Engineering

Mechanical Engineering fields

Okayama University *Year* 2005

Development of Wrist Rehabilitation Equipment Using Pneumatic Parallel Manipulator

Masahiro Takaiwa
Okayama University

Toshiro Noritsugu
Okayama University

Proceedings of the 2005 IEEE
International Conference on Robotics and Automation
Barcelona, Spain, April 2005

Development of Wrist Rehabilitation Equipment Using Pneumatic Parallel Manipulator

Masahiro Takaiwa
Department of Systems Engineering
Okayama University
3-1-1 Tsushimanaka Okayama, 700-8530 Japan
takaiwa@sys.okayama-u.ac.jp

Toshiro Noritsugu
Department of Systems Engineering
Okayama University
3-1-1 Tsushimanaka Okayama, 700-8530 Japan
toshiro@sys.okayama-u.ac.jp

***Abstract*— In this study, we aim at developing a mechanical device to support humans rehabilitation motion of their wrist joint instead of or to help a physical therapist. Pneumatic parallel manipulator is introduced as the mechanical equipment from a view that pneumatic actuators bring minute force control property owing to the air compressibility and parallel manipulator's feature of multiple degrees of freedom is suitable for a complex motion of human wrist joint. Impedance control system is introduced to realize several rehabilitation modes. The validity of the proposed system is confirmed through some experiments.**

***Index Terms*— Pneumatic servo system, Rehabilitation,Parallel Manipulator, Human Wrist joint**

I. INTRODUCTION

According to a Japan physical therapy white paper in 2002[1], there are currently about 5,000 of rehabilitation facilities and some people guess that at least 80,000 of physical therapists (P.T. hereafter) are required to be distributed evenly at all of these rehabilitation facilities, in the mean while actual number of P.T. is only about 30,000. An introduction of robot technology is expected to be a key solution to cope with these insufficiency of a nursing labors in a medical/welfare fields. Some rehabilitation equipments have been developed up to now[2][3][4] but most of them are for an upper limb training and are necessarily large sized one.

In this study, we focus on a rehabilitation motion of human wrist joint and aim at developing a mechanical equipment to support a rehabilitation training of wrist joint instead of P.T.

As shown in Fig.1, human wrist joint is composed with a pair of elliptic joint bones and they are filled with bone liquid as a role of lubrication. Through an interview with actual P.T., it is emphasized that, in a rehabilitation motion at a wrist joint, training motion should execute while applying a constant tension force along the direction of forearm in order to prevent a friction between joint bones. Hence, in order to perform like this motion, multiple D.O.F force/moment and position/orientation control mechanism is required for the rehabilitation equipment of a wrist joint.

In this study, a pneumatic parallel manipulator is introduced from a view that it has 6 D.O.F. enough to correspond to complex wrist motion and has backdriveability

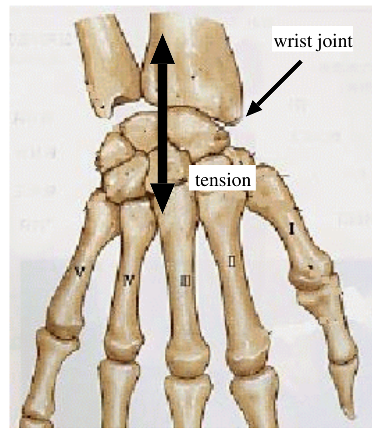


Fig. 1. Construction of wrist bones

resulted from air compressibility, which has possibility to be used as safety function.

In this study, impedance control strategy is applied on the manipulator to implement several rehabilitation exercise by adjusting impedance parameters appropriately. The estimation of wrist impedance for the sake of evaluation of the exercise is also investigated. The validity of the proposed rehabilitation system are confirmed through some experiments.

II. DEVELOPED MECHANICAL EQUIPMENT FOR WRIST REHABILITATION

In this study, a pneumatic parallel manipulator shown in Fig.2 (a) is introduced as a wrist rehabilitation equipment. 6 pneumatic cylinders are employed as driving actuators to form so called Stewart type platform[5].

