Quality of Life (QOL) and maintains health conditions. As one of the treatment methods done to lumbago (low back pain), the waist fixation method with the spinal brace or the orthosis is prescribed. A waist active orthosis implemented with pneumatic flexible actuators have been developed. However, several problems of the previous actuator were that the strain and the generated force were small for the orthosis. Thus, this paper proposes the improved actuator for the orthosis. The improved actuator is modeled and the reliability of static and dynamic model is validated through experiment. As a result, it was confirmed that the improved actuator had the strain of 2 times and the generated force of 1.3 times, in comparison with the previous actuator. And the dynamic model including volume of actuator could be represented by a second-order form with a dead time.

Index Terms—waist active orthosis, Lumbago relief, pneumatic textile actuator, modeling, system identification

I. INTRODUCTION

It is important to improve the QOL and maintain the health condition for elderly people. Our special attention is directed to lumbago because many people feel a low back pain in daily life. As one of the treatment methods done to lumbago, the waist fixation method [1] with a spinal brace or an orthosis is performed. Generally, an orthosis is wrapped around the waist made of cloth and the rubber textile. However, the existing orthosis have the three difficult and important issues.

1) Problem difficult to meet on-demand requirements: It is difficult to change size or shape of the orthosis by daily demand actions and physical conditions of users.

2) Problem to suppress blood stream: The orthosis causes many physical problems such as pain, skin eruptions, and bloodstream suppression for a long time use.

3) Problem difficult to customize: It is difficult to select size and shape of the appropriate orthosis which is best fitted to an individual body.

In order to solve these issues, a waist active orthosis implemented with pneumatic flexible actuators is developed and pressure control method of pneumatic flexible actuators is established. However, the customizing issues have not been solved. In this study, firstly, the prototype of pneumatic textile actuator (hereafter called PTA) has been developed. But several problems of the previous actuator were that the strain and the generated force were small for the orthosis. The previous actuator is indirectly driven by a McKibben actuator. Thus, the improved actuator changes to the driving method that can be contracted directly by a silicone tube. Therefore the improved actuator is modeled and the reliability of static and dynamic model is validated through experiment.

II. STRUCTURE OF IMPROVED PTA

In order to provide orthosis for the waist which effectively fastens the pelvis, the proposed orthosis does not slip up even if a hard exercise is conducted during carrying. And the orthosis has effects on the support of the pelvis and pain relief in the prognosis of lumbago treatment or the recurrent prevention and prophylaxis of lumbago. The previous PTA has a structure which inwrought with a long McKibben-type actuator [2] into two soft cloths (See Fig. 1(a)). When the compressed air is injected into the supply port, the McKibben-type actuator contracts to an axial direction. As the result, the PTA shrinks indirectly by the seam constraint. Thus, two problems of the previous PTA were that the strain and the generated force were small for the orthosis.

On the other hand, the improved PTA has a structure which inwrought with a silicone tube into two soft cloths as shown in Fig. 1(b). Fig. 1(c) shows the prototype of the active orthosis for the lumbago relief. The proposed active orthosis consists of five PTAs (=belts) and the body pressure sensor. The size of the orthosis is 970×200×7mm, and the mass is 300g. The active orthosis has a double structure. One structure is the body-orthosis that is configured in the main belt and the ilium belts (right and left). Another structure is two X-type belts.

Fig. 2(a) shows the operating principle of PTA. When the compressed air is injected into the supply port, the silicone tube expands a radial direction. As the result, the PTA shrinks directly by the constraints of the seam constraint and the hard cloth.
Hence, the generated force \( F \) of PTA width \( l \) is

\[
F = 2\pi lb P \left\{ \frac{\cos \theta}{\theta (\theta + \cot \theta)} \right\} - F_{diss}
\]

where each partial differentiation with Eq. (2) is as follows

\[
\frac{\partial V}{\partial \theta} = \frac{2\pi lb^2 \cot^2 \theta}{(\theta + \cot \theta)^2} \quad \frac{\partial L}{\partial \theta} = -\frac{b \theta \cos \theta}{(\theta \sin \theta + \cos \theta)^2}
\]

When the clothes of PTA are made with the material which can’t shrink, the half pitch length \( b \) of the seam doesn’t change. The static model of the improved PTA has been given by

\[
F = P(\alpha_1 \varepsilon + \alpha_0) - (\beta_2 \varepsilon^2 + \beta_1 \varepsilon + \beta_0)
\]

\[
\alpha_1 = 2\pi lb \alpha, \quad \alpha_0 = 2\pi lb \beta, \quad \beta_2 = kL_0^2, \quad \beta_1 = kL_0 \eta + f \gamma \quad \text{and} \quad \beta_0 = f \eta \text{ are PTA characteristics constants, respectively. Clearly, the force } F \text{ depends on both pressure } P \text{ and strain } \varepsilon.
\]

