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Impedance Control of Two d.o.f CPM Device for Upper Limb Disorders ⋆

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Abstract: Continuous passive motion (CPM) is an orthopedic treatment or a physiotherapy and is tried to apply after surgery for the injured radial collateral ligament (RCL) in the elbow joint. After the surgery, the reaction force at hand of the patient increases due to an increase of the joint stiffness and may be excessively large. For this, it is effective to reduce the excessive reaction force by controlling pro-/supination of forearm. Also, the RCL in the elbow joint is extended due to pro-/supination of forearm, and the extension may aggravate the injury of the RCL. Thus, it is required to suppress both the excessive extension of the RCL and the reaction force. In this paper, a novel impedance control of CPM device that can suppress both the excessive extension of the RCL and the reaction force is proposed.

1. INTRODUCTION

As human has a lot of joints and utilizes many degrees of freedom for living and working, reduction or loss of the degree of freedom will deteriorate the quality of life. So, it will be important to recover the joint functions immediately after injury or surgery, and many studies have been performed on the development and application of orthopedic treatment or rehabilitation training devices (Frusho *et al*, 2005; Marroidis *et al*, 2005).

Among these treatments or rehabilitations, continuous passive motion (CPM) is the orthopedic treatment or physiotherapy method that promotes recovery of the impaired joint (Salter *et al.*, 1960). In the sense of regeneration of periarticular tissues, the effectiveness of CPM has been confirmed, e.g. recover times with CPM is shorter than that with a cast (Salter, 1993). One of the reason why CPM is used is to expand the range of motion (ROM) of the joint after the surgery that injure radial collateral ligament (RCL) in the elbow joint(Blauth *et al*, 1992; Cohen *et al*, 1998).

After the surgery, the joint stiffness increases, and the stiffness causes that the joint becomes more difficult to move physically (Driscoll *et al.*, 2000). Due to the stiffness, the reaction force from the patient increases and may be excessively large at the end of the ROM. It is effective to reduce excessive reaction force in order to expand the ROM. For reduction of the reaction force in CPM for the elbow joint, controlling pro-/supination of forearm is effective (Miyaguchi *et al.*, 2007). The RCL in the elbow joint is extended by pro-/supination (Mbaka *et al.*, 2006), which may aggravates the injury of the RCL. So, it is required to introduce an appropriate control strategy so as not to generate the excessive extension of the RCL.

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In this paper, a novel impedance control which can suppress both the excessive extension of the UCL and the reaction force is proposed. The extension of the RCL in CPM with the proposed controller is estimated by a skeleton model of upper limb.

2. FOCUSED DISORDERS

There are several surgical approaches to the elbow joint(Blauth *et al*, 1992; Cohen *et al*, 1998). A disadvantage of all surgical approaches is an insufficient view of a single incision to the ulnar aspect of the elbow joint so that they require an additional resection and a reconstruction of the RCL (Blauth *et al*, 1992; Cohen *et al*, 1998). The RCL as shown in Fig.1 is injured in the surgical operation frequently, and requires not to extend excessively. The RCL is a ligament in the elbow joint which connects the humerus and radius. The RCL injured by the resection and reconstruction after the surgery must not be extended excessively. After the surgery, the stiffness of a joint develops

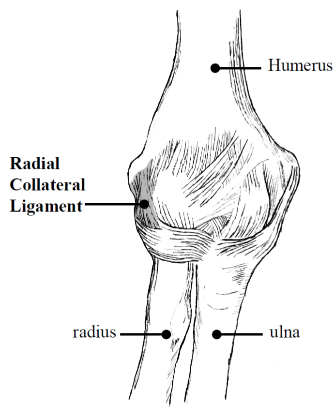

Fig. 1. Image of the radial collateral ligament

as a progression of four stages : bleeding, edema, granulation tissue and fibrosis as shown in Fig.2. The stiffness begins to develop after the surgery immediately (Driscoll *et al.*, 2000).

In progression of the stiffness, CPM generates pumping effect, and acts as a pump the accumulated fluid in the periarticular tissue away from the joint. The pumping effect is to generate oscillation of intra-articular pressure by the reciprocal motion of the joint. It causes that recover time with CPM is shorter than that with a established treatment method such as using cast (Salter, 1993).

