Development of Active Orthosis for Lumbago Relief - Modeling of Pneumatic Textile Actuator for Orthosis

Kayoko Uno, Shinsaku Fujimoto, Tetsuya Akagi, and Wataru Kobayashi
Department of Intelligent Mechanical Engineering, Okayama University of Science,
1-1 Ridaicho, Kita-ku, Okayama, Japan
E-mail: t13r011uk@ous.jp, fuji@are.ous.ac.jp, akagi@are.ous.ac.jp, kobayashi@are.ous.ac.jp

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

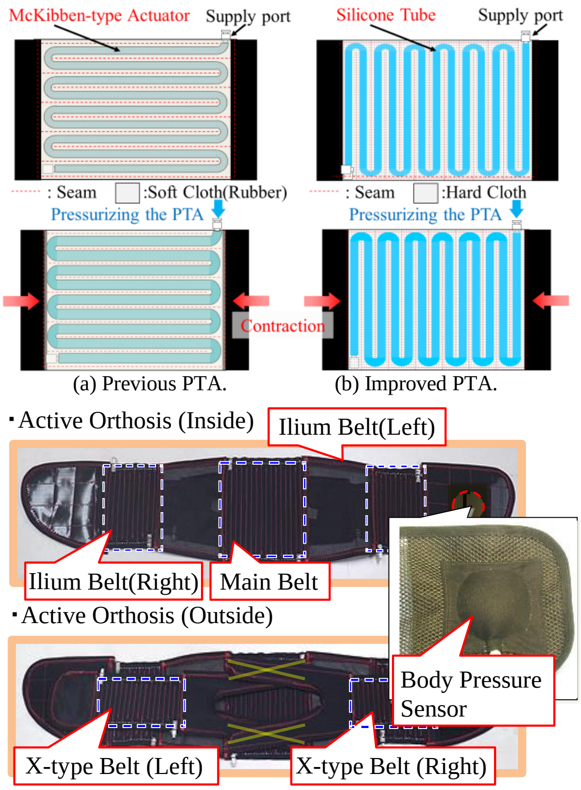
In order to provide orthosis for the waist which effectively fastens the pelvis, the proposed orthosis does not slip up even if a hard exercise is conducted during carrying. And the orthosis has effects on the support of the pelvis and pain relief in the prognosis of lumbago treatment or the recurrent 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 inject 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 $970 \times 200 \times 7$mm, 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.

Manuscript received November 20, 2016; revised April 11, 2017.

doi: 10.18178/ijmerr.6.5.413-416



(c) Prototype of Active Orthosis

Figure 1. Previous PTA and improved PTA

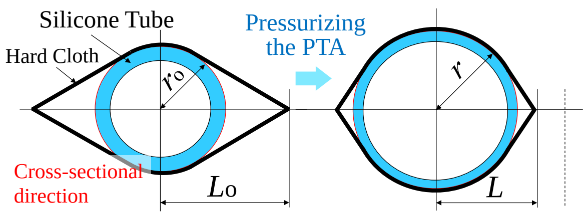


Figure 2. Operating principle of improved PTA.

III. Modeling of Improved PTA

This chapter will be described about the construction methods of a static model and a dynamic model. And the orthoses control valve system is modeled and the reliability of supply and exhaust model is validated through experiment.

A. Structure of Active Orthosis

From the view of energy conservation, the input work of the improved PTA should equal the output work which a system includes force dissipation or force loss F_{diss} as shown in Fig. 3. Suppose that the actuator is in this ideal condition, a following equation of static model holds.

$$P \cdot dV = -(F + F_{diss}) \cdot dL \tag{1}$$

where P is the internal gauge pressure, dV is the volume change, F is the force generated by the PTA, and dL is the axial displacement, respectively.

Since the force term F+F_{diss} of Eq. (1) is given by

$$F + F_{diss} = -P\frac{dV}{dL} = -P\frac{\partial V}{\partial \theta}\cdot\frac{\partial \theta}{\partial L} \tag{2}$$

Hence, the generated force F of PTA width l is

$$F = 2\pi lbP\left\{\frac{\cos\theta}{\theta(\theta+\cot\theta)}\right\} - F_{diss} \tag{3}$$

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

$$\frac{\partial V}{\partial \theta} = \frac{2\pi lb^2\cot^2\theta}{(\theta+\cot\theta)^3},\ \frac{\partial L}{\partial \theta} = -\frac{b\theta\cos\theta}{(\theta\sin\theta+\cos\theta)^2} \tag{4}$$

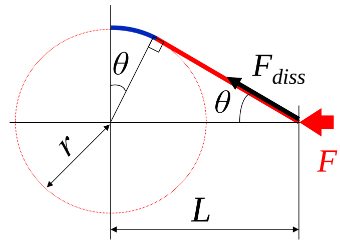


Figure 3. Static model of improved PTA.

