Improvement of Wearable Power Assist Wear for Low Back Support

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Abstract—This study focuses on developing a safe, lightweight, power assist device that can be worn by people who like caregivers during lifting or static holding tasks to prevent low back pain (LBP). Therefore in consideration of their flexibility, lightweight, and large force to weight ratio we have developed a Wearable Power Assist Wear for caregivers, two types of pneumatic actuators are employed in assisting low back movement for their safety and comfort. The device can be worn directly on the body like normal clothing. Because there is no rigid exoskeleton frame structure, it is lightweight and user-friendly. In this paper, we proposed the new type of the wearable power assist wear and improved the controller of control system.

Keywords- LBP, Quasi-servo valve, Control system, PID control, Arduino NANO

I. INTRODUCTION

Recent years, the number of people in Japan age 65 and over was about 31 million, account for about 25% of the population[1]. With the rapid arrival of an aging society, the demand for professional caregivers has increased drastically. It was said that 70% of caregivers experience back pain reference[2]. So the development of wearable power assist devices and non-wearable lifting assist devices are greatly needed in nursing care fields.

Wearable robots are a mechatronic systems that are designed around the shape and function of the human body. Early designs were mainly exoskeleton types[3][4][5]. These robots have multiple degree of freedom(DOF), but are not suitable for use in small spaces and in daily life.

To meet the aging society’s needs for power assist robotic technology, and devices that wear like normal clothing, this study proposes a new wearable power assist device for low back support using pneumatic actuators. First, the biomechanical model of the human spine was analyzed to better understand the reason for low back pain(LBP) [6]. Since many health caregivers are troubled by low back pain problems, the requirement for low back support is needed. It is critical to understand the cause of LBP when designing power assist wear for low back support. LBP is common in various occupations, its presence being related to activities requiring repetitive lifting, repeated activities in bending forward positions, and lifting high energetic loads. Related results also suggest that bending activities involving higher degrees of trunk flexion are associated with disabling types of LBP in certain working populations. Such work characteristics are common among nursing caregivers. The prevalence of LBP in nursing is high compared to other occupations and in relation to other types of work. Risk factors include physical work such as manual lifting and transferring of patients, working conditions such as working time and rest during the night shift, and the working environment. Among these factors, exposures to frequent manual lifting and transferring of patients are widely recognized factors. Based on this analysis, two types of pneumatic actuators were selected to support the human’s back from two aspects: increased support force and related lever arm length. And in this study, for cut the weight of the device, we used the quasi-servo valve to control the air. In order to provide efficient assisted force, control strategies were determined to minimize the interference of human actions and provide assistance effectiveness for the proposed device. The proposed design has been proven through experiments.

II. WEARABLE POWER ASSIST WEAR

A. Elongation-type pneumatic rubber artificial muscle

Developing wearable power assist devices that wear like normal clothing requires the development of a new type of pneumatic rubber artificial muscle[7] to meet the requirements of safety and user-friendliness. In this part, an elongation-type of pneumatic rubber artificial muscle referred as actuator A, is employed for the special requirement in assisting low back movement.

![Figure 1. Pneumatic rubber artificial muscle](image)

Fig. 1 shows the structure of the elongation-type pneumatic rubber artificial muscle. It is composed of a rubber tube covered with a bellows sleeve and closed with ties at both ends. The outer diameter of the rubber tube is 12 (mm); the
inner diameter is 10 (mm). The bellows sleeve is woven of twisted fiber cord, which has a maximum expansion diameter of 14 (mm) and a minimum contraction diameter of 4 (mm). When first pressurized, the elongation-type pneumatic rubber artificial muscle expands slightly in the radial direction, putting the internal rubber tube into close contact with the external sleeve. As the pressure continues to rise, due to the fact that radial expansion is limited by the external sleeve, the artificial muscle expands in the axial direction, and it becomes longer. The higher the pressure, the longer it becomes.

Figure 2. Relation between supplied pressure and Displacement

Fig. 2 shows the relation between supplied pressure and $L_d$, related displacement of elongation-type pneumatic rubber artificial muscle with no external load connected. The maximum length is attained when it is pressurized; and the minimum length is attained when it is not. For this type of muscle (original length $L_o=320$ (mm)), the total length can reach 490 (mm) ($L_d=170$ (mm)) when pressurized to 500 (kPa).