In the third and the fourth stage, periarticular tissue swells due to accumulation of periarticular fluid, and the stiffness of the joint increases. From the stiffness, the reaction force at hand of the patient becomes large, and the joint becomes physically more difficult and painful to move (Driscoll *et al.*, 2000). The increase of the reaction force is a feature of an arthrogryposis that decreases the ROM. For expansion of the ROM in these stage, it is required that the reaction force is reduced.

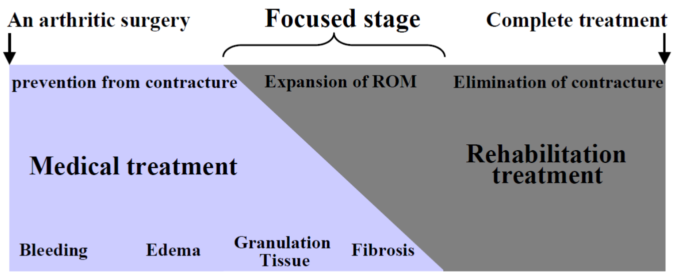

Fig. 2. Progression of four stages after surgery or injury

3. SKELETON MODEL OF UPPER LIMBS

In order to estimate the extension of the RCL in the elbow joint, we use the skeleton model that mimics the structure of the upper limbs as shown in Fig.3. In the figure, θ_p is pronation angle. The figure shows the skeleton model at supinated position; $\theta_p = -90$[deg]. The joint (A) and (B) are the proximal and the distal point of the ulna, respectively. The joint (C) and (D) are the distal and the proximal point of the radius, respectively. In the figure, the original point is proximal point of ulna. $\boldsymbol{r_1}$, $\boldsymbol{r_2}$, $\boldsymbol{r_3}$, $\boldsymbol{r_4}$ and $\boldsymbol{r_5}$ are the vector from Joint (A) to (B), from (B) to (C), from (C) to (D), from (D) to (A) and X-axis to (D), respectively. This skeleton model is verified by X-ray and MRI in previous study (Kasten *et al.*, 2002).

The length of vectors is equivalent to

$$|\boldsymbol{r_1}| = |\boldsymbol{r_3}| = l_1, \quad |\boldsymbol{r_2}| = |\boldsymbol{r_4}| = l_2 \tag{1}$$

This simple assumption makes it be applied easily in practice.

$\boldsymbol{r_2}$ is orthogonal vector w.r.t Y-axis and is rotated around Y-axis. Hence, $\boldsymbol{r_2}$ is written as

$$\boldsymbol{r_2} = l_2\,[-\sin\theta_p,\ 0,\ \cos\theta_p] \tag{2}$$

x and z element of $\boldsymbol{r_3}$ is determined as following because $r_{2x} + r_{3x} = l_2$ and $r_{2z} + r_{3z} = 0$.

$$r_{3x} = l_2(1 + \sin\theta_p), \quad r_{3z} = -l_2\cos\theta_p \tag{3}$$

Hereby, $r_{\alpha\beta}$ represents β element of vector $\boldsymbol{r_\alpha}$. From eq.(3) and $|\boldsymbol{r_3}| = l_1$, vector $\boldsymbol{r_3}$ is determined as

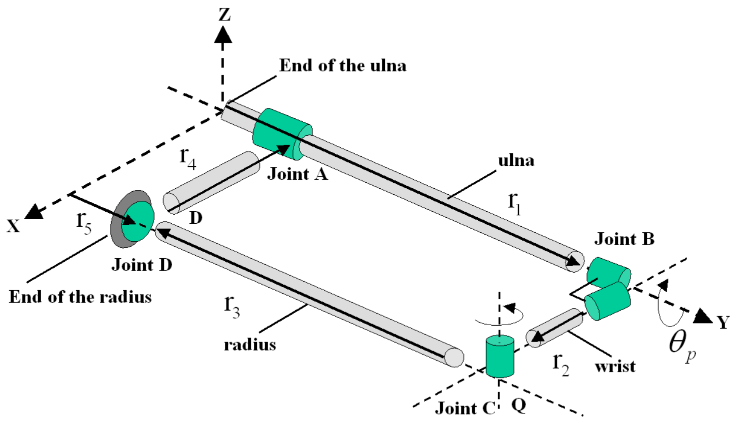

Fig. 3. Skeleton model of upper limbs

$$\boldsymbol{r_3} = l_2\left[1 + \sin\theta_p,\ -\sqrt{\frac{l_1^2}{l_2^2} - 2(1 + \sin\theta_p)},\ -\cos\theta_p\right] \tag{4}$$

