DESIGN OF AN UPPER LIMB INDEPENDENCE-SUPPORTING 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. The independence-supporting device has two modes corresponding to livelihood support and rehabilitation. A compliance control system and a position control system are designed for those modes. We evaluate the independence-support mode's effectiveness through some experimentation.

Keywords: Medical systems, Pneumatic systems, Actuators, Human-machine interface, Quality of work 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, but if the time not to exercise is long, then contracture will progress again. Then, a rehabilitation instrument is necessary for motion exercise to be performed after exercise with the physiotherapist.

Some continuous passive motion (CPM) devices are used as rehabilitation instruments for the maintenance or restoration of 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 easily put on and taken off. According to an annual report on the aging society in Japan, a super-aging society is expected in the near future [1]. A simultaneous increase of patients and a decrease of medical workers is feared. In addition to aging, the number of handicapped people is expected to increase because of sickness and injury, and for other reasons. Because of many people's physical handicaps, activities of daily life (ADL) will become difficult. Moreover, the burdens for those giving treatment will increase.

Handicapped people require training for rehabilitation to recover their ability to use upper limbs. Additionally, impairment of abilities is known to be can recoverable through rehabilitative training. In a clinical scene of rehabilitation, the patient and the 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]–[8]. In a clinical scene, such a device should be a simple mechanism with a simple control system that is easy to use.

Therefore, we developed an upper limb rehabilitation support device with a wide operating range. It is compact and has a link mechanism. 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 use these actuators for welfare apparatus, the system would become complex and bulky, which is undesirable. The necessary functions increase when a target patient extends the device. Thereby the rehabilitation device becomes ever larger, and its operation becomes increasingly complicated. Therefore, we used a pneumatic cylinder to drive the device because the shock can be absorbed using air compressibility: 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 on the livelihood support device and a compliance control system is applied on the device instead of an O.T.'s motion of rehabilitation training. Some experiments were performed to evaluate the device and its control system.

2. DESIGN OF SUPPORT DEVICE

Fig. 1 depicts the upper limb independent support device. This device has five degrees of freedom by virtue of its link mechanism. It consists of joint 1, joint 2, and joint 3. Joint 1 reciprocates on the y-axis by a linear guide to supports the upper limb for the reach action, as depicted in Fig. 2(a). Joint 3, with an attached gas spring (Y0061, Tokico; Hitachi Ltd.), rotates around the x-axis, as depicted in Fig. 2(b). Joint 2, with an attached a pneumatic cylinder, rotates around the x-axis to support arm flexion and extension, as depicted in Fig. 2(c). Joint 1 and joint 3, with attached rotation joints, can rotate around the z-axis, as shown in Figs. 2(d) and 2(e). Joint 2 is operated actively by a pneumatic cylinder, but the other joints are operated individually by the patient.