The elongation-type pneumatic rubber artificial muscle can be seen as a spring with a variable stiffness coefficient. The output contractile force can be expressed as (1).

$$F = k(P, L_d)L_d$$  \hspace{1cm} (1)

Where $F$ is the output contractile force, $k$ is the stiffness coefficient of the spring model, $P$ is the supplied pressure, and $L_d$ is the displacement of the elongation-type pneumatic rubber artificial muscle. When it is pressurized, due to the interaction between the expanding force of the internal pressure and the elasticity of the rubber tube, the stiffness coefficient becomes larger as the pressure increases. The longer the artificial muscle, the more elastic potential energy, and the larger the output contractile force.

B. Layer-type pneumatic actuator

Figure 3. Overview of TPU balloon

The layer-type pneumatic actuator called actuator B, is composed of two TPU balloons. The TPU material is a composite material that combines the properties of rubber and plastic. It has excellent weight bearing capacity and impact resistance, and it is widely used in producing massage chairs and airbags. The TPU balloon used in this device is 150 (mm) long, 100 (mm) wide, and 2 (mm) thick, as shown in Fig. 3. When the balloon is supplied with compressed air, it will become taller, reaching 50 (mm). A TPU balloon can take a maximum air pressure of 250 (kPa). The expansion force reaches 450 (N) at a pressure of 60 (kPa). TPU balloons are put inside pockets made with nylon bands. In this device, the actuator is installed in the inner layer of the garment. In order to increase the moment arm A of assistance force, the expansion displacement in height can be adjusted by changing the air pressure applied.

C. Previous control system

Fig. 4 shows the whole structure of the control system. The system consists of A/D board (PCI-3133, Interface Corporation), D/A board (PCI-3341A, Interface Corporation), pressure sensor (AP-43, KEYENCE Corporation), pneumatic servo valve (EVD-1500-008AN, CKD Corporation), and IMU sensors.

![Figure 4. Structure of previous control system](image)

III. TESTED ASSIST WEAR DEVICE FOR WAIST

A. Assist wear device

This research focuses on developing a safe, lightweight, power assist device that can be worn by people during lifting or static holding tasks to prevent LBP. In consideration of their flexibility, light weight, and large force to weight ratio, two types of pneumatic actuators were employed in assisting low back movement for their safety and comfort. The biomechanical model of the human spine was analyzed, and to understand the main causes of LBP: when the human is bending forward and lifting a load. The erector spinae muscles have a small lever arm, causing the spine to bear a large amount of force, several times the body weight. By taking into account the biomechanic structure of the human spine, this device can provide support in two ways. Actuator A acts as an external muscle power generators to reduce the force requirement for the erector spinae muscles. Actuator B acts as a moment arm for the contractile force generated by actuator A, and increase the effective torque. The device shown in Fig. 5 can be worn directly on the body like normal clothing. Because there is no rigid exoskeleton frame structure, it is lightweight and user friendly.
B. Waterproof actuators

This study proposed actuators for use in environments of high humidity. The basic concept for the waterproofing of the actuators is summarized as follows.

a) The actuators don't use substances of metal. Because it prevents corrosion.

b) Between the actuator and the pulp is glue with acrylic resin. The connector portion of the actuators processed acrylic-silicon glue is resistant to water.

The waterproofing of the actuators is resistant to water.

IV. QUASI-SERVO VALVE

Fig. 7 shows the schematic diagram of the tested servo valve[8]. The valve consists of two on/off type control valves (GO10HE-1, Koganei Co.Ltd.) whose both output ports are connected each other. The valve connected with the actuator is a two-port valve. The other is a three-port valve that can change the direction of fluid flow such as a supply or exhaust. The two-port valve is driven by pulse width modulation (PWM) method in order to adjust the valve opening per time. It becomes the quasi fluid resistance. Then, the latter valve is called as "PWM valve", the former is called as "switching valve". The size of the valve is 33×19.6×10 (mm), and the mass is 15.3 (g).

Each valve is controlled by a micro-computer through the transistors. The maximum supply pressure of the on/off valve is 500 (kPa), and the maximum output flow rate is 38 (L/min).

In the case of supplying to the actuator, the switching valve is turned on while the PWM valve is being turned on according to the duty ratio. In the case of exhausting, the switching valve is turned off while the PWM valve is being driven. In the case of closing, the PWM valve is turned off.

