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Impedance Control of Two D.O.F. CPM Device for Elbow Joint

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1. Introduction

Recently, new technology that supports human will be an emergent issue as population ages and birthrate declines. As human having a lot of joints utilizes many degrees of freedom (d.o.f.) for living and working, reduction or loss of d.o.f. will deteriorate the quality of life. So, it will be important to recover joint functions immediately after injury or operation. Accordingly, many studies have been performed on the development and application of orthopedic treatment or rehabilitation training devices (Furusho et al., 2005; Duong et al., 2005; Mavroidis et al., 2005; Hogan et al., 2006). In the tendency, continuous passive motion (CPM) was proposed as an orthopaedic treatment and a physiotherapy method that promotes recovery from the injuries after surgery of joints (Salter et al., 1960). The CPM is intended to accelerate the regeneration of periarticular tissues, to prevent contracture, and to correct range of motion (ROM) (Salter, 1993), and is more effective than conventional treatment method with casts (Salter, 1993; O'Driscoll et al., 2000).
There are many works on the CPM devices for the lower limbs. Particularly, the CPM devices for the knee joint have been widely used. It was reported that these devices induce quick recovery and improve the joint ROM more effectively (Tanaka, 1998; Sakaki et al., 2000; Akdogan et al., 2006). The knee joint has a simple hinged joint, which is the same structure as the CPM devices for the knee joint, so that the CPM devices can perform effective CPM by easy setting. On the other hand, there are few researches about CPM devices for the upper limbs because of the musculoskeletal complexity. Most conventional CPM devices for the elbow joint have only one d.o.f., and perform the flex-/extension with fixed forearm to avoid the complex setting of the device (Kawaji, 2006).
The human's elbow joint, which consists of a radius, ulna, humerus and biological tissues, has complex structure, and is structurally different from the conventional CPM devices for the elbow. This difference causes some problems such as fluctuation of rotation center of the flex-/extension, excessive reaction force due to the inappropriate pose of the forearm, etc. For the former, Usui et. al. have proposed an algorithm that compensates the fluctuation of the rotation center while the rehabilitation(Usui et al., 2004). But, for the latter there are few researches about the variation of the reaction force due to the forearm position i.e., the pro-/supination.

On the other hand, high safety is required for the CPM device in practical use. It is well known that the stiffness of joints increases after surgery (O'Driscoll, 2000; Kim, 2005). So, the reaction force near the end of the ROM increases excessively due to the large stiffness, and this excessive reaction force may aggravate joint injury. Because of the excessive reaction force due to the inappropriate pose of the forearm, the conventional CPM devices for the elbow joint have lower therapeutic effect than those for the knee joint, so practical use of the CPM device for the elbow joint is fewer than that for the knee joint.

For the problem that the reaction force increases excessively, the method with pneumatic actuators (Noritsugu et al., 1997; Tsgarakis et al., 2003) and impedance control for decrease of load to joint (Moughamir, 2005) were proposed. Although these actuators and control method can realize the suppression of the reaction force, but narrow the range of the flex-/extension because of soft control. Narrowing the range of the flex-/extension decreases the effectiveness to correct the joint ROM. Therefore, to correct the ROM with CPM devices, it is needed to suppress the excessive reaction force without narrowing the range of the flex-/extension. In the upper limbs, the reaction force increases excessively due to the inappropriate pose of forearm. Therefore, control of the pro-/supination is effective to decrease the reaction force.

In this paper we propose a new impedance control scheme of two d.o.f. CPM device for the elbow joint, which performs not only the flex-/extension but also the pro-/supination in order to suppress the excessive reaction force without narrowing the range of the flex-/extension. First, the relation between the pro-/supination and flex-/extension is confirmed, and it is clarified that adequate reference trajectory of the pro-/supination is required to suppress the excessive reaction force. Next, a new impedance control is designed for the reference trajectory measured from normal subject. Finally, some experimental results with simulated patient are shown, from which the effectiveness of the proposed scheme is evaluated.