By eq.(4) and $r_{5y} = r_{1y} + r_{3y}$, vector $\boldsymbol{r_5}$ can be derived as

$$\boldsymbol{r_5} = l_2\left[0,\ \frac{l_1}{l_2} - \sqrt{\frac{l_1^2}{l_2^2} - 2(1 + \sin\theta_p)},\ 0\right] \tag{5}$$

From eq.(5), r_{5y} is a monotone increasing function w.r.t θ_p in the range of $-90 < \theta_p < 90$. The RCL that connects the radius and the humerus is extended by the axial displacement of the ulna, and we regard the displacement r_{5y} that means the distance from X-axis to Joint (D) as the extension of the RCL.

In this paper, link parameter l_1 and l_2 is determined by MRI measurement. The MRI photograph of the subject is shown in Fig.4. In the figure, l_{dia} and b_{dia} are the distance from radial head to the ulnar styloid and the width of the radial head, respectively. l_1 is determined as l_{dia}, and l_2 is determined as b_{dia} according to the previous study (Kasten *et al.*, 2002). The link parameters l_{dia} and b_{dia} were measured as 218[mm] and 25[mm], respectively.

Using the link parameters, r_{5y} can be simulated according to θ_p. The anatomical ROM of pro-/supination is -85[deg]$< s <$75[deg] (Neumann, 2002), and we regard the ROM of r_{5y} as 0.0[mm]$< s <$5.7 [mm] from the simulation.

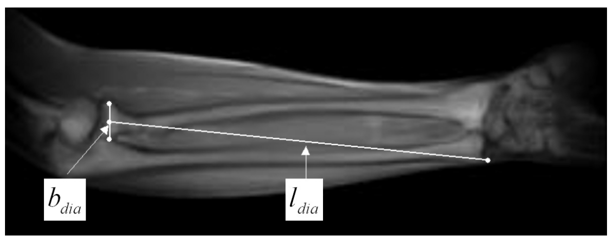

Fig. 4. Image of MRI measurement

4. ISSUES OF CPM DEVICE

The CPM devices developed by the authors are shown in Fig.5 and Fig.6. The both CPM devices have one d.o.f. The CPM device (KM702) shown in Fig.5 is a type of

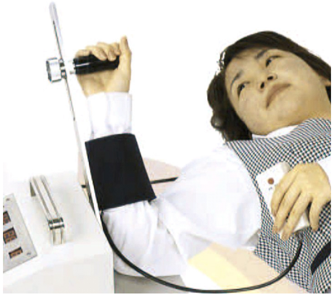

Fig. 5. CPM device with fixed joint gripper(KM702)

Fig. 6. CPM device with free rotation gripper(AH705)

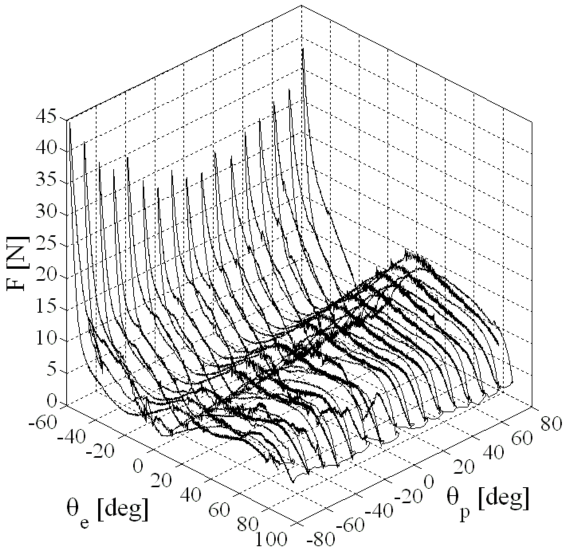

Fig. 7. Reaction force in CPM using fixed gripper

fixed gripper and involves the problem that the reaction force at hand of a patient will increase due to fixed pro-/supination. To examine the reaction force using fixed gripper, we measure the extension angle θ_e, the pronation angle θ_p and the Euclidean norm of reaction force F at hand with fixed pro-/supination using a device for measurment. The device is AH706 attached encoder, force sensor, and is usable as the one d.o.f CPM device in the case of fixed or free pro-/supination according to replace the mechanical parts.