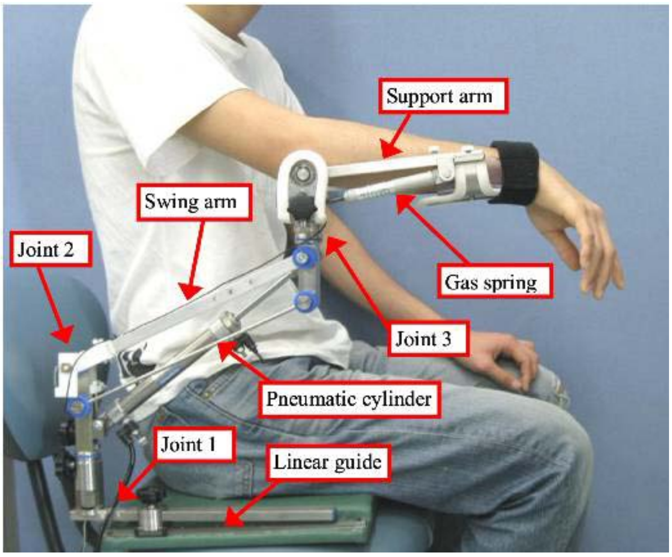
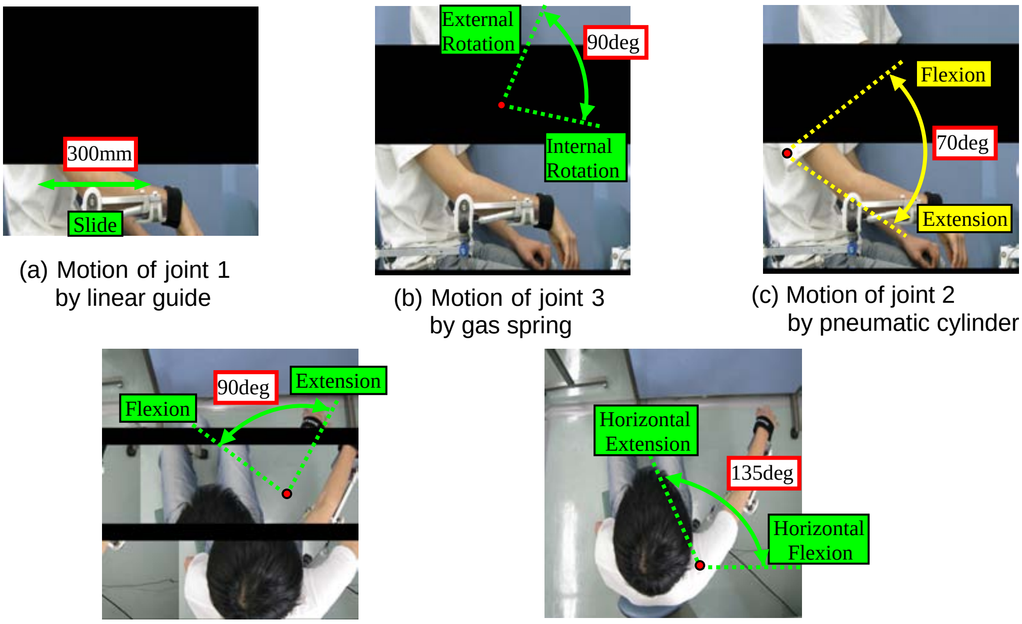


Figure 1. Independent support device



(a) Motion of joint 1 by linear guide

(b) Motion of joint 3 by gas spring

(c) Motion of joint 2 by pneumatic cylinder

(d) Motion of joint 3 by rotation joint

(e) Motion of joint 2 by rotation joint

Figure 2. Motion for the livelihood and the rehabilitation

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

3. INDEPENDENT SUPPORT FUNCTION

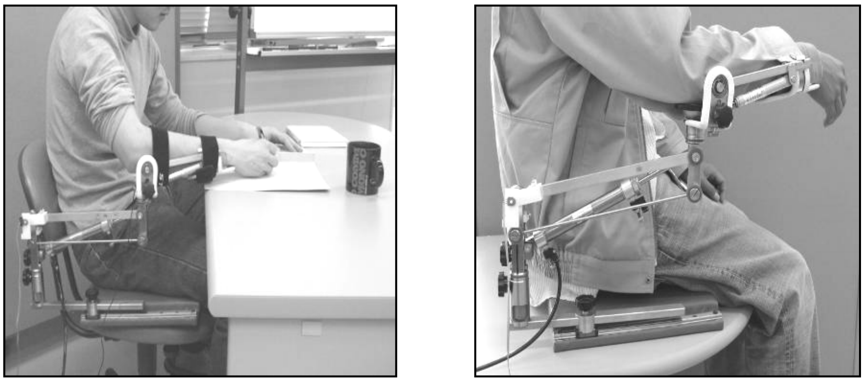
We assume that patients with paralysis who remain independent will use the device, as will patients with decreased muscular power attributable to an accident or aging. The independent support device has two support functions that correspond to livelihood support and rehabilitation contents. By undergoing 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 limbs. The device supports training that operates the upper limb on the desk, as portrayed in Fig. 3(a). In this function, a position control (on rotation angle of joint 2) is applied to support an upper limb's vertical motion (i.e. shoulder flexion and extension). According to this function, a patient who has trouble operating the arm to resist gravity can train easily on 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 Fig. 3(b); 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 trouble. In this "Mode B", compliance control was applied to operate with the device as an occupational therapist. The patient can conduct ergo-therapy corresponding to the level of the patient's muscular power.



(a) Mode A (b) Mode B

Figure 3. Support Function

4. CONTROL SYSTEM

Fig. 4 depicts 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 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.