2. Issues of Conventional CPM Devices

The upper limb, which consists of a radius, ulna, humerus and biological tissues, has the complex viscoelastic property. As a result of the complex viscoelasticity, the forearm is naturally pro-/supinated as the elbow is flexed/extended. Also, the reaction force of the elbow changes due to the pro-/supination. For the upper limb with the complex viscoelasticity, CPM devices with one d.o.f., which perform the flex-/extension with fixed forearm, have been used in clinical practice. As an example, a CPM device in Fig.1(a) which was developed in our laboratory has fixed gripper that constrains the pro-/supination. The constraint of the pro-/supination involves the problem that the reaction force increases excessively near the end of the ROM because the natural pro-/supination is prevented.

In order to cope with this problem, a CPM device with a new gripper was developed in our laboratory as shown in Fig.1(b) (Kawaji, 2006). The gripper of this CPM device can rotate around pro-/supination axis freely, and consequently realize the natural pro-/supination due to the flex-/extension in normal subject. But, in the case of the patient with contracture, the natural pro-/supination is prevented. The prevention of the natural pro-/supination causes the excessive reaction force. Thus, it will be difficult to expand the ROM effectively. For this difficulty, it will be effective to control the pro-/supination motion actively. Simultaneously, it is required for the CPM devices to take safety strategy to the mechanism and the control algorithm, because the elbow might be injured at the end of ROM in the case that forearm is moved forcibly.

(a) Fixed gripper type (KM702) (b) Free rotation gripper type (AH706)
Fig. 1. Developed CPM devices

3. Analysis of Pro-/Supination Angle in CPM

In order to investigate the characteristic of the pro-/supination, the pro-/supination angle and the reaction force due to the flex-/extension are measured using the free rotation gripper. As we aim to clarify the natural pro-/supination due to the flex-/extension, the subject for the measurement is a normal subject.

3.1 Analysis of pro-/supination with free rotation gripper

At first, we measure in the case of the free rotation gripper. A CPM device for the measurement is shown in Fig.2. The device is usable as the CPM device with both the free and fixed pro-/supination by replacement of the mechanical parts. The wrist is constrained by the belt attached to the CPM device in order to suppress the motion of the wrist. A force sensor and encoders are attached in order to measure the norm of the reaction force F [N],

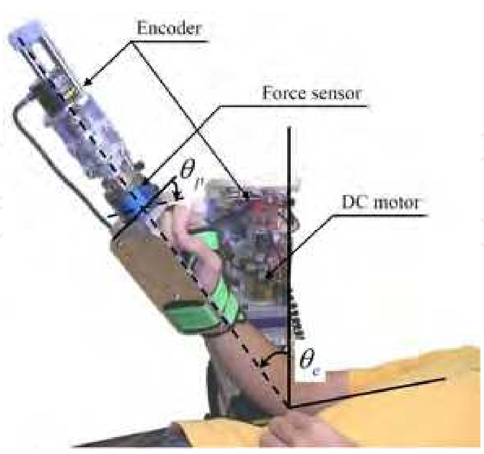

Fig. 2. CPM device for measurement

the flex-/extension angle θ_e [deg] and the pro-/supination angle θ_p [deg].

In the measurement experiment, the initial angle of the upper limb was set as follows: the elbow is flexed to a right angle, the angle between the upper arm and the trunk is 10[deg]

and the forearm is at intermediate position between the pronated position and the supinated position. The norm of force sensor is set as 0[N] at the initial position. The velocity of the CPM device's arm is controlled with constant velocity 0.75[rpm]. The measurement time was 5 minutes.
The relationship between pro-/supination angle θ_p and flex-/extension angle θ_e are shown in Fig.3. And, the relationship between θ_e, θ_p and reaction force F is shown in Fig.4.

