Design of Upper Limb Assistive Device Using a Pneumatic Cylinder

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Abstract: This paper describes the design of a device to support a patient's upper limb motion. For safety, light weight, and flexibility, it uses a pneumatic cylinder for which the optimum arrangement is presented. This independence-supporting device has two modes corresponding to livelihood support and rehabilitation. Based on human motion, a compliance control system and a position control system are designed for those modes. As described herein, we evaluate the independence-support mode effectiveness through experimentation.

Keywords: Medical systems, Pneumatic systems, Actuators, Human-machine interface, Quality of daily life.

1. INTRODUCTION

Restriction of motion of a joint's range is called contracture. A joint's range of motion exercise is effective for preventing contracture. However, if the exercise is performed by a physiotherapist, then a joint's range of motion will improve. If a period without exercise is long, then contracture will progress again. Therefore, a rehabilitation instrument must be available for a person to perform motion exercises after exercise sessions with a physiotherapist.

Some continuous passive motion (CPM) devices are used as rehabilitation instruments for the maintenance or restoration of a joint's range of motion (ROM). During CPM therapy, the joint area is secured to the CPM device, which then moves the affected joint through a prescribed arc of motion for an extended period of time. In fact, CPM devices are available for numerous joints such as the knee, ankle, jaw, hip, elbow, shoulder, and finger.

Nevertheless, most instruments use motors to provide high power. For that reason, they are heavy and large. Installation and movement of instruments at facilities are difficult. It is also difficult to use such devices freely at home. Additionally, it is not possible to use such a device at rest, which is the most effective time for rehabilitation training.

We therefore specifically examine a rehabilitation instrument that is small, light, and which can be put on and taken off easily. According to an annual report on the aging society in Japan, a super-aging society is expected to prevail in the near future [1]. Simultaneous increase of patients and decreasing of medical workers are feared. In addition to aging, the number of handicapped people is expected to increase because of illness and injury, and for other reasons. Because of many people's physical handicaps, activities of daily life (ADL) will become difficult. Moreover, the burdens on those giving treatment are expected to increase.

Handicapped people require training for rehabilitation to recover their ability to use upper limbs. Additionally, impairment of abilities is known to be recoverable through rehabilitative training. In a clinical scene of rehabilitation, a patient and an occupational therapist (O.T.) train together. The O.T. demonstrates and facilitates motions that give a constant load to patient's limbs and which move their limbs, slowly repeating flexion and extension. The machine can often substitute for the O.T.'s motion during rehabilitation. Some rehabilitation devices have been developed [2-7]. In a clinical scene, such a device should be a simple, easy-to-use mechanism with a simple control system.

Therefore, we developed an upper limb rehabilitation support device with a wide operating range. It is compact, with a link mechanism [7]. Welfare apparatus, such as the rehabilitation support device that we developed, must be safe, flexible, and lightweight because this device must have contact with humans during operation. A DC motor and a hydraulic actuator are used for industrial robots. However, if we were to use these actuators for welfare-supporting apparatus, then the system would become complex and bulky, which is undesirable. The necessary functions increase when a target patient extends the

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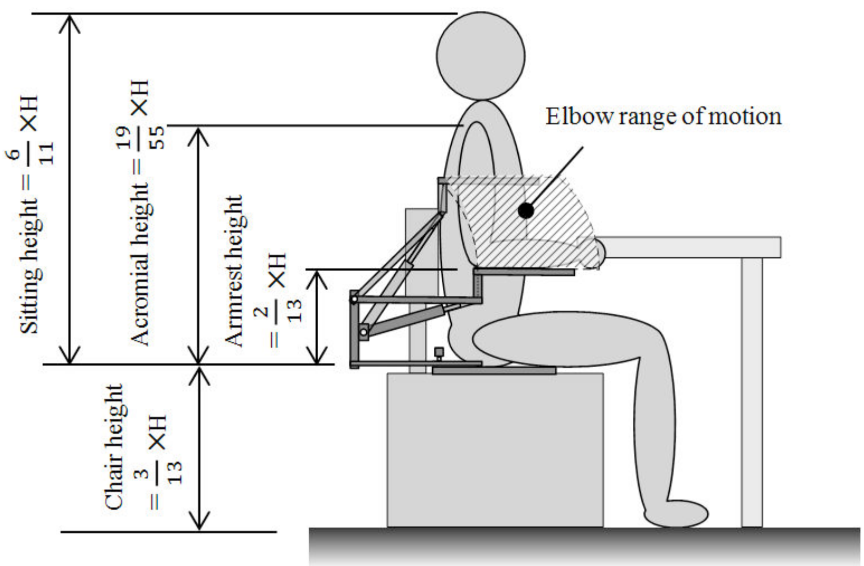


Figure 1: Japanese body dimensions and the wearing state of the upper limb support device.

device. Thereby, the rehabilitation device becomes ever larger, and its operation becomes increasingly complicated. We used a pneumatic cylinder to drive the device because the shock can be absorbed using air compression: it has a simple structure with a high power–weight ratio.

For this study, the target patients are few and the rehabilitation instrument can be designed to have only two modes with two control systems, which many patients find necessary. Furthermore, a position control system is applied for the livelihood support device. A compliance control system is applied on the device instead of an O.T.'s motion of rehabilitation training. Some experiments were conducted to evaluate the device and its control system.