Fig.2 (b) shows the schematic diagram of the manipulator. The position/orientation of the upper platform is expressed by a hand coordinate frame $\boldsymbol{h} = [x, y, z, \phi, \theta, \psi]^T$ using roll-pitch-yaw angle notation. The origin of hand coordinate frame $\boldsymbol{h}$ is set above a center point of upper platform at a manipulator is in a standard posture. The standard posture is that where the length of all the piston rod are at their middle. Similarly a link vector is defined as $\boldsymbol{\ell} = [\ell_a, ..., \ell_f]^T$ with an element of a displacement of each piston rod.

Force/moment vector, considered at an origin of $\boldsymbol{h}$ is defined as $\boldsymbol{f_h} = [\boldsymbol{f_{he}}^T | \boldsymbol{\tau_{he}}^T]^T = [f_x, f_y, f_z, |\tau_\phi, \tau_\theta, \tau_\psi]^T$. Also the equivalent force vector acts on piston rod is denoted with $\boldsymbol{f_e}$ which satisfy the following relation by the principle of virtual work.

$$\boldsymbol{f_h} = \boldsymbol{J}^T \boldsymbol{f_e} \tag{1}$$

, where J is a Jacobi matrix which forms the next relation.

$$\frac{d\boldsymbol{\ell}}{dt} = \boldsymbol{J}\frac{d\boldsymbol{h}}{dt} \tag{2}$$

Fig.2 (c) shows the utilizing situation. Human (patient) put their forearm above the upper platform along with x axis of manipulator and train rehabilitation exercise by holding a bar attached with a 6-axis force/moment sensor equipped on an upper platform.

The force/moment sensor is placed on the x axis and the origin of hand coordinate frame is set to agree with that of human wrist joint. Hence the force/moment applied at wrist joint $\boldsymbol{f_h} = [\boldsymbol{f_{he}}^T | \boldsymbol{\tau_{he}}^T]^T$ is obtained from the measured one by a force/moment sensor $\boldsymbol{f_s} = [\boldsymbol{f_{se}}^T | \boldsymbol{\tau_{se}}^T]^T$ as

$$\boldsymbol{f_{he}} = \boldsymbol{R}\boldsymbol{f_{se}} \tag{3.a}$$

$$\boldsymbol{\tau_{he}} = \boldsymbol{R}\boldsymbol{\tau_{se}} + \boldsymbol{P_h} \times (\boldsymbol{R}\boldsymbol{f_{se}}) \tag{3.b}$$

, where $\boldsymbol{R}[3 \times 3]$ and $\boldsymbol{P_h}$ is a rotation matrix calculated based on the orientation of upper platform ϕ, θ, ψ and position vector between center point of wrist joint and sensor, respectively.

A wrist joint has 3 D.O.F. motion as shown in Fig.3. Pronation/supination, radial flexion/ulnar flexion and flexion/extension motion are generated by the rotational motion around x axis(ψ), y axis (θ) and z axis(ϕ) of manipulator, respectively.

Table 1 (a) shows the moving area of a manipulator, where the number in a parenthesis is a ratio for human working range. For the direction except the supination/pronation, the moving area of manipulator covers that of human completely. In the mean while, maximum generation force with supply pressure of 400 kPa for each axis is also represented in Table 1 (b).

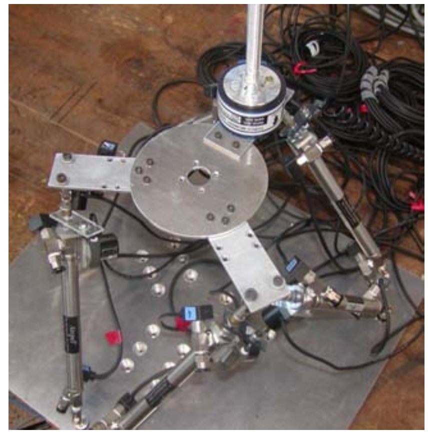
Fig.4 shows a pneumatic driving circuit. A low friction type pneumatic cylinders (Airpel Co. Ltd., 9.3 mm in internal diameter, 100 mm in rod stroke) are employed. Pressure in each cylinder's chamber, p_1, p_2 are detected by pressure sensors and the displacement of piston rod ℓ is measured by wire type rotary encoder. The A/D converter is of 12 bit resolution.