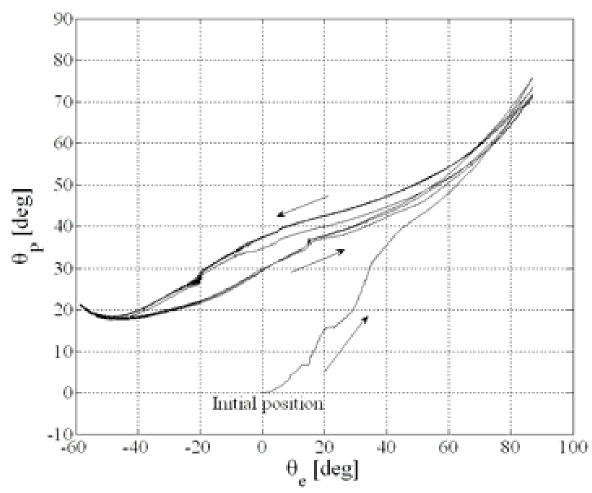

Fig. 3. Trajectory of pronation angle with free rotation gripper

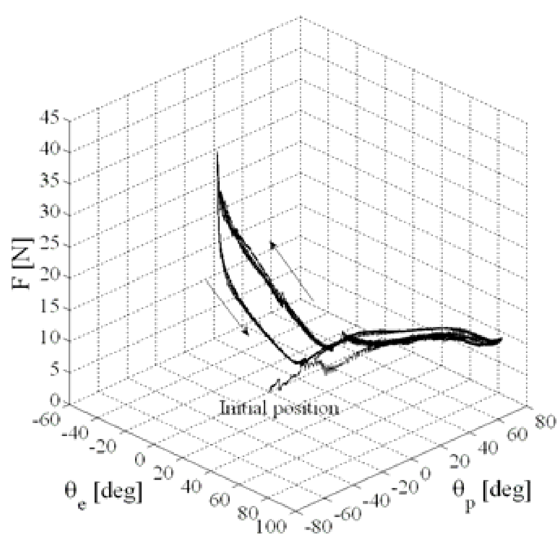

Fig. 4. Reaction force with free rotation gripper

In Fig.3, It is confirmed that the forearm is naturally pronated and supinated as the elbow is extended and flexed. Also, it is observed that the trajectory of the pro-/supination is converged to a certain trajectory. In Fig.4, the reaction force F varies due to the movement of the upper limb, and increases excessively near the end of the ROM where the elbow joint is flexed.

3.2 Analysis of pro-/supination with fixed gripper

Secondly, the reaction force F in the case of the fixed pro-/supination is measured to evaluate the type of the CPM device with fixed gripper as shown in Fig.1(a). In the measurement, θ_p is fixed at every 10[deg] between −80[deg] to +80[deg]. The measuremental result is shown in Fig.5.

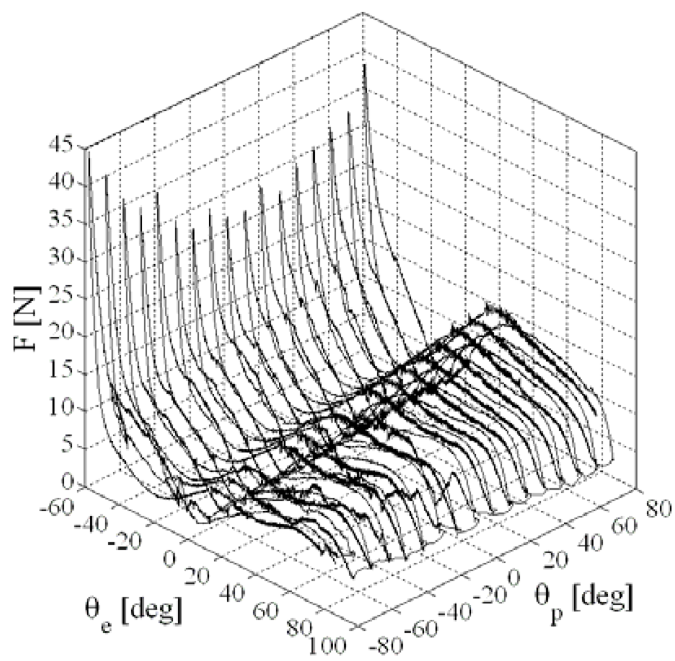

Fig. 5. Reaction force with fixed gripper

From the figure, it is observed that F increases at the flexed position ($\theta_e = -60[\text{deg}]$), and the reaction force at the flexed position is excessively enlarged if the pro-/supination angle is not set appropriately. Such the excessive reaction force might injure the elbow joint. And θ_p that minimizes the reaction force at the flexed position in Fig.5 is approximately same as θ_p at the flexed position in Fig.4. It is clarified that the pro-/supination of the normal subject in the case of free pro-/supination suppresses the reaction force at the flexed position.