A compliance control system for "Mode B" is applied to change the joint 3 stiffness. The compliance control equation is written as

$$\tau = K(\theta_d - \theta) \qquad (1)$$

Therein, θ_d stands for the desired angle, 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 difference between the desired angle and the measured angle *($\theta d - \theta$)*.

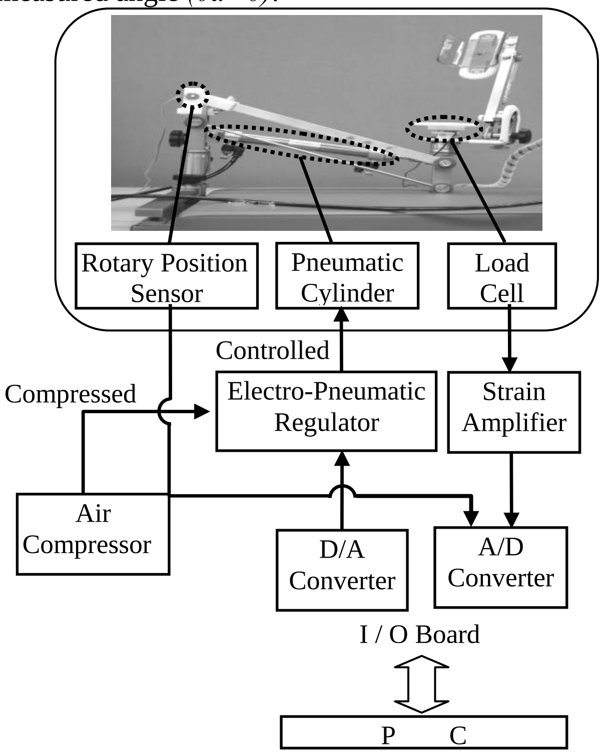


Figure 4. Control system of rehabilitation support device

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 is performed with and without a load (wrist part, 1 kg; elbow part, 1.8 kg), which assumes the weight of a human arm. The loads of the wrist and elbow part 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).

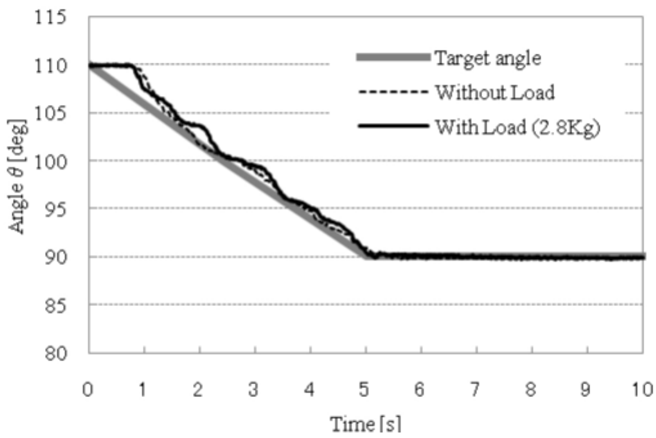


Figure 5. Experimental results of position control

Fig. 5 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.

Fig. 6 presents the experimentally obtained results of compliance control. The solid line represents the theoretical value of the generated torque from eq. (1). 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 6 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.

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.