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

$$F = P(\alpha_1\varepsilon + \alpha_0) - (\beta_2\varepsilon^2 + \beta_1\varepsilon + \beta_0) \tag{5}$$

where coefficients α_1 = $2\pi lb\alpha$, α_0 =$2\pi lb\beta$, β_2 =$kL_o\gamma$, β_1 =$kL_o\eta+f\,\gamma$ and β_0 =$f\,\eta$ are PTA characteristics constants, respectively. Clearly, the force F depends on both pressure P and strain ε.

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 ε 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.

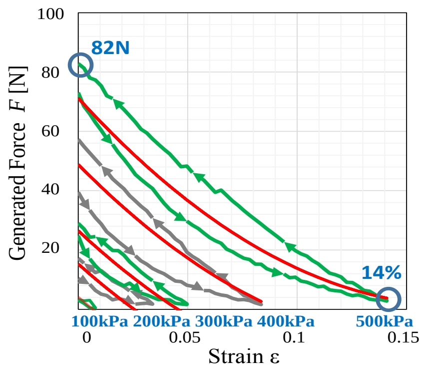


Figure 4. Verification experiment of static model (Results of measurement and model output signals).

B. Tested Valve Using Two on/off Valuves

The tested valve consists of two on/off-type control valves (SMC Co. Ltd., S070C- SDC-32) that both output ports are connected each other. One valve is used as the supply valve, and another is used as the exhaust valve. Two valves can adjust output flow rate like a variable fluid resistance by means of the fast switching. The size 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 220g.

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.

$$Q_i = A_{si} P_s \sqrt{\frac{2}{RT_a}}\, g(z_i), \quad z_i = \frac{P}{P_s} \text{ : Supply State} \qquad (6)$$

$$Q_o = A_{so} P_a \sqrt{\frac{2}{RT_a}}\, g(z_o), \quad z_o = \frac{P_a}{P} \text{ : Exhaust State} \qquad (7)$$

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

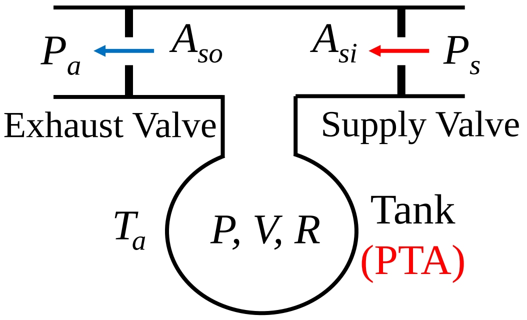


Figure 5. Analytical model of the orthosis control valve

The pressure P in the volume V of PTA is given by next equations.

$$\dot{P} = \frac{dP}{dt} = \frac{\kappa R T_a}{V}(Q_i) \text{ : Supply State} \qquad (8)$$

$$\dot{P} = \frac{dP}{dt} = \frac{\kappa R T_a}{V}(-Q_o) \text{ : Exhaust State} \qquad (9)$$

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

The systems of Eqs. (5) and (6) are non-linear systems with respect to the input of sectional area A_{s*}(*=i or o). Here, the simple idea is to approximate a non-linear system by a linear one (around the pressure point P=P_E.

$$\dot{x} = -\frac{2.70\times10^2 \cdot A_{so}}{V}x - \frac{4.61\times10^4}{V}v \text{ : Supply State} \quad (10.1)$$

$$\dot{x} = -\frac{2.78\times10^2 \cdot A_{si}}{V}x + \frac{4.68\times10^4}{V}v_i \text{ : Exhaust State} \quad (10.2)$$

In the linearization, the atmospheric pressure P_a , the room temperature T_a (=298.15 K), the gas constant R (=8.314) the supply pressure P_s of 500 kPa were used. And the sectional area of the supply port A_{si} (=2.02×10^{-7} m^2) and the area of exhaust port A_{so} (=2.30×10^{-7} m^2) were adopted the values of catalog specification (on/off valve). The obtained linear system can be expressed by the first-order transfer function. The pole of first-order system depends on the volume V of PTA. The smaller volume of PTA, the faster response speed becomes.

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

$$v(s) = A_*(s) = \frac{A_{s*}}{T_o s + 1}\cdot e^{-Ls}\cdot u(s)$$

$$\text{New Input} \begin{cases} u(s) = \ \ 1 & : \textit{Supply Mode} \\ u(s) = -1 & : \textit{Exhaust Mode} \\ u(s) = \ \ 0 & : \textit{Hold Mode} \end{cases} \qquad (11)$$

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 (500kPa) 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.

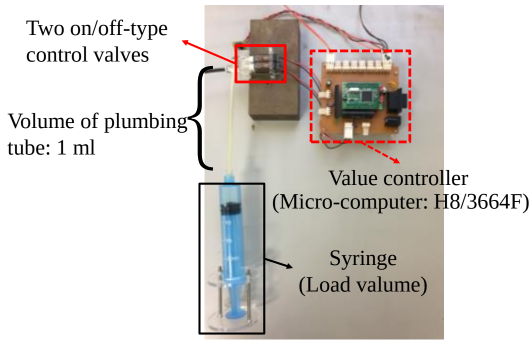


Figure 6. Verification experimental device.