3.2 Approximation of pro-/supination trajectory

As it is difficult for patient to pro-/supinate as normal subject, the pro-/supination trajectory of the patient using the free rotation gripper deviates from that of the normal subject. This causes that the excessive reaction force is applied to the patient. So, it is expected that an ideal CPM that suppresses the reaction force without narrowing the range of flex-/extension can be realized when an adequate reference pro-/supination angle trajectory is given. Since θ_p of the normal subject using the free rotation gripper suppresses reaction force at flexed position, in the following we regard the pro-/supination trajectory shown in Fig.7 as an adequate trajectory to suppress the reaction force.

Because the normal subject's trajectory is a certain trajectory with respect to the flex-/extension, we express the reference trajectory of the pro-/supination as the function of θ_e. The non-linear trajectory in Fig.3 is approximated with following polynomials,

$$\theta_r(\theta_e) = \sum_{i=0}^{N} \alpha_i \theta_e^i \tag{1}$$

where α_i is the coefficients determined by least squares method and we set $N = 7$ so as to minimize the error sufficiently. The approximated trajectory θ_r is shown in Fig.6. From the figure, it is confirmed that the trajectory of normal subject can be approximated well by eq.(1).

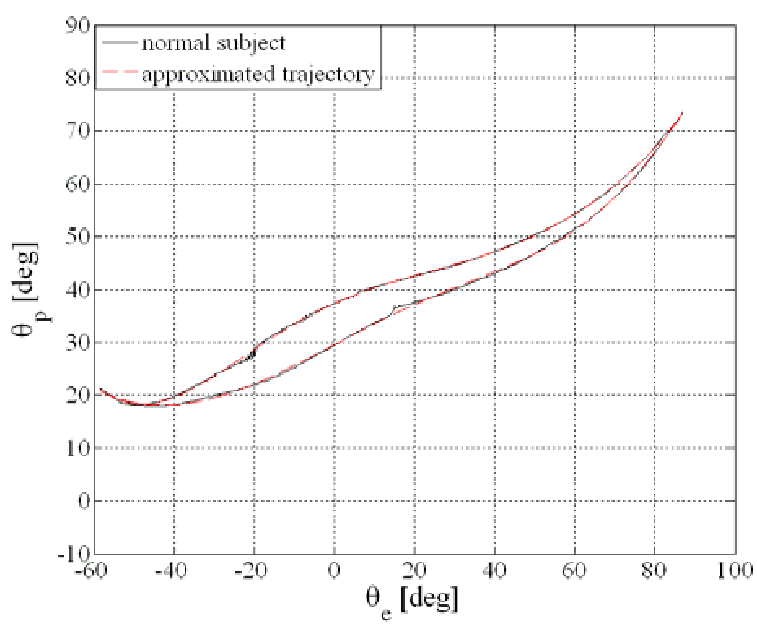

Fig. 6. Approximated pronation trajectory

4. Two d.o.f. CPM device

For the control of the pro-/supination and flex-/extension, we developed the two d.o.f. CPM device for the elbow joint as shown in Fig.7. This CPM device controls and measures θ_p and θ_e directly by DC motors with rotary encoder. A force sensor is attached at the end of the arm which measures the reaction force F.

The velocity of the arm for the flex-/extension is controlled with slow constant velocity 0.75[rpm]. The range of the flex-/extension of the CPM device is controlled by switch box operation of patient according to medical condition. It realizes treatment or rehabilitation for the flex-/extension suited to the patient (Kawaji et al., 2006).