A control signal u corresponds to an driving voltage of a flow control type servo valve (FESTO, 50 ℓ/min) through D/A converter(resolution of 12 bit), which regulates the difference pressure of each cylinder. Supply pressure p_s is set to be 400 kPa. A control system is implemented under RT-Linux with 5 ms of sampling interval.

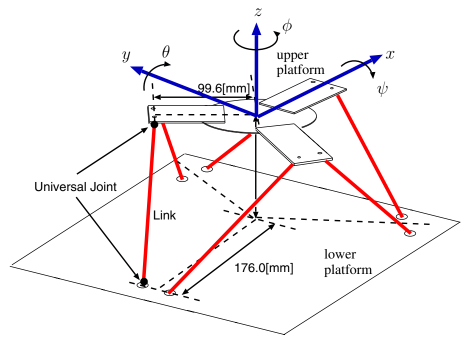
The linearized state equations of pressure in cylinder's chamber are described by the following equation.

$$T_p\frac{dp_1}{dt} = -p_1 + k_p u - k_v\frac{d\ell}{dt} \tag{4.a}$$

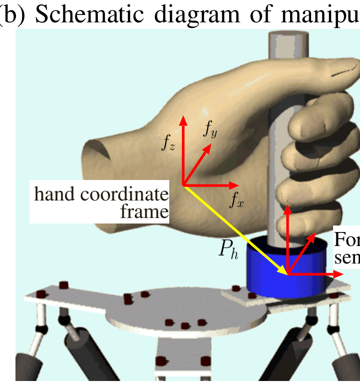
$$T_p\frac{dp_2}{dt} = -p_2 - k_p u + k_v\frac{d\ell}{dt} \tag{4.b}$$



(a) Pneumatic parallel manipulator



(b) Schematic diagram of manipulator



(c) arrangement of coordinate frame

Fig. 2. Developed pneumatic parallel manipulator

Equation of motion of piston rod is expressed by Eq.(5).

$$p_1A_1 - p_2A_2 = f_g = m\frac{d^2\ell}{dt^2} + b\frac{d\ell}{dt} + f_e \tag{5}$$

III. Control System

Fig.5 shows a proposed control system employing a position based impedance control system using a disturbance observer[6]. A force/moment applied by human(patient) $F_h(s)$ is measured by a 6 axis force/moment sensor and fed back through an inverse of a mechanical impedance model $I_{mp} = M_t s^2 + B_t s + K_t$. A position control system is constructed in order that its closed loop transfer function $G_r(s)$ may be the following 3rd order system, where A=38,