V. CONTROL SYSTEM OF WEARABLE POWER ASSIST WEAR

A. Improved control system

The previous control system used PC and big solenoid valve. Because it is not easy to move freely. In this study we use the microcomputer (Arduino NANO) to control the assister wear. Fig. 9 and Fig. 10 show the exterior of improved control system and structure of improved control system. The size of the improved control system is 90×100×90 (mm), and the mass is 250 (g).

The improved control system used an acceleration sensor(KXM52-1050, Kionix Corporation) and an EMG sensor(101020058, Seeed Corporation) and a pressure sensor(SEU11-4UA-S3, PISCO Corporation), five quasi-servo valves. Each one of the sensors are used to detect inclination $\theta$ of the human body, the force that human output, air pressure value.
B. PID control

In this study, we performed to construct a pneumatic flow controller supplied to the actuators using PID control. The reason for selecting the PID control, it is possible to compensate the steady-state error. Control output $U$ of PID control is expressed by the following (2).

$$U = K_p e + K_i \int e dt + K_d \frac{de}{dt}$$  (2)

$K_p$ is proportional gain, $K_i$ is the integral gain, $K_d$ is the derivative gain. These control parameters are adjusted based on Ziegler-Nichols' Ultimate Gain method.

C. Device control strategy

The block diagram of control system is shown in Fig. 11. Through the acceleration sensor mounted on the human body, the human movement can be determined. At the time that the power assistance is needed during the human bends forward and lifts the load, the reference pressure $P_s$ is determined through the posture to pressure algorithm, the controller will output the desired driving voltage on the quasi-servo valve, regulate compressed air, and then the required assistance force can be obtained.

Fig. 12 shows flow chart of the control system. First of all, each one of the sensors detect inclination of the human body ($\theta$) and air pressure value ($P_{\text{value}}$). And EMG sensor is calculated the difference between the current value and the previous value ($de$). Next it decided to target air pressure ($Pa$) of the $\theta$, it is to adjust the air pressure by using PID control. Finally if $de$ is than 30, Wearable Power Assist Wear starts to assist. If not, once again, decide each one of pressure values.

D. Control experiment

Fig. 13 shows an experimental setup for pneumatic control of an actuator[9] [10]. In this experiment, the compressed air that is input to the actuator is provided by an air compressor [CHST-25, ANEST IWATA Corporation]. The input air pressure is arranged using the improved control system. The air pressure that is input to the actuator is measured using a pressure sensor. The measured air pressure is input to a PC through an A/D board with the sampling time set to 20 (ms).
Experiment result is shown in Fig.14 (a), the desired air pressure that is input to the actuator are set to 100, 200, 300, 400, and 500 (kPa). Each lines shows the results of the PID control. From this experimental result, it can be seen that the air pressure reaches the target value. At the maximum pressure (500 (kPa)), the air pressure is stable at about 2.5 (seconds).

Experiment result (b) shows response of exhaust air pressure. The desired air pressure that is input to the actuator are set to 400, 300, 200, and 100 (kPa). At the minimum pressure (100 (kPa)), the air pressure is stable at about 1.7 (seconds).

E. Waterproof controller

This study makes control system for use in environment of high humidity. The basic concept for the waterproof of the control system is summarized as follows.

a) Put into the waterproof case in order to use the control system in a high-humidity environment.

b) This is considered for use in such as the bathroom. Therefore, choose a case that not affected by the direct injection of water.

It is possible to [a] by miniaturized controller. For [b], it choose a case that not affected by the direct injection of water (From a distance of 3 (m), 100 (L/min), 100 (kPa)).

VI. CONCLUSION

In this study, we had proposed a power assist wear for low back support, a device using new types of pneumatic actuators. Compared with McKibben-type pneumatic rubber artificial muscle, the contraction rate of elongation-type pneumatic rubber artificial muscle is larger. As it does not use an exoskeleton structure, the device can be wear on the human body just like normal clothing. It can provide assistance force for the low back, reducing the possibility of LBP, and the assistance power of the device can be adjusted by changing the pressure of the compressed air. The effectiveness of the device has been verified through experiments.

This study that is aimed to improve the pressure control performance using the quasi servo valve for Wearable Power Assist Wear. For the control system, we improved control system which enable free movement. The control system include quasi-servo valve for adjust the compressed air is light, and the mass is 250 (g). Because it is possible to equip the human body. Also we performed to construct a pneumatic flow controller supplied to the actuators by PID control method. The PID control parameters are adjusted based on the limit sensitivity method. The effectiveness of the improved control system has been verified through experiments.

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