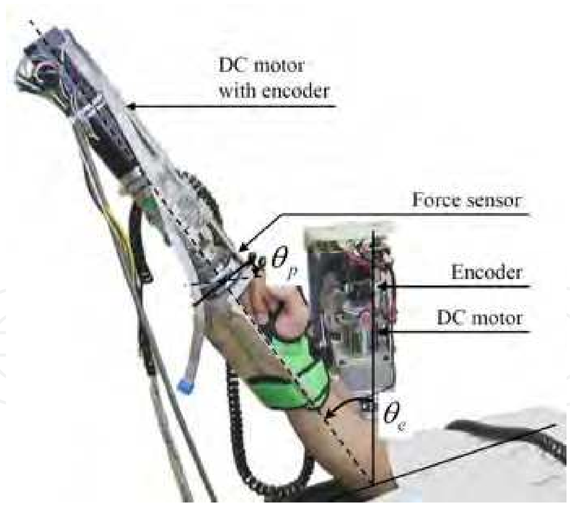

Fig. 7. CPM device with flex-/extension and pro-/supination

5. Impedance Control Scheme

It is obvious that the pro-/supination trajectory of the patient who has contracture is different from that of normal subject because the patient's pro-/supination that consists of the movement of the ulna and radius is restrained. Thereby, with the CPM device used in clinical treatment, automatic control of pro-/supination function will be required to follow the reference trajectory approximated from the normal subject. To control the pro-/supination angle during the flex-/extension, we will propose the control scheme shown in Fig. 8.

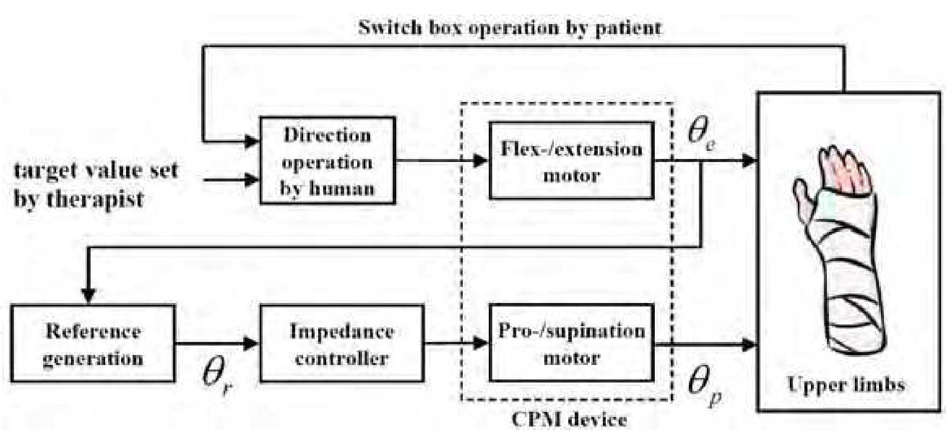

Fig. 8. Proposed impedance control scheme

In this scheme, using the extension angle, the reference angle of the pro-/supination is generated by eq.(1). To follow the reference trajectory of the pro-/supination while CPM movement, next two points should be considered.

A) The CPM device is controlled to follow the reference trajectory smoothly so as not to generate the large force and velocity.
B) The assistance force to follow the reference must be small near the end of the ROM.

To realize the flexible control of CPM device, active control methods such as impedance control or force control etc. have been studied (Gorinevsky, 1997). However, the force control is not suited for medical use since the arm of CPM device make sudden movements in the case that the human's arm comes free from the arm of CPM device. For this, we introduce an impedance control in this paper.
When the pro-/supination angle of the patient is close to that of the normal subject, the patient's condition is similar to the normal subject's one. In this case, the generated assistance torque of the CPM device should be small. When the pro-/supination angle of the patient deviates from that of the normal subject, it will be effective to make the assistance torque large.
For the conditions A) and B), let the reference impedance at the wrist be given as

$$\tau_p = \mathrm{M_I}\ddot{e}_p + \alpha \mathrm{D_I}\dot{e}_p + \alpha K_I e_p \tag{2}$$

$$e_p = \theta_r(\theta_e) - \theta_p \tag{3}$$

$$: \alpha = \frac{|e_p|}{\hat{e}_{p\max}} \tag{4}$$

where θ_r is the reference of normal subject in eq.(1), τ_p is the pronation torque, $\hat{e}_{p\max}$ is the maximum error and $\mathrm{M_I}$, $\mathrm{D_I}$ and K_I are the inertia, damping and stiffness factor, respectively. The stiffness factor is determined as follow so that the assist torque becomes the maximum value $\tau_{p\max}$ at $\alpha = 1$.