2. DESIGN OF SUPPORT DEVICE

2.1. Ergonomic Design

The upper limb support device has an elbow-supporting two-link mechanism mounted on a simple seat mat. Its dimensions and movable region were determined in reference to designs of ergonomically designed chairs. Figure **1** shows Japanese body dimensions [8] and the wearing state of the upper limb support device, where the human body height is represented by H. Figure **2** shows the measurements of upper limb's motion in daily life.

2.2. Consideration of a Forearm Support

Chairs used ordinarily are of the elbow-resting type, which supports upper limb motion. Support of the elbow alone might be sufficient without supporting the forearm. If so, the forearm support mechanism is not needed, which enables simplification of the device. In this section, the necessity of forearm support mechanism was investigated through measurements of muscle potential. Based on the results obtained, we studied an actuator used in the forearm support mechanism through measurements of loads exerted to the elbow part and the wrist part of the device.

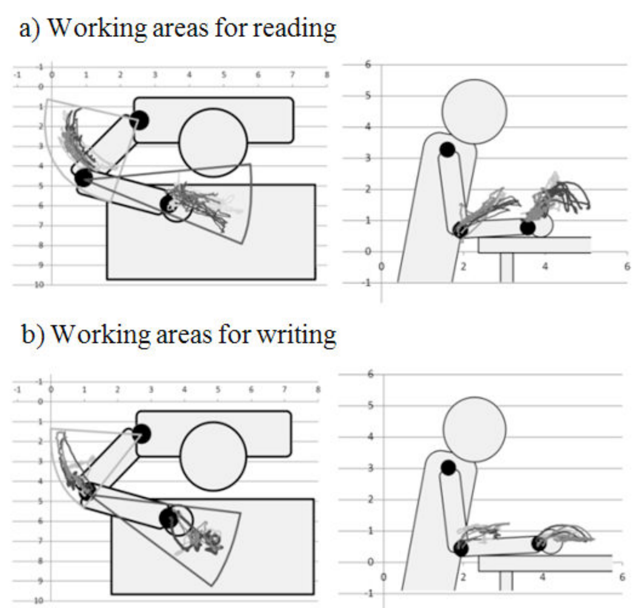


Figure 2: measurements of upper limb's motion in daily life.

2.2.1. EMG of a Forearm

Electrodes were provided at five locations that are involved primarily in upper limb motion: the greater pectoral muscle, broadest muscle of back, deltoid muscle front part, deltoid muscle middle part, and deltoid muscle rear part. The surface muscle potential was measured. The data, which were obtained with sampling frequency of 1000 Hz, were stored in a digital recorder (DR-M3MK2; Teac Corp.). Data processing was then performed using a PC. In these experiments, the absolute values of the raw waveform were passed through a low-pass filter with a time constant of 300 ms for smoothing.

Subjects were requested to wear the device and to perform motions of five types of shoulder joint flexion and extension, shoulder horizontal flexion and extension, reach action, elbow joint flexion and extension, and elbow joint external–internal rotation for cases where the forearm support device is provided and not provided. Subjects repeated the same motion slowly three times for every movement. The necessity of the forearm support device was checked through comparison of the muscle potential between cases in which the forearm support device is provided and not provided.

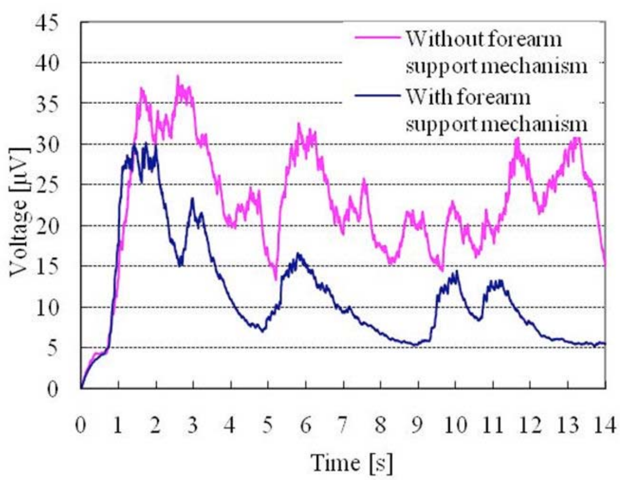


Figure 3: Electromyogram of elbow's flexion and extension (Deltoid muscle front part).

Figures **3** and **4** respectively show muscle potential waveforms of deltoid muscle front part at elbow joint flexion and extension and of deltoid muscle front part at reach action. The case without the forearm support mechanism exhibited greater values for each case. It is considered that without the supporting mechanism, the total load from the elbow to forefront (forearm) is supported. The elbow acts as the fulcrum. Therefore, the load to the muscle becomes greater than that of with the supporting mechanism case. Application of an unnecessary load to the muscle is not desirable for handicapped people who use the device. Therefore, it might be said that the forearm support mechanism is indispensable to support the upper limb safely.

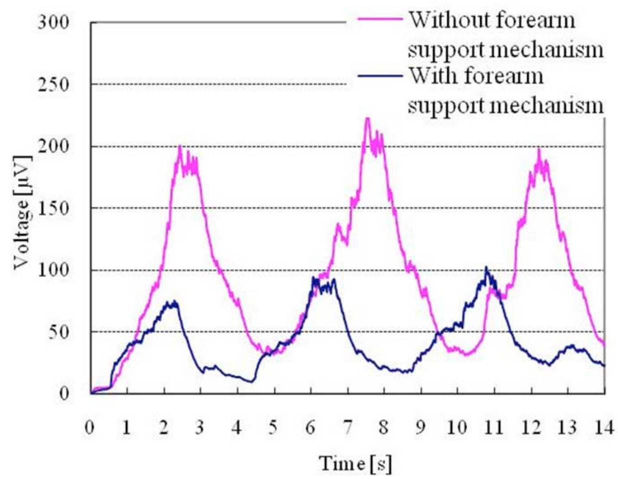


Figure 4: Electromyogram of reach motion (Deltoid muscle front part).