The measurement result is shown in Fig.7. In this paper, the subject of experiments is a same normal adult. In the figure, the θ_p is fixed at every 10[deg] between -80[deg] and +80[deg]. The elbow joint is flexed to 60[deg] and is extended to 90[deg]. The CPM device arm moves reciprocally with uniform velocity 0.75[rpm].

From the figure, the reaction force increases as the elbow joint is flexed. The reaction force at flexed position can vary from 27[N] to 45[N] according to θ_p. There is a problem that the reaction force may be large excessively in case that setup pronation angle is inadequate.

For this problem, we have developed the CPM device with free rotation gripper as shown in Fig.6. The gripper of the CPM device rotates around pro-/supination axis freely. To examine the reaction force using free rotation gripper, we

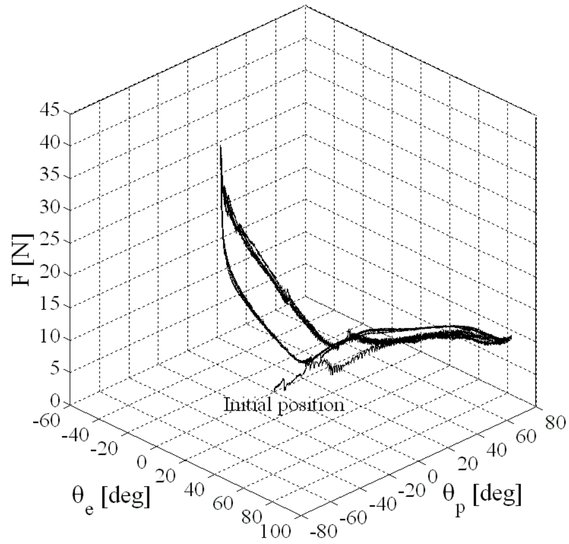

Fig. 8. Reaction force in CPM using free rotation gripper

measure θ_e, θ_p and F with the free rotation gripper. The measurement result is shown in Fig.8. In the region near the flexed position, the reaction force is large in the figure. Noting F and θ_p at flexed position and comparing Fig.7 with Fig.8, θ_p minimizing reaction force at flexed position is approximately equivalent to θ_p at flexed position in the case of free pro-/supination. This pronation angle suppresses the reaction force at flexed position.

The real patient cannot pro-/supinate as a normal subject. It causes that reaction force of the patient increases excessively. It is expected that the CPM that suppresses the reaction force without reducing the movement of the elbow joint can be realized when the adequate reference pro-/supination angle trajectory is given. Since θ_p using free rotation gripper suppresses reaction force at flexed position, the pro-/supination trajectory as shown in Fig.8 is an ideal trajectory that can suppress reaction force. Hence, we regard the pro-/supination trajectory according to flex-/extension as an adequate reference trajectory.

5. TWO D.O.F CPM DEVICE AND CONTROL LOW

5.1 Two d.o.f CPM device

For control of pro-/supination and flex-/extension, we have developed the two d.o.f CPM device for the elbow joint as shown in Fig.9.

This CPM device can control and measure θ_p and θ_e directly by DC motors with rotary encoder. A force sensor is attached at the end of the arm which can measure the pronation torque τ_p[Nm] and F[N].

The flex-/extension of the arm of the device is controlled by the switch box operated by a patient according to medical condition. So, treatment or rehabilitation training of flex-/extension suited to the patient will be available. The operation of a patient can realize conservative and safety movement (Kawaji *et al.*, 2006).