$$K_I = \frac{\tau_{p\max}}{\hat{e}_{p\max}} \tag{5}$$

For the condition A), impedance control is applied within the area $|e_p| \le \hat{e}_{p\max}$. In eq.(2) viscoelasticity terms are nonlinear with respect to $\dot{e}_p$ and e_p . So, $\alpha \mathrm{D_I}$ and αK_I become small in the case that θ_p gets close to θ_r, and the equation (2) becomes inertia system when $e_p = \dot{e}_p = 0$. When $|e_p|$ is large, the CPM device moves to reference slowly since the viscosity term is sufficiently large.
For the condition B), viscoelasticity terms should be changed due to the flex-/extension angle. So let maximum error area $\hat{e}_{p\max}$ be modified by θ_e based on the following equation.

$$\hat{e}_{p\max} = \exp(-\mathrm{W_F}\theta_e) + \exp(\mathrm{W_E}\theta_e) \tag{6}$$

where $\mathrm{W_F}$ and $\mathrm{W_E}$ are setting parameters to design the maximum error area at the flexed and extended position, respectively. From the viewpoint of control system design, the impedance characteristics can be adjusted with $\mathrm{W_F}$, $\mathrm{W_E}$ in clinical use. Fig.9 shows the reference trajectory θ_r and $\hat{e}_{p\max}$ when $(\mathrm{W_F}, \mathrm{W_E}) = (0.04, 0.03)$. The width of hatching area indicates the maximum error area $\hat{e}_{p\max}$. From the figure, $\hat{e}_{p\max}$ is enlarged near the end of the ROM. It realizes small assistance torque because K_I becomes small with eq.(5). So, the condition B) will be satisfied.

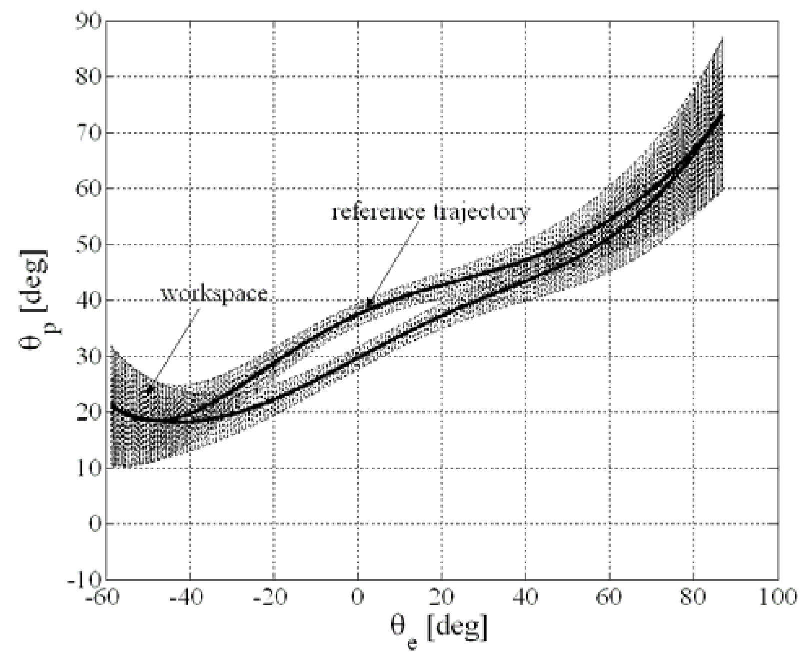

Fig. 9. Error space in pro-/supination plane

From eq.(2), (3) and (6), τ_u can be expressed as follows,

$$\tau_u = (\mathrm{M_c} + \mathrm{M_I})\ddot{e}_p + (\mathrm{D_c} + \alpha \mathrm{D_I})\dot{e}_p + \alpha K_I e_p - \mathrm{M_I}\ddot{\theta}_r - \alpha \mathrm{D_I}\theta_r - \alpha K_I \theta_r \tag{7}$$

Also, the parameters $\mathrm{M_I}$, $\mathrm{D_I}$ are adjusted by trial and error to prevent oscillatory response.

6. Experimental Result

We experiment in order to ascertain whether the proposed control scheme suppresses the reaction force without narrowing. In the experiments, the reaction force of subject whose pro-/supination is controlled is compared to that of the subject whose pro-/supination is free in the same range of the flex-/extension.
The subject for the experiments wears the bracing device (Armbrace, made by Bledsoe) as shown in Fig.10. The working range of the bracing device can be set mechanically. If the working range of the bracing device is set smaller than one of the CPM device, the bracing device deforms near the end of the ROM, and emulates the large stiffness of the contracture. The pro-/supination is constrained by the belt of the bracing device. The bracing device can emulate restriction of the elbow joint due to the contracture although the subject is normal. Thus, we regard the subject with the bracing device as a simulated patient whose condition is similar to arthrogryposis.