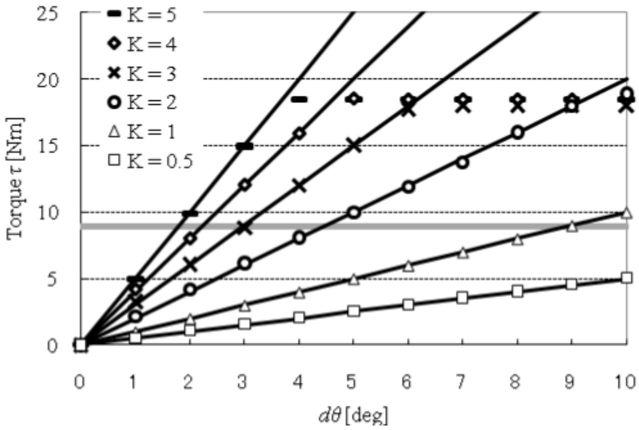
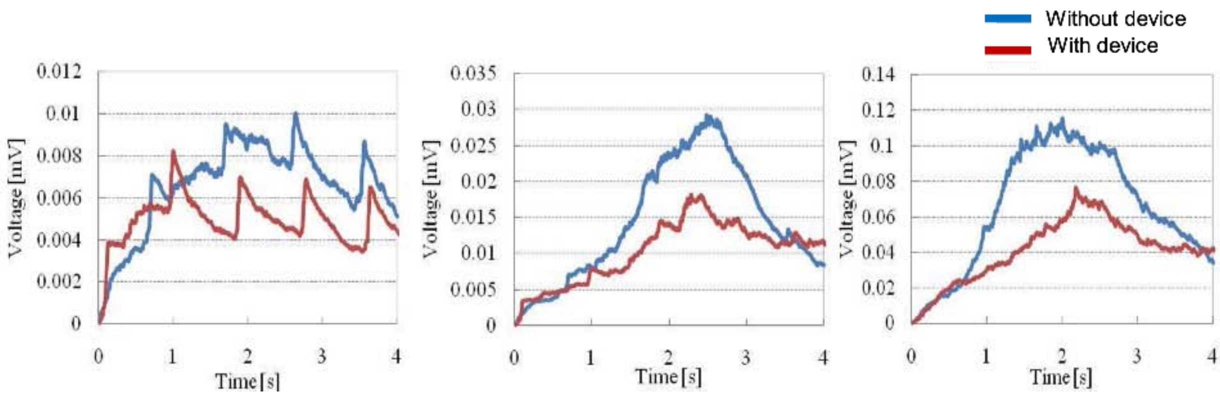


Figure 6. Experimental results of compliance control

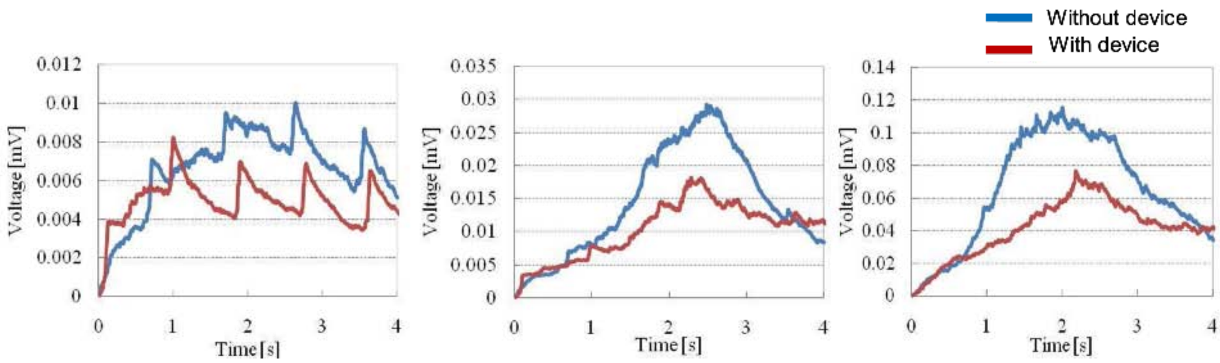
6. EVALUATION OF EMG

Evaluation of the upper limb rehabilitation device measured the EMG of the body. The measurement part is a greater pectoral muscle, a broadest muscle of back, and a deltoid muscle front part in each of Mode A and Mode B. Furthermore, Fig. 7 and Fig. 8 present measurement results of EMG. The EMG that was effective for the dorsal flexion was confirmed.



(a) Greater pectoral muscle (b) Broadest muscle of back (c) Deltoid muscle front part

Figure 7. EMG in "Mode A"



(a) Greater pectoral muscle (b) Broadest muscle of back (c) Deltoid muscle front part

Figure 8. EMG in "Mode B"

7. CONCLUSION

For this study, we developed an upper limb independence support device using a pneumatic cylinder. A summary of the obtained results is presented as follows.

- By arranging the pneumatic cylinder optimally, the device is compact. Nevertheless, it provides widely various movements.
- The device has two support modes corresponding to livelihood support and rehabilitation contents. A position control system was applied in Mode A to support recovery of a patient's practical function of 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. The results confirm that the rotation angle of joint 3 followed the target angle smoothly.
- A compliance control performance for Mode B was verified experimentally, revealing high correlation with measured values and theoretical values of torque of joint 3.

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

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