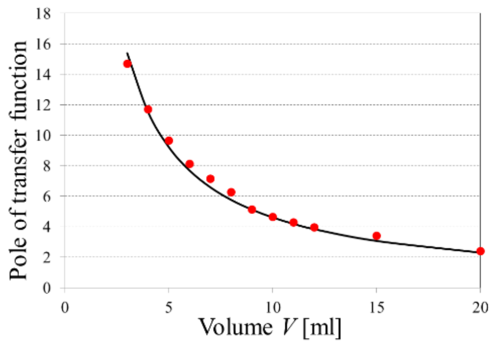
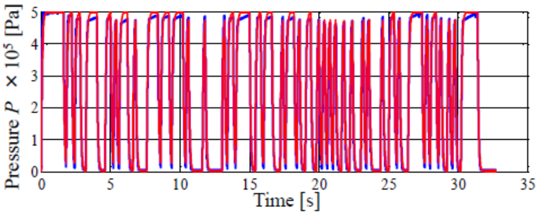


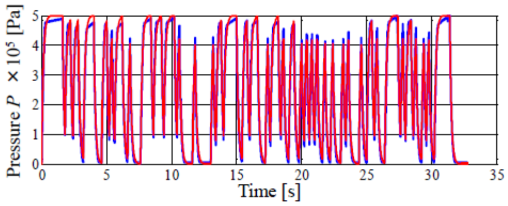
Figure 7. Relationship between the volume and the pole of Eq. (10).

Fig. 7 shows the relationship between the volume and the pole of the transfer function to confirm the effectiveness 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.

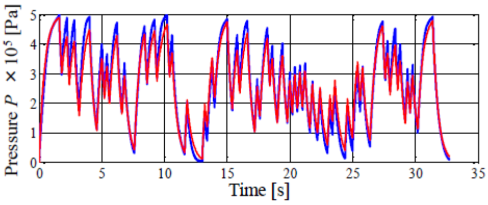
Fig. 8 shows the experimental results and output of the proposed model at the volume *V*= 3, 7 and 20 ml. From Fig. 8, it can be seen that the pole of Eq. (10) corresponds reasonably well with the pole of the real system. The proposed model was a very simple model, but it could be confirmed that the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



(a) Volume : V = 3ml



(b) Volume : V = 7 ml



(c) Volume : V = 20 ml

Figure 8. Results of verification experiment

IV. Conclusions

This study was aimed to develop the PTA of the orthosis for lumbago 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.

Acknowledgment

The authors would like to acknowledge financial support for this work provided by QOL (Quality of Life) Innovative Research (2012–2016) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] S. Schulte, H. Rossler, P. Ziehe. and F. Higuchi, “Bracing and supporting of the lumbar spine,” *Prostheses and Orthotics International*, vol. 6, no. 3, pp. 139-146, 1982.

[2] H. F. Schulte, “The characteristics of the mckibben artificial muscle, the application of external power in prosthetics and orthotics,” *National Academy of Sciences–National Research Council*, vol. 94-115, 1961.

[3] R. B. van Varseveld and G. M. Bone, “Accurate position control of a pneumatic actuator using on/off solenoid valves,” *IEEE/ASME Transactions on Mechatronics*, vol. 2, no. 3, pp. 195-204, 1997.

[4] Y. Moriwake, T. Akagi, S. Dohta, and F. Zhao, “Development of low-cost pressure control type quasi-servo valve using embedded controller,” in *Proc. International Symposium on Robotics and Intelligent Sensors*, 2012, pp. 493-500

[5] L. Ljung, *System Identification -Theory for the User*, Second ed., Prentice Hall, 8-12 and 79-139, 1999.

Kayoko Uno, undergraduate student, studies in Okayama University of Science since 2013. Her research topics are focused on Development of waist Active orthosis using developed flexible pneumatic-actuator and lower limb orthosis for walking assist.

Shinsaku Fujimoto is currently a professor with the Department of Intelligent Mechanical Engineering at Okayama University of Science, Japan. He received his BS in Engineering in 1990, his Master of Engineering in 1992 and his Doctor of Engineering in 1995 from Okayama University of Science, Japan. His research interests include 3D passive dynamic walking, control for power-assisted wheelchair and dynamic measurement. He is a member of The Japan Society of Mechanical Engineers, The Society of Instrument and Control Engineers and The Robotics Society of Japan.

Tetsuya Akagi is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Okayama University of Science in 1998.

He started at Tsuyama National College of Technology, Japan as a research associate on 1998. Then, he joined Okayama University of Science as a lecturer from 2005. His research interests include mechatronics and robotics; especially wearable control systems using microcomputers and wearable control devices such as flexible pneumatic actuator, soft sensor and wearable control valve.

Wataru Kobayashi is currently an assistant professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Shibaura Institute of Technology in 2015. His research interests are robust control theory and aqua drive system; especially rehabilitation and life support systems.

He is a member of The Japan Society of Mechanical Engineers, The Society of Instrument and Control Engineers, The Japan Fluid Power System Society, and The Society of Life Support Engineering.