2.2.2. Device of a Forearm Support

Figure **5** shows an experimental device used for the evaluation of the forearm support device. Compressed air from a compressor is set to 0.4 MPa by a regulator. As presented in Figure **5**, the subject places an upper limb on the device and relaxes quietly so that no necessary load is applied to the device. A load cell is provided at two locations on the load cell at the elbow part and at the wrist part. For measurements, the support arm length was adjusted using a span adjuster to fit a subject's forearm length.

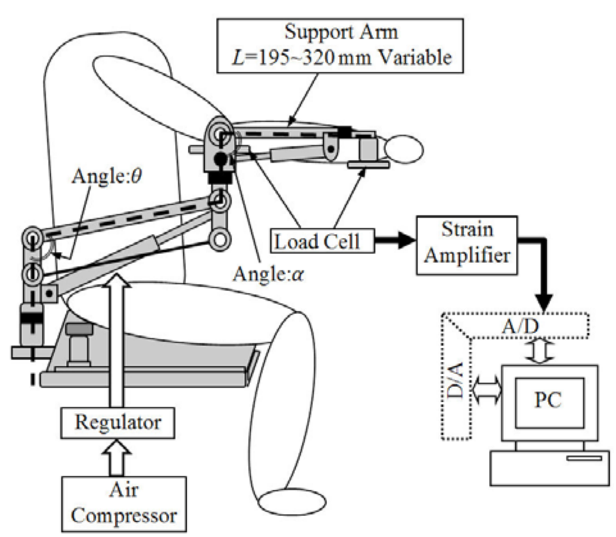


Figure 5: Experimental setup of load measurement.

Table **1** shows the respective ratios of loads at the elbow part to wrist part for all subjects. Table **1** data show that loads at the wrist part are much smaller than

Table 1: Ratio of Wrist Part's Load to Elbow Part's Load

	Body weight [kg (N)]	Length of forearm [mm]	Weight of elbow part [N]	Weight of wrist part [N]	Ratio of wrist part's wight to elbow part's weight [%]
Subject A	64 (627.2)	240	17.2	1.9	11.1
Subject B	52 (509.6)	250	16.4	1.6	9.8
Subject C	62 (607.6)	260	17.1	1.8	10.5
Subject D	58 (568.4)	260	16.9	1.8	10.7
Subject E	53 (519.4)	280	15.5	2.1	13.5

those at elbow part. The forearm part can then be supported by a small force. Therefore, a compact gas spring that requires no power source can be used for the actuator despite its low power.

Next, details of the gas spring must be determined. Figure **6** shows a model diagram of the forearm support mechanism.

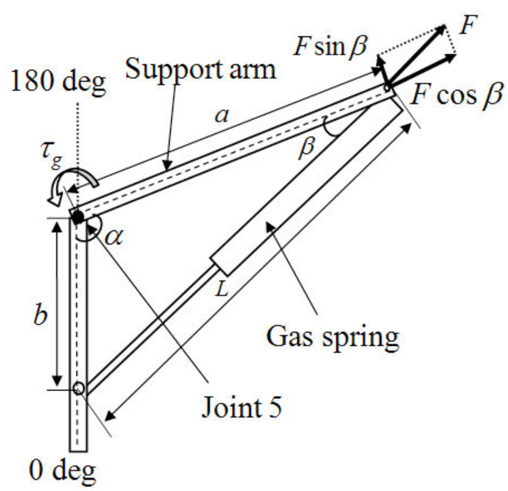


Figure 6: Model of forearm support mechanism.

Torque τ_g by the gas spring is expressed as shown below.

$$\tau_g = F \cdot a \sin\beta \tag{1}$$

Therein, α is the angle of Joint 5; *a* denotes the length of the support arm; *b* denotes the effective length of the pillar of a knee; *F* is catalogue value of the gas spring (maximum 32 N, minimum 27 N). Table **2** shows some specifications of the gas spring used for torque calculations.

Angle β between the support arm and the gas spring is expressed as shown below.

$$\beta = \cos^{-1}\left(\frac{a^2 + L^2 - b^2}{2aL}\right) \tag{2}$$

Table 2: Specification of Gas Spring (Y0061 EF1, TOKICO)

Maximum length [mm]	181.0
Minimum length [mm]	131.0
Stroke [mm]	50.0
Diameter of body [mm]	15.0
Diameter of rod [mm]	6.0
Maximum force [N]	32.3
Minimum force [N]	27.4

Furthermore, if torque by wrist's part is expressed by τ_w using wrist's weight of subject B, then the relation between τ_g and τ_w is expressed by Figure **7**. It can be shown from Figure **7** that τ_g and τ_w are well balanced between 90 deg and 120 deg, suggesting that the support of the forearm part is possible.