Fig. 10. Bracing device

In the experiments, the range of the flex-/extension of the CPM device was determined as $-60[\text{deg}] \leq \theta_e \leq 90[\text{deg}]$. The working area of the bracing device was set as $-45[\text{deg}] \leq \theta_e \leq 90[\text{deg}]$ so as to be smaller than one of the CPM device. $\tau_{p\max}$ was set as 3.0[Nm] based on the maximum torque examined by normal subject, and the impedance parameters were set as $(M_I, D_I) = (0.004, 0.8)$. The parameters of the maximum error area were adjusted as $(W_F, W_E) = (0.04, 0.03)$.

Experimental results are shown in Fig.11 and Fig.12. In Fig.11, the reference trajectory of the normal subject, the trajectory of the patient with the free rotation gripper and the experimental result using the proposed impedance control are represented by solid line, dotted line and heavy line, respectively. From the figure, the variation of the prosupination angle of the simulated patient is smaller than that of the normal subject because the arm is restricted by the bracing device. On the other hand, using the proposed impedance controller, the experimental trajectory is close to that of the normal subject.

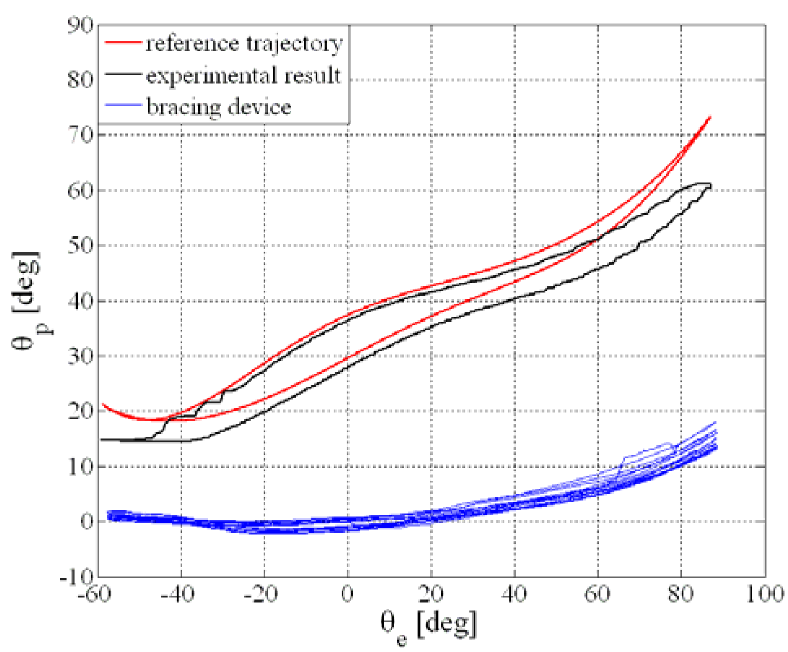

Fig. 11. Trajectory of pronation angle in CPM using the impedance control

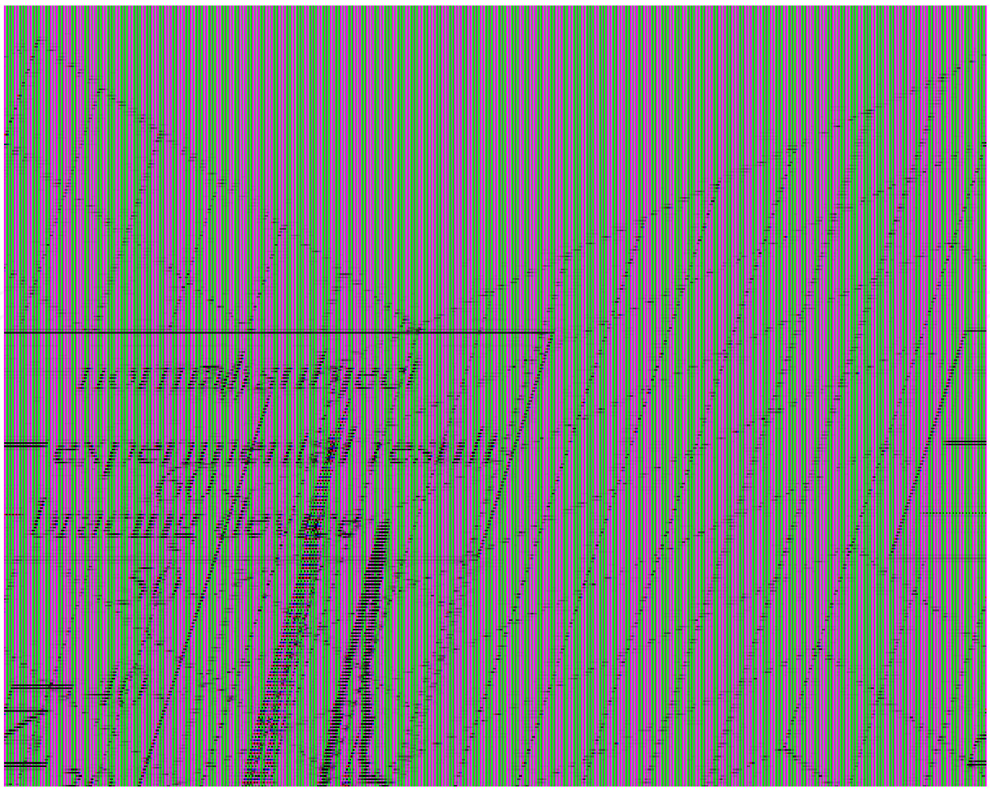

Fig. 12. Reaction force in CPM using the impedance control

Fig.12 shows the reaction force. The reaction force of the simulated patient increases excessively comparing with that of the normal subject. On the contrary, the reaction force of the simulated patient with the proposed control scheme comes close to that of the normal subjects and is suppressed near the flexed position.

From these experimental results, it is clarified that the proposed scheme is effective to realize the ideal CPM that the excessive reaction force is suppressed without narrowing the range of the flex-/extension.

7. Conclusion

In this paper, we have proposed the novel impedance control scheme of the CPM device for the elbow joint which controls the pro-/supination angles to follow the reference of the normal subject. The effectiveness was validated with the simulated patient wearing the bracing device.