In order to prove versatility of Eq. (5), the comparison was done between the measurement data and force model. It can be seen in Fig. 4 that both generated force \( F \) and strain \( \varepsilon \) increase with pressure. The static force model of the improved PTA is located in the average of the hysteresis loop. Therefore, the accurate fitting is demonstrated in Fig. 4.

\[
\text{Figure 3. Static model of improved PTA.}
\]

\[
\text{Figure 4. Verification experiment of static model (Results of measurement and model output signals).}
\]
of the on/off valve is 36×14.5×7.2 mm, and the mass is 5 g. The total mass of the orthosis control valve including the controller (Micro-computer: Renesas Co. Ltd., H8/3664F) is very light, that is about 220 g.

C. Dynamic Model of Improved PTA [3], [4]

Fig. 5 shows the analytical model of the orthosis control valve. The mass flow rate of supply valve \( Q_i \) and the exhaust valve \( Q_o \) are given as follows.

\[
Q_i = A_{si} P_s \sqrt{\frac{2}{R_a}} g(z_i), \quad z_i = \frac{P}{P_a} : \text{Supply State} \quad (6)
\]

\[
Q_o = A_{so} P_a \sqrt{\frac{2}{R_a}} g(z_o), \quad z_o = \frac{P}{P_a} : \text{Exhaust State} \quad (7)
\]

where \( R \) and \( T_a \) mean a gas constant and an absolute temperature, respectively.

\[
\rho = \frac{dP}{dt} = \frac{\kappa RT_a}{V} (Q) : \text{Supply State} \quad (8)
\]

\[
\rho = \frac{dP}{dt} = \frac{\kappa RT_a}{V} (-Q) : \text{Exhaust State} \quad (9)
\]

where \( \kappa \) means a specific heat ratio (=1.4). The pressure \( P \) in the volume \( V \) of PTA is given by next equations.

Fig. 5 shows the relationship between the volume and the pole of Eq. (10). In the Fig. 7, each circle point denotes the pole of the transfer function that is obtained by the system identification (ARX model [5]). And, the solid line denotes the pole of Eq. (10) that is the inverse proportion to the volume \( V \) (the first term on the right-side of Eq. (10)).

On the other hand, suppose that the sectional area \( v = A_{si} \) of the on/off valve is opened (or closed) slowly. Suppose that the switching area \( A_{si} \) (*=i or o) of valve is approximated by dead time \( T_s = 3 \text{ ms} \) and time constant \( T_o = 3.5 \text{ ms} \) of a primary delay system.

\[
v(s) = A_{si} = \frac{A_{si}}{T_s s + 1} \cdot e^{-T_s s} \cdot u(s)
\]

New Input

\[
\begin{align*}
\ & u(s) = 1 : \text{Supply Mode} \\
\ & u(s) = -1 : \text{Exhaust Mode} \\
\ & u(s) = 0 : \text{Hold Mode}
\end{align*}
\]

From Eqs. (7) and (8), the transfer function of on/off valve system with volume of PTA is given by a second-order form and a dead time. The transfer function of the control valve system with volume of PTA is given by a second-order form with a dead time [5].

D. Verification Experiment of Dynamic Model

In order to validate the reliability of the linear model, the verification experiment of supply (500 kPa) and exhaust (0 kPa) motion was performed on conditions of different volumes from 3 ml to 20 ml by using the syringe as shown in Fig. 6. However, the volume of the syringe is fixed to the desired volume \( V \) and minimum volume 3 ml is the initial volume of the tested PTA.

Fig. 7 shows the relationship between the volume and the pole of Eq. (10). In the Fig. 7, each circle point denotes the pole of the transfer function that is obtained by the system identification (ARX model [5]). And, the solid line denotes the pole of Eq. (10) that is the inverse proportion to the volume \( V \) (the first term on the right-
hand side). From Fig. 6, it can be seen that the pole of Eq. (7) corresponds reasonably well with the pole of the real system.

Fig. 8 shows the experimental results and output of the proposed model at the volume $V=3$, $7$ and $20$ ml. From Fig. 8, it can be seen that the pole of Eq. (10) corresponds reasonably well with the pole of the real system. The proposed model was a very simple model, but it could be confirmed that the actual valve system including volume.

**IV. CONCLUSIONS**

This study was aimed to develop the PTA of the orthosis for lumbar relief and the resulting knowledges are summarized as follows:

1) The improved PTA was modeled and the reliability of static and dynamic model was validated through experiment.

2) The improved actuator had the strain performance of 2 times and the generated force of 1.3 times, in comparison with the previous actuator.

3) The dynamic model including volume of PTA could be represented by means of a second-order form with a dead time.

4) The pole of a valve system including volume was the inverse proportion to the volume.

In our future works, we will design the control valve system by using the dynamic model of a second-order form with a dead time.

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