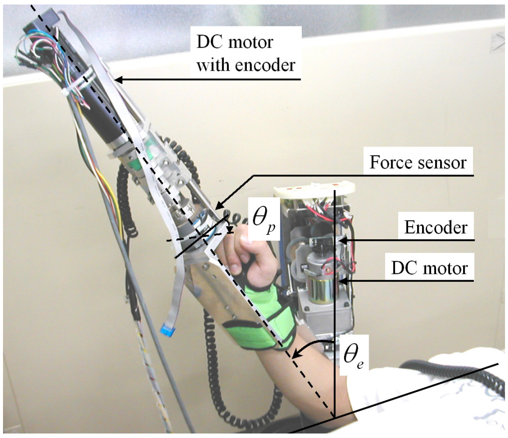

Fig. 9. Two d.o.f CPM device

5.2 Control low of two d.o.f CPM device

The pro-/supination trajectory of the patient is different from that of normal subject. From the measurement result in previous section, pro-/supination trajectory with flex-/extension of the normal subject using free rotation gripper is a certain trajectory. The pro-/supination trajectory of patient should move closer to that of normal subject in final stage of therapy. For the patient who has injury to the RCL, it is necessary to control so as not to generate excessive extension of RCL.

Therefore, next two points should be considered to perform CPM so as not to aggravate the injury.

A) Control the pro-/supination to follow to the trajectory of normal subject in order to suppress the excessive reaction force.
B) Control so as not to generate the excessive extension of the RCL in order to prevent from the injury.

In order to satisfy these two points, the control low that allows the error to reference trajectory is needed. To realize the control low, we introduce an impedance control in this paper.

The condition of the patient can be considered as that of the normal subject in case that the trajectory of the patient is almost same as that of the normal subject. In this case, assist torque to control pro-/supination is unnecessary. On the contrary, when the trajectory of the patient deviates from that of the normal subject, it is effective that the assist torque to pro-/supination becomes large because the condition of the patient can be regarded as an arthrogryposis.

Hence, the reference impedance at the wrist can be given as

$$\tau_p = M_I \ddot{e}_p + \alpha D_I \dot{e}_p + \alpha K_I e_p \tag{6}$$

$$e_p = \theta_r(\theta_e) - \theta_p \tag{7}$$

$$: \alpha = \frac{|e_p|}{\hat{e}_{p\max}} \tag{8}$$

where θ_r, τ_p, $\hat{e}_{p\max}$ are the reference trajectory of pronation angle, the assist torque of pro-/supination, the upper bound of the error, respectively. M_I, D_I, K_I are the inertia, damping, spring constant, respectively.

For the condition A), θ_r is the approximated trajectory of the normal subject as shown in Fig.8 using polynomial equation as following.

$$\theta_r(\theta_e) = \sum_{i=0}^{N} \alpha_i \theta_e^i \tag{9}$$

where α_i is the coefficient determined by the least squares method and we set $N = 7$ so as to minimize the error sufficiently. we approximate one reciprocal trajectory since the trajectory of the normal subject using free rotation gripper is almost same trajectory every reciprocal movement. The approximated trajectory is represented as heavy line in Fig.10. In the figure, θ_p will be large near the extended position as following the reference trajectory, so that r_{5y} will be large since r_{5y} is monotonic increase w.r.t θ_p.

For the condition B), assist torque from the CPM device should be small at the extended position. In addition, the assist torque from the CPM device to a patient should be small at the flexed position since the load of the joint will be large at flexed position. For these reason, the viscoelasticity terms should change due to the flex-/extension angle. $\hat{e}_{p\max}$ is modified by θ_e based on the following equation.

$$\hat{e}_{p\max} = \exp(-\mathrm{W_f}\theta_e) + \exp(\mathrm{W_e}\theta_e) \tag{10}$$

where $\mathrm{W_f}, \mathrm{W_e}$ are the free parameters to design the $\hat{e}_{p\max}$ at flexed position and extended position, respectively. At the end of the ROM, $\hat{e}_{p\max}$ will be large and the assist torque to a certain error will be small using eq.(10). Fig.10 shows the reference trajectory θ_r and the area $\hat{e}_{p\max}$ when $\mathrm{W_f} = 0.04$, $\mathrm{W_e} = 0.03$. In the figure, the width of hatching area indicates the value of $\hat{e}_{p\max}$.