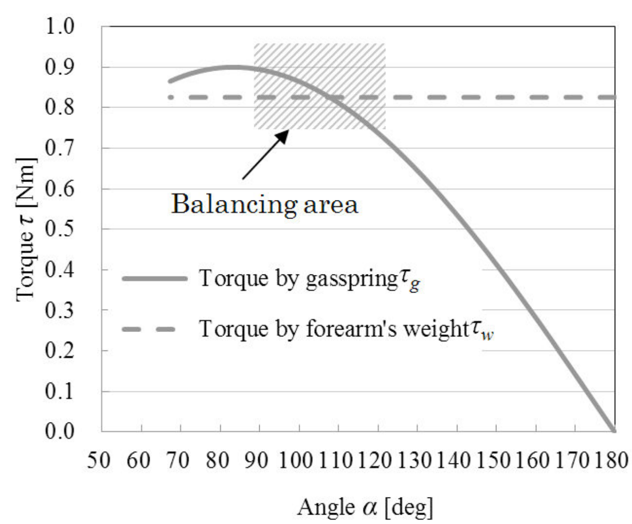


Figure 7: Calculated results for rotation angle α and torque τ.

2.3. Outline of the Support Device

Figure **8** shows the upper limb support device. This device has five degrees of freedom by virtue of its link mechanism. It consists of joint 1, joint 2, joint 3, joint 4 and joint 5. Joint 1 reciprocates on the x-axis by a

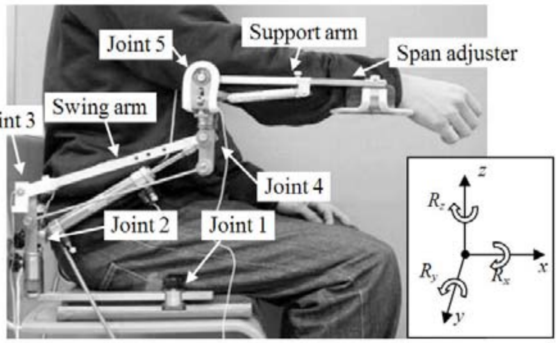
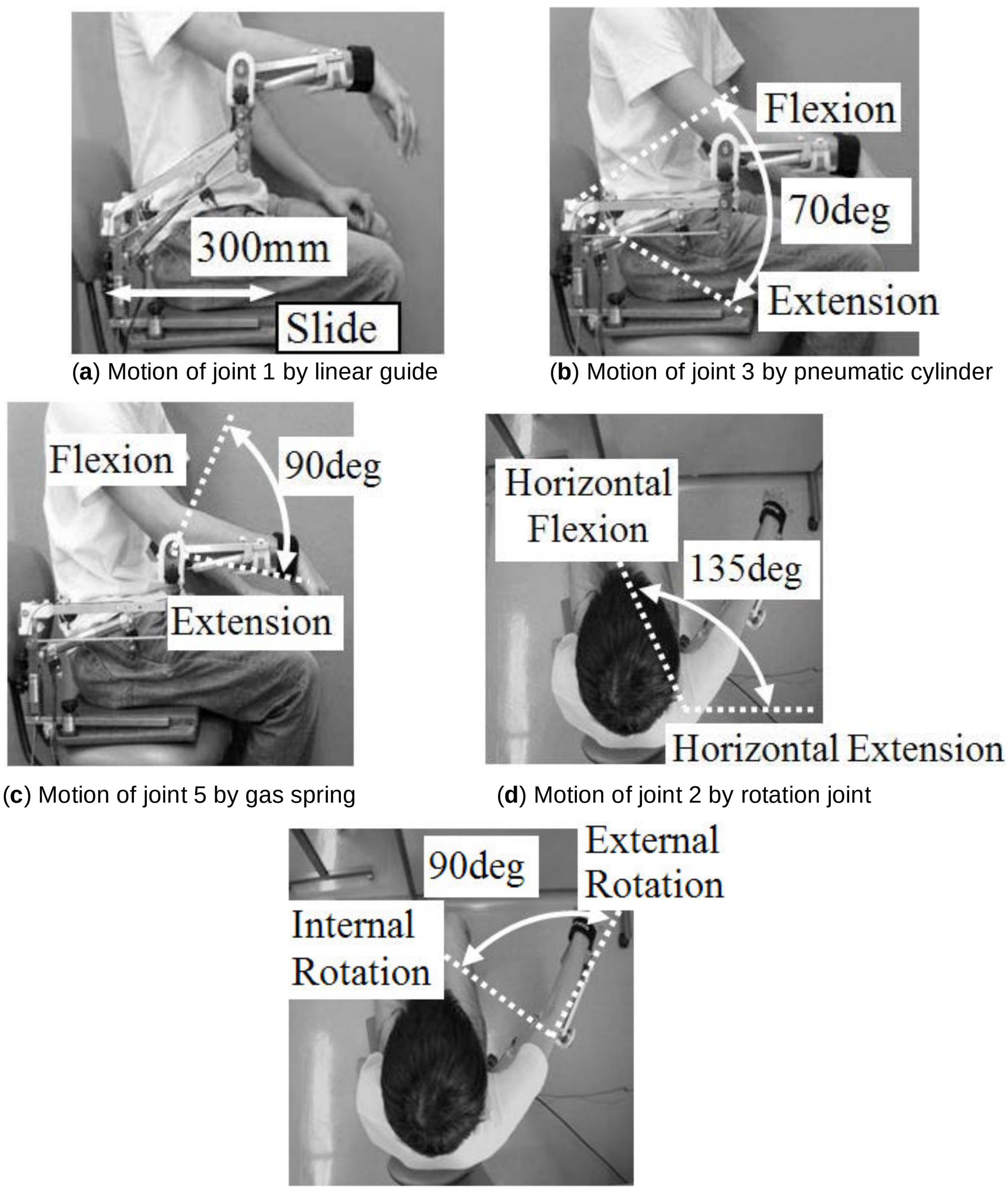