From the experimental results for the subject with bracing device, it was clarified that the proposed scheme is effective to suppress the excessive reaction force. This will realize the CPM which does not burden the patient. Furthermore, the characteristics of the proposed control system can be adjusted intuitively by W_F, W_E.

In the proposed scheme, the trajectory of normal subject is applied as the reference trajectory. However, the parameters such as arm length, shape and dynamic characteristics of the joint etc. are different individually. So, the reference trajectory generation will be an important problem in practice application. Also, impedance control for flex-/extension, motion analysis and evaluation of the proposed scheme by doctors or physical therapists remain as future investigations.

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Mechatronic Systems Applications

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Mechatronics, the synergistic blend of mechanics, electronics, and computer science, has evolved over the past twenty five years, leading to a novel stage of engineering design. By integrating the best design practices with the most advanced technologies, mechatronics aims at realizing high-quality products, guaranteeing at the same time a substantial reduction of time and costs of manufacturing. Mechatronic systems are manifold and range from machine components, motion generators, and power producing machines to more complex devices, such as robotic systems and transportation vehicles. With its twenty chapters, which collect contributions from many researchers worldwide, this book provides an excellent survey of recent work in the field of mechatronics with applications in various fields, like robotics, medical and assistive technology, human-machine interaction, unmanned vehicles, manufacturing, and education. We would like to thank all the authors who have invested a great deal of time to write such interesting chapters, which we are sure will be valuable to the readers. Chapters 1 to 6 deal with applications of mechatronics for the development of robotic systems. Medical and assistive technologies and human-machine interaction systems are the topic of chapters 7 to 13.Chapters 14 and 15 concern mechatronic systems for autonomous vehicles. Chapters 16-19 deal with mechatronics in manufacturing contexts. Chapter 20 concludes the book, describing a method for the installation of mechatronics education in schools.