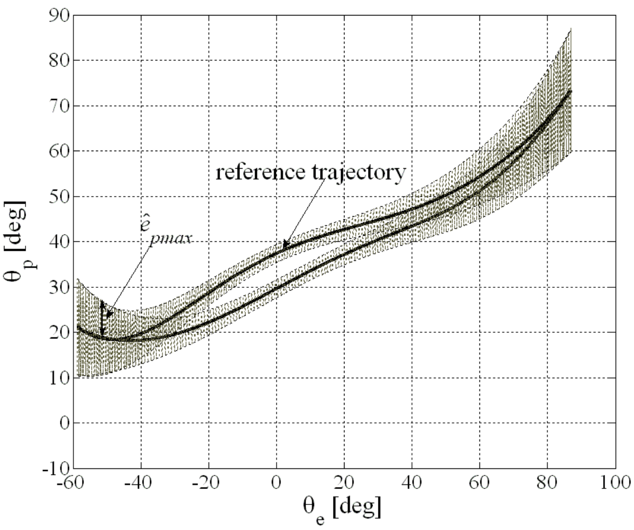

Fig. 10. $\hat{e}_{p\max}$ in pro-/supination plane

The equation of motion of CPM device is represented as

$$M_c \ddot{\theta}_p + D_c \dot{\theta}_p = \tau_u + \tau_p \tag{11}$$

where τ_u is the torque of the DC motor to control pro-/supination. From eq.(6), (7) and (11), τ_u can be expressed as follows

$$\tau_u = -\alpha M_c K_I M_I^{-1} e_p + (D_c - \alpha M_c D_I M_I^{-1})\dot{\theta}_p + (M_c M_I^{-1} - 1)\tau_p \quad (12)$$

where the spring constant is determined so as to generate maximum torque $\tau_{p\max}$ at $\alpha = 1$.

$$K_I = \frac{|\tau_{p\max}|}{\hat{e}_{p\max}} \quad (13)$$

The parameters M_I, D_I are adjusted by trial and error to prevent oscillation, and $\mathrm{W_f}$, $\mathrm{W_e}$ are adjusted by physical therapists or medical doctors. The proposed control scheme of the CPM device is shown in Fig.11.

6. EXPERIMENT

6.1 Experimental condition

The subject for experiments wears the bracing device (Armbrace, made by Bledsoe) as shown in Fig.12. Though the subject wore bracing device is a normal subject, the bracing device can emulate the arthritic disorder of the elbow joint since pro-/supination is restricted by the belt of the bracing device. The condition of the subject with the bracing device can be regarded as an arthrogryposis.

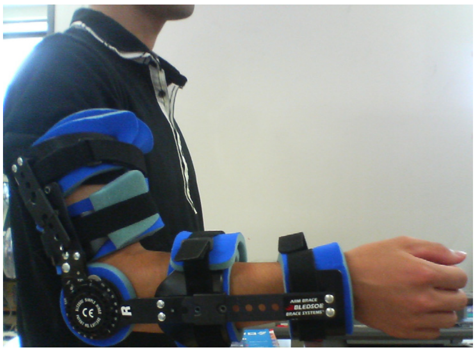

Fig. 12. Bracing device

6.2 Evaluation of impedance control

In order to confirm the effectiveness of the impedance control from the viewpoint of reduction of reaction force, an experiment was performed with the parameters $\{\mathrm{W_f},\ \mathrm{W_e}\}$ set as $\{0.04,\ 0.03\}$.

The experimental result is shown in Fig.13, where $|\tau_{p\max}|$ is set as 3.0[Nm] based on the maximum torque of the forearm, and the impedance parameters are set as $\{M_I, D_I\} = \{0.02,\ 0.8\}$.

In the Fig.13, reference trajectory of the normal subject, trajectory of the simulated patient and experimental result are represented by solid line, dash line and heavy line, respectively. From the figure, the trajectory of pro-/supination angle of the simulated patient deviates from that of the normal subject, and the reaction force of the simulated patient is larger than that of the normal subject because the arm is constrained by the bracing device. The experimental trajectory using impedance control is close to that of the normal subject, and the reaction force of the simulated patient is close to that of the normal subject and is suppressed. From the experimental result, it has been confirmed that the impedance control is effective for reduction of excessive reaction force.