Figure 8: Upper limb assistive device.

linear guide to support the upper limb for the reach action, as depicted in Figure **9a**. Joint 3, with an attached a pneumatic cylinder, rotates around the y-axis to support arm flexion and extension, as depicted in Figure **9b**. Joint 5, with an attached gas spring (Y0061, Tokico; Hitachi Ltd.), rotates around the x-axis, as depicted in Figure **9c**. Joint 2 and joint 4, with attached rotation joints, can rotate around the z-axis, as shown in Figures **9d** and **9e**. Joint 3 is operated actively by a pneumatic cylinder, but the other joints are operated individually by the patient.

A simple link mechanism is used with the device. However, it has a wide operating range. Consequently, by using the device, the patient can operate the upper limb without unpleasantness. Additionally, the device weight is about 4 kg. Therefore, it is possible to do



(**a**) Motion of joint 1 by linear guide

(**b**) Motion of joint 3 by pneumatic cylinder

(**c**) Motion of joint 5 by gas spring

(**d**) Motion of joint 2 by rotation joint

(**e**) Motion of joint 4 by rotation joint

Figure 9: Motion for the livelihood and the rehabilitation.

(**a**) Mode A

(**b**) Mode B

Figure 10: Support function.

training without choosing a particular place because the device is portable.

3. SUPPORT FUNCTION

We assume that patients with paralysis will use the device, as will patients with decreased muscular power attributable to an accident or aging. The support device has two support functions that correspond to livelihood support and rehabilitation contents. By undergoing rehabilitation with a device, it is expected that the treated person's load is decreased, and that a patient can therefore train at home.

3.1. Livelihood Support Function "Mode A"

"Mode A" is a function to recover practical function of an upper limb. The device supports training that operates the upper limb on the desk, as portrayed in Figure **10a**. In this function, position control (on rotation angle of joint 2) is applied to support an upper limb's vertical motion (i.e. shoulder flexion and extension). The patient trains to use a "peg board" etc., while the arm is being supported by the device. Because of this function, a patient who has the physical disabled arm to resist gravity can train easily at a desk.

3.2. Rehabilitation Support Function "Mode B"

The device supports the patient's upper limb flexion and extension motion for rehabilitation, as portrayed in Figure **10b**; because of this function, the patient's muscular power recovery and movable region of expansion are expected. In a clinical scene, the O.T. adjusts training considering the level of the patient's difficulty. In this "Mode B", compliance control was applied to operate the device as with an occupational therapist. Patients can experience ergo-therapy corresponding to their own respective levels of muscular power.

4. CONTROL SYSTEM

Figure **11** shows the device control system. The electropneumatic regulator (ETR200-1; Koganei Corp.) regulates the pneumatic cylinder's (T-DA20×100; Koganei Corp.) inner pressure. A rod in the pneumatic cylinder expands and contracts when the pneumatic

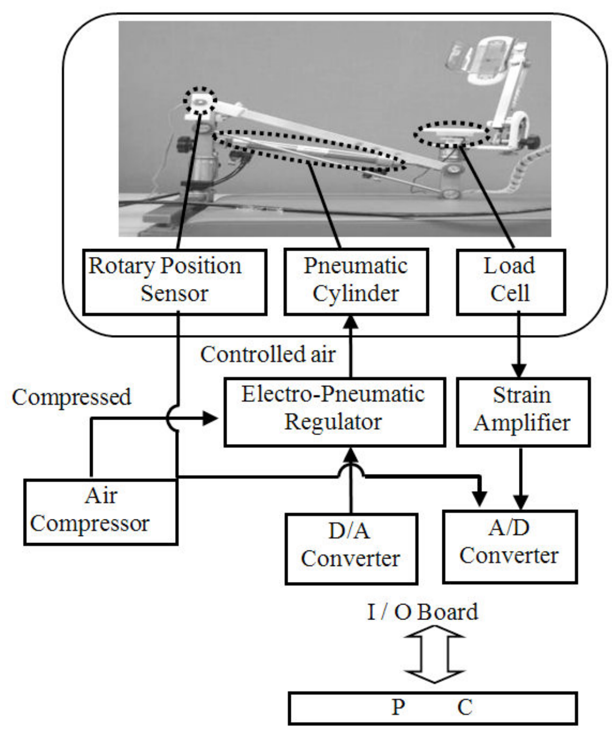


Figure 11: Control system of rehabilitation support device.