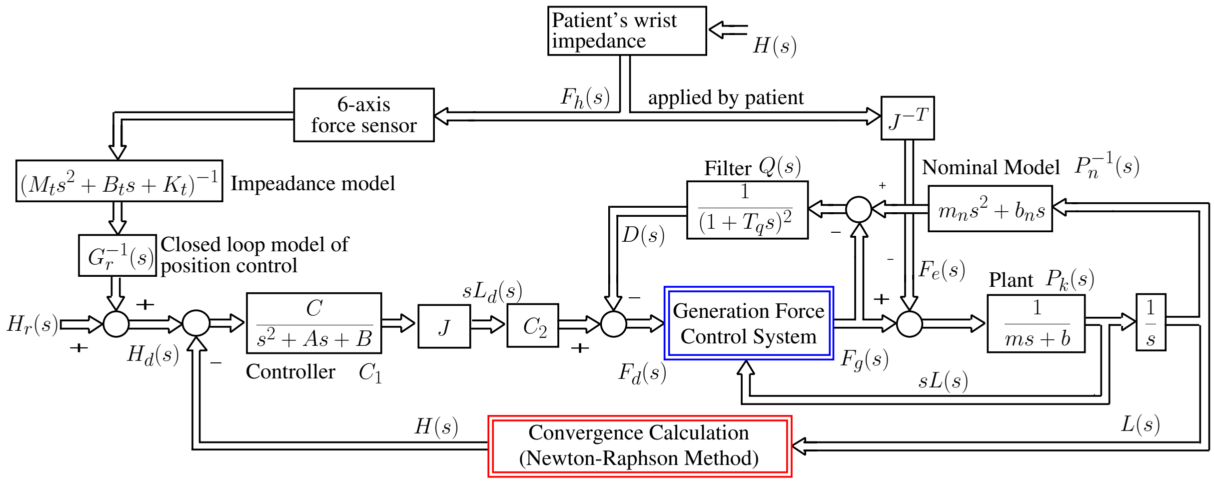


Fig. 5. Proposed control system

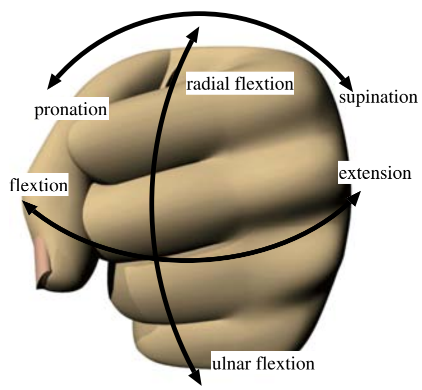


Fig. 3. wrist motion

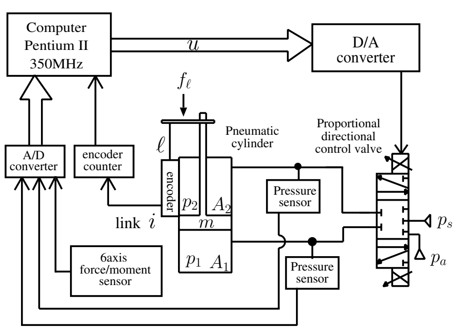


Fig. 4. Pneumatic driving circuit

B=410,C=1400.

$$H(s) = G_r(s)H_d(s) = diag\{\frac{C}{s^3 + As^2 + Bs + C}\}H_d(s) \quad (6)$$

where $H_d(s) = H_r(s) + I_{mp}(s)^{-1}G_r(s)^{-1}F_h(s)$ is desired position. Consequently the closed loop equation can be expressed by Eq.(7) to form a desired impedance property.

$$F_h(s) = I_{mp}(G_r H_r(s) - H(s)) \quad (7)$$

TABLE I

BASIC SPECIFICATION OF MANIPULATOR

(a) working area of manipulator

x	-94.7 ↔ 94.7[mm]	ϕ	-1.6 ↔ 1.6[rad] (120%)
y	-86.7↔ 86.7	θ	-1.4↔ 1.4 (106%)
z	-55.4↔ 55.4	ψ	-0.60↔ 0.60 (37.7%)

(b) generation force range

x	-61.0↔ 61.0 [N]	ϕ	-10.5↔ 10.5[Nm]
y	-54.0↔ 54.0	θ	-5.1↔ 5.1
z	-104.0↔ 104.0	ψ	-5.9↔ 5.9

TABLE II

PARAMETER GLOSSARY

T_p, T_{pn}	Time constant of pressure response and its nominal value
K_p, K_{pn}	Steady gain of pressure response and its nominal value
K_v	Steady gain between piston velocity and pressure
m, m_n	Equivalent mass for one cylinder and its nominal value
b, b_n	Viscous coefficient and its nominal value
f_h	External force applied by human
f_e	External force equivalently applied on a link
f_s	External force measured by force/moment sensor
A_1, A_2	cross sectional area of head/piston side cylinder chamber
p_1, p_2	air pressure in head and piston side chamber
ℓ	displacement of piston rod
J	Jacobi matrix
T_q, T_{pq}	Time constant of filter