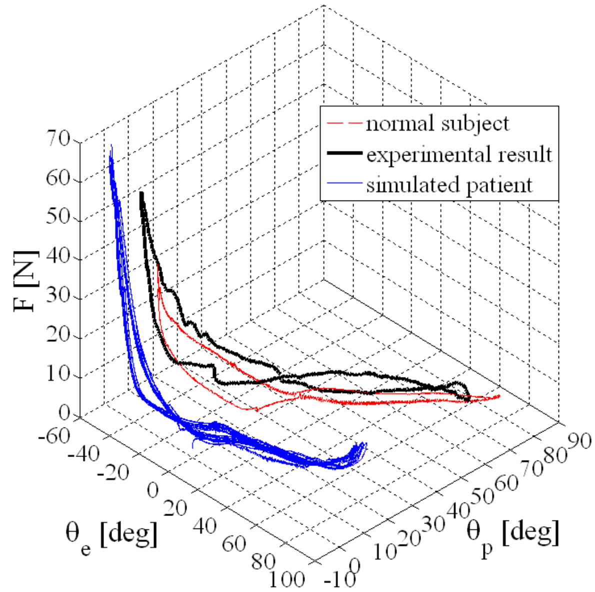

Fig. 13. Reaction force in CPM using impedance control

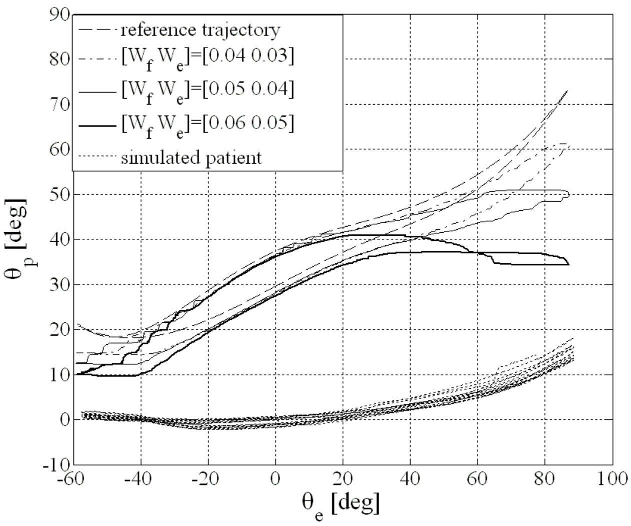

Fig. 14. Experimental result (θ_p)

6.3 Evaluation of parameter tuning

$\mathrm{W_f}$ and $\mathrm{W_e}$ are the parameters to adjust assist torque at flexed and extended positions of the elbow joint, respectively. In order to validate the effectiveness of impedance control with eq.(10) for suppressing the excessive extension of the RCL, the experiments is carried out in several ways to set parameters $\{\mathrm{W_f},\ \mathrm{W_e}\}$, and trajectory of r_{5y} in CPM is estimated by the skeleton model shown in Fig.3. The parameters $\{\mathrm{W_f},\ \mathrm{W_e}\}$ are set as gain $1 : \{0.04,\ 0.03\}$, gain $2 : \{0.05,\ 0.04\}$ and gain $3 : \{0.06,\ 0.05\}$. The experimental results of θ_p and r_{5y} are shown in Fig.14 and Fig.15, respectively. In these figure, the reference trajectory of the normal subject and the trajectory of the simulated patient are represented as dash line and dot line, respectively. The experimental trajectories using the impedance control with gain 1, gain 2 and gain 3 are represented as dashed dotted line, solid line and heavy line, respectively.