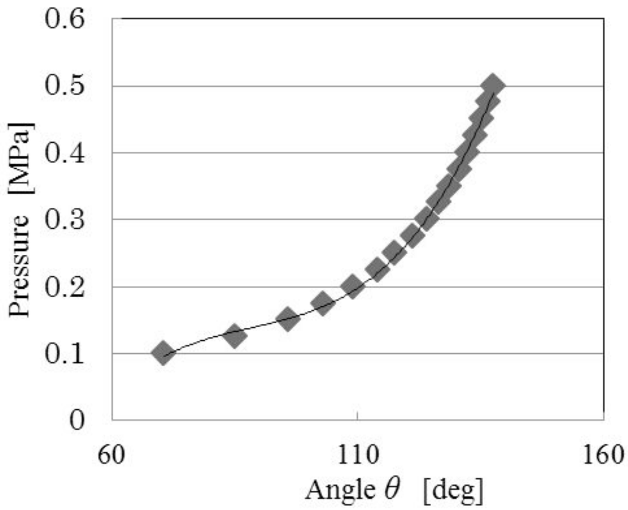


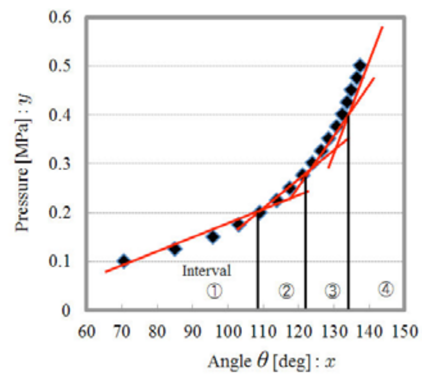
Figure 12: Relationship of angle and input pressure.

cylinder's inner pressure changes. The swing arm rotates around the y-axis. The rotation angle of joint 3 is measured using the rotary position sensor. The load cell (LMA-A-100N; Kyowa Electronic Instruments Co. Ltd.), installed in a stand for the elbow, measures the force that the patient is adding.

4.1. Control system of "Mode A"

Figure **12** presents static characteristics of the control target (rehabilitation support device). It is not possible to approximate a relation between the angle and input pressure unless it is greater than a function defined by a polynomial of degree three, which means that it has nonlinear characteristics. Then, in this study, the control target is linearized by piecewise linearization, by which the control target is divided into four regions to attain broken line approximation, as depicted in Figure **13**. Number of divisions decided four by trial and error method. The control system design was conducted after linearization.

Figure **14** shows a block diagram of the control system applied this time. The control system consists of feedforward (FF) and feedback (FB) type [9]. This control method outputs basic outputs in advance. The remaining deviation alone is addressed in the form of feedback in cases where characteristics of the control target are known to some extent and characteristics are changed because of changes in the external environments. Because a delay attributable to FB becomes smaller at the rate of output, the control system only slightly causes hunting. The control system was constructed using Matlab/Simulink (The MathWorks, Inc.). The PID controller parameters were determined through trial and error: KP = 0.15, KI = 0.42, KD = 0.1. The sampling frequency at control is 10 ms.



$$y=\begin{cases}0.0030851x-0.1409009 & (0<x\le 109.2) & ①\\ 0.0061891x-0.4776108 & (109.2<x\le 121.4) & ②\\ 0.0105963x-1.0136109 & (121.4<x\le 130.9) & ③\\ 0.0183208x-2.0253827 & (130.9<x) & ④\end{cases} \quad \cdots(3)$$

Figure 13: Linearized static character.

4.2. Control System of "Mode B"

A compliance control system for "Mode B" is applied to change the joint 3 stiffness [10, 11]. Figure **15** shows a block diagram of the control system. The compliance control equation is written as shown below.

$$\tau = K(\theta_d - \theta) \tag{4}$$

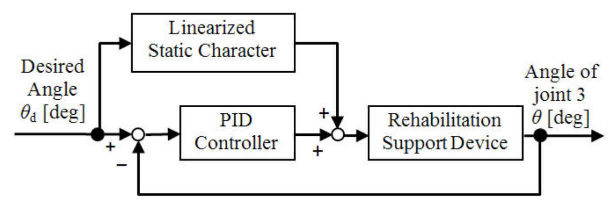


Figure 14: Position control system.

Therein, θ_d stands for the desired angle, θ_r is the difference between the desired angle and angle change according to torque that the patient is adding, θ signifies the measured angle, τ denotes the torque of the joint 3, and K represents the constant of stiffness. In addition, $d\theta$ is defined as the angle error between the desired angle "θd" and the measured angle "θ".

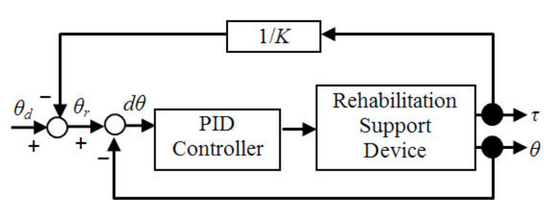


Figure 15: Compliance control system.

5. EXPERIMENTS

In this section, we describe compliance control for Mode A and position control for Mode B. Furthermore, we evaluate the effectiveness of the rehabilitation support mode through experimentation.

5.1. Position Control “Mode A”

This experiment was performed with and without a load (wrist part, 1 kg; elbow part, 1.8 kg), designed to simulate the weight of a human arm. The wrist and elbow part loads were estimated using the ratio of the weight of each part to the weight of a human. Moreover, the target value was given from 110 deg to 90 deg in the ramp input, which was assumed to represent the arm extension (shoulder joint).

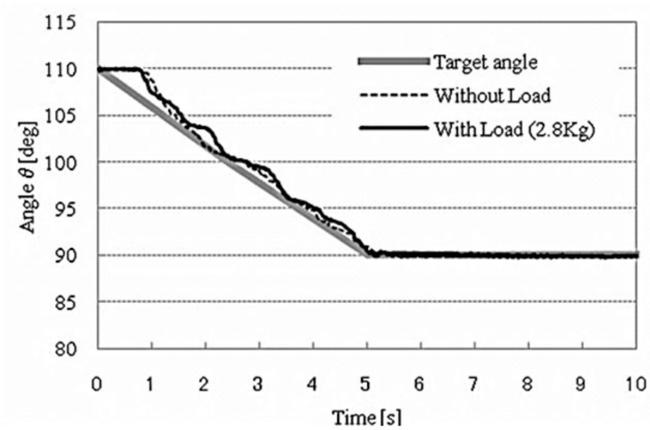


Figure 16: Experimental results of position control.