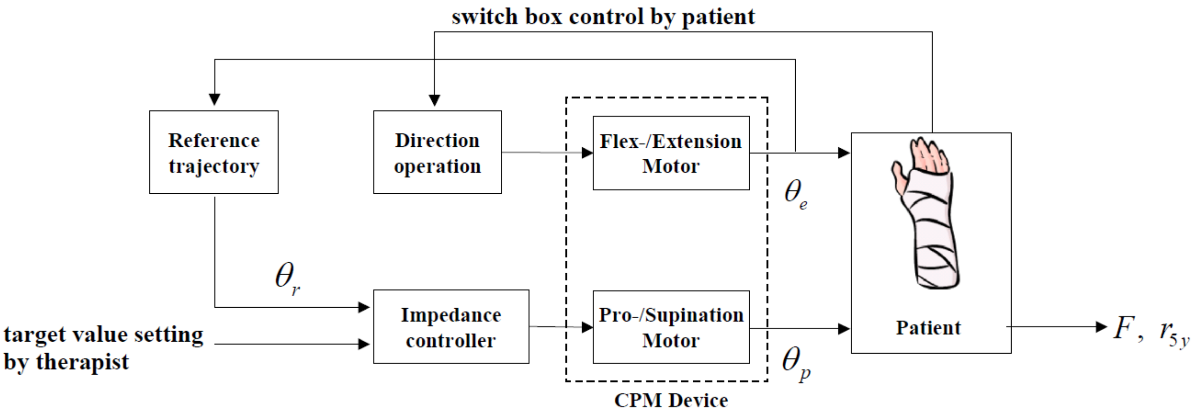

Fig. 11. Impedance control scheme for CPM device

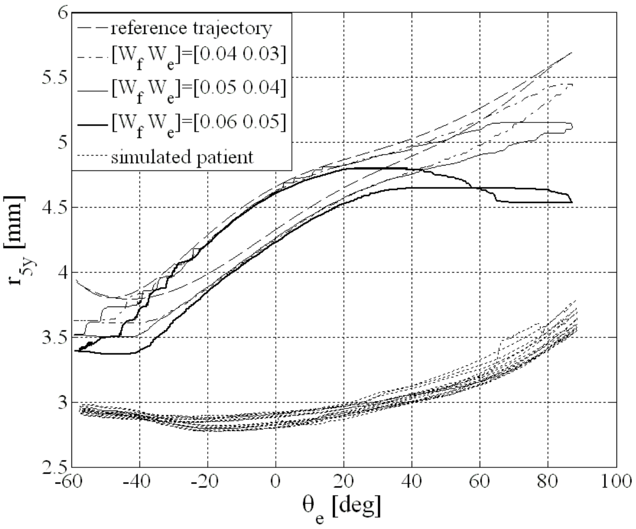

Fig. 15. Experimental result (r_{5y})

In Fig.15, reference trajectory at the extended position θ_e = 90[deg] is 5.7[mm], and r_{5y} is close to the limit of ROM of the RCL in case that r_{5y} follows the reference trajectory perfectly. The maximum values of r_{5y} of trajectory using the impedance control with gain 1, gain 2 and gain 3 are 5.4[mm], 5.1[mm] and 4.8[mm], respectively. So, it is confirmed that extension of the RCL can be suppressed by setting large W_e. Regarding on the trajectory of r_{5y} with gain 3, r_{5y} is bounded as 4.8[mm] at $\theta_e = 30$[deg]. Thus, even if W_e is set as more than 0.05, maximum of r_{5y} cannot be smaller than 4.8[mm]. At flexed position $\theta_e = -60$[deg] in Fig.15, the values of r_{5y} with gain 1, gain 2 and gain 3 are 3.6[mm], 3.5[mm] and 3.4[mm], respectively, and r_{5y} changes hardly at the flexed position. Therefore, it is concluded that r_{5y} has a low sensitivity for the parameter W_f.

7. CONCLUSIONS

In this paper, we have proposed a novel impedance control that is aimed for suppressing both the excessive extension of the RCL and the reaction force. The extension of the RCL in CPM with the proposed impedance control was shown in order to validate the effectiveness. From experimental results, it was clarified that the proposed impedance control is effective to reduce the reaction force and the maximum of extension of the RCL can be suppressed. In the proposed method, the extension of the RCL at the end of the ROM was adjusted by setting the parameters W_f and W_e.

It will be issue to design controller by setting the maximum extension of the RCL. Also, evaluation of the proposed method in medical sense and design of a controller for other disorders are future works.

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