Figure **16** portrays the experimentally obtained results of position control. The rotation angle smoothly followed the target value without overshooting. It converged to the target angle (90 deg). Therefore, when the device is used for assistance of rehabilitation training on a desk, the patient’s arm can be moved to the position that the patient desires. The device is useful safely, without giving discomfort to the patient.

5.2. Compliance Control “Mode B”

The rehabilitation support device is fixed with a jig so that the rotation angle θ might be 90 deg. We measured the $d\theta$ and generated torque τ.

Figure **17** presents the experimentally obtained results for compliance control. The solid line shows the theoretical value of the generated torque from eq. (4). The gray solid line shows torque according to the weight of the arm of a typical adult male (65.7 kg body weight; arm weight 3.2 kg). Comparison of experimentally obtained results and theoretical values presents a strong correlation. Figure **16** shows the generated torque as 18 Nm; the torque by the arm weight is 8.9 Nm, as depicted by the gray solid line. Sufficient margins exist from the torque by the weight of the arm to the limit of the generation torque. Therefore, the patient can add force from the state to put the arm on the device.

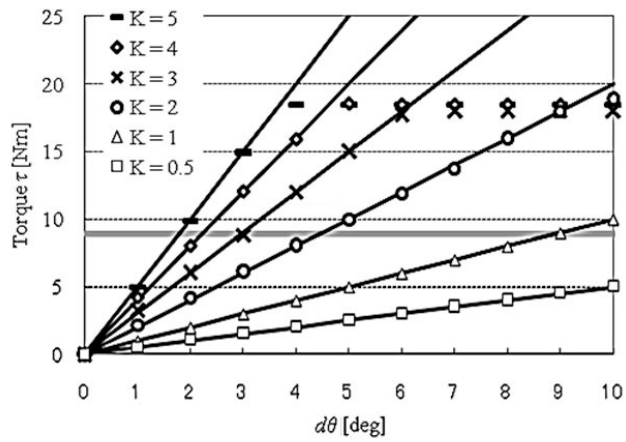


Figure 17: Experimental results of compliance control.

We confirmed that the joint 3 stiffness rose by increasing the constant of the stiffness through this experiment. When actually using the device for rehabilitation, we assume that the constant of stiffness is set low for a patient with weak muscles, and that the constant of stiffness is set high for patients with strong muscles, presumably those in advanced stages of recovery.

6. EVALUATION OF EMG

Evaluation of the upper limb rehabilitation device measured the EMG in shoulder’s horizontal and horizontal extension. The measurement locations are a greater pectoral muscle, a broadest muscle of the back, and a deltoid muscle front part in each of Mode A and Mode B. Furthermore, Figures **18** and **19** present measurement results of EMG, showing that it was effective for dorsal flexion.

7. CONCLUSIONS AND FUTURE CONSIDERATIONS

In this study, we developed an upper limb independence-support device using a pneumatic cylinder based on ergonomic design. A summary of the obtained results is presented as follows.

- The device has two support modes corresponding to livelihood support and

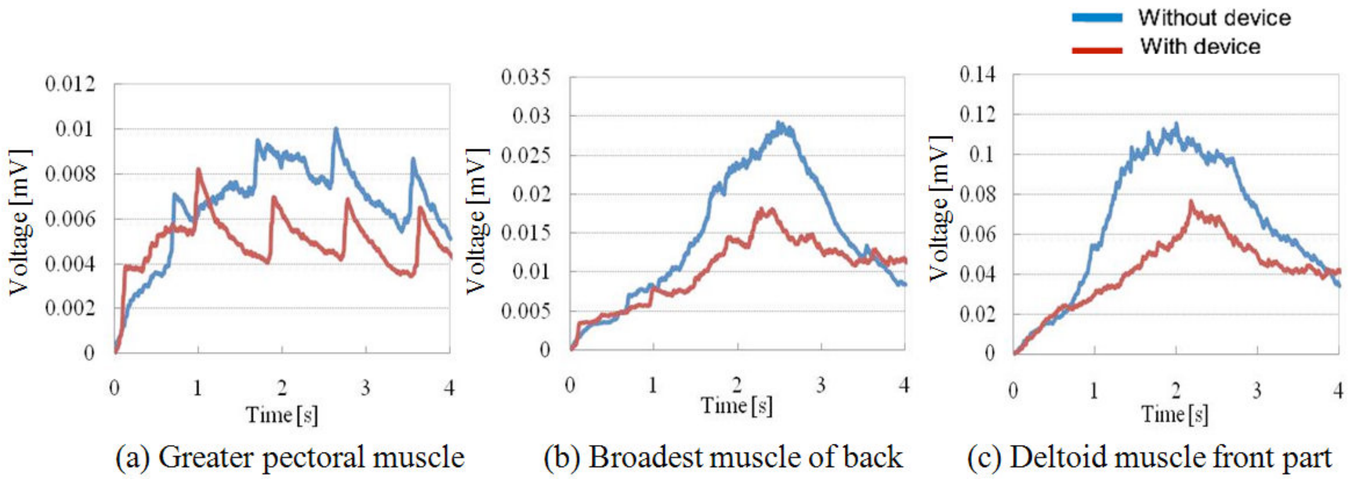


Figure 18: EMG in "Mode A".

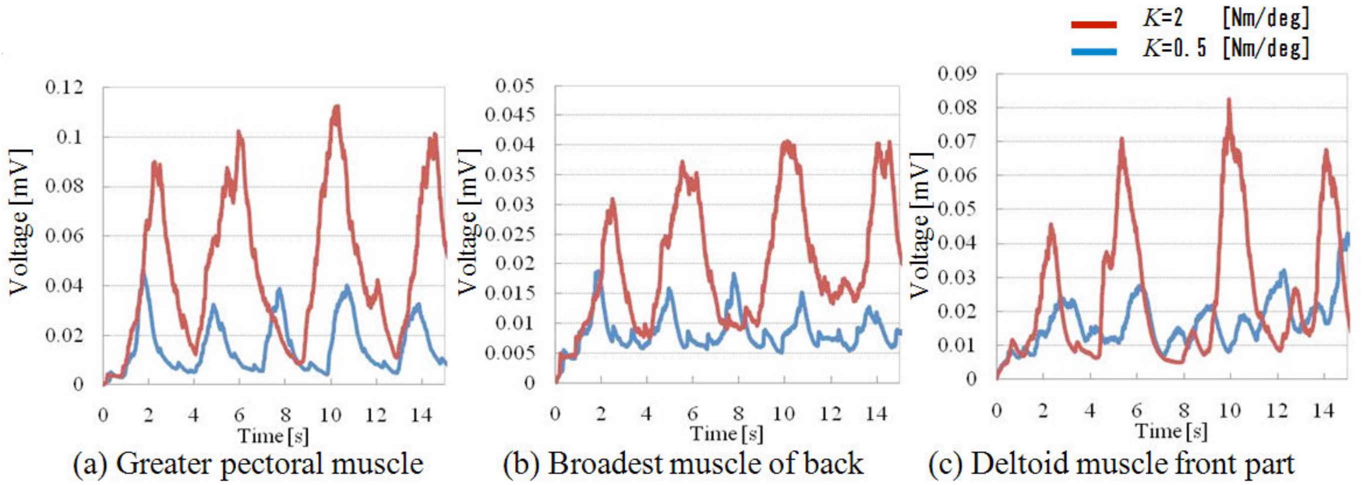


Figure 19: EMG in "Mode B".

rehabilitation contents. A position control system was applied in Mode A to support the recovery of a patient's practical the upper limb. In Mode B, a compliance control system was applied to support a patient's muscular power. In Mode B, to support recovery of a patient's practical recovery and movable region expansion, a compliance control system was applied.

- The position control performance for Mode A was verified experimentally. Results confirm that the rotation angle of joint 3 followed the target angle smoothly.

These results confirmed that the device that we developed can support a patient's training activities.

Future development goals are weight reduction of the control boxand adding a function of meal support for a more improved quality of life.

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REFERENCES

[1] Government of Japan Cabinet office, Annual report on the Aging 2006.

[2] Kiguchi K, Tanaka T, Watanabe K, Fukuda T. Design and Control of an Exoskeleton System for Human Upper-Limb Motion Assist, IEEE/ASME International Conference on Advanced Intelligent Mechatronics 2003; pp. 926-931.

[3] Yamamoto K, Hyodo K, Ishii M, Matsuno T. Development of Power Assisting Suit for Assisting Nurse Labor. JSME Int J Ser B 2002; 45(3): 703-11. http://dx.doi.org/10.1299/jsmec.45.703

[4] Saga N, Saito N, Chonan S. Development of a Support Arm System Using Artificial Muscle Actuator and Gas spring, 2nd Frontires in Biomedical Devices Conference 2007.

[5] Saga N, Saikawa T, Okano H. Flexor Mechanism of Robot Arm Using Pneumatic Muscle Actuators, IEEE International

Conference on Mechatronics & Automation 2005; pp. 1261-1266.

[6] Noritsugu T, Ando F, Yamanaka T. Rehabilitation Robot Using Rubber Artificial Muscle (1st Report Realization of Exercise Motion with Impedance control). J RSJ 1995; 13(1): 141-48.

[7] Bien Z, Kim D-J, Chung M-J, Kwon D-S, Chang PH. Development of a Wheelchair-based Rehabilitation Robotic System (KARESII) with Various Human-Robot Interaction Interfaces for the Disabled, Advanced Intelligent Mechatronics 2003; pp. 902-907.

[8] Japanese body size data book 2004-2006, Research Institute of Human Engineering for Quality Life 2011.

[9] Araki M, Taguchi H. Two-Degree-of-Freedom PID Controllers. Int J Control Automation Syst 2003; 1(4): 401-11.

[10] Richardson R, Brown M, Bhakta B, Levesley M. Impedance control for a pneumatic robot-based around pole-placement, joint space controllers. ELSEVIER Control Engineering Practice 2004; 13: 291-303. http://dx.doi.org/10.1016/j.conengprac.2004.03.011

[11] Tsumugiwa T, Fuchikami Y, Kamiyoshi A, Yokogawa R, Yoshida K. Stability Analysis for Impedance Control of Robot in Human-Robot Cooperative Task System. J Adv Mech Design Syst Manufacturing 2007; 1(2): 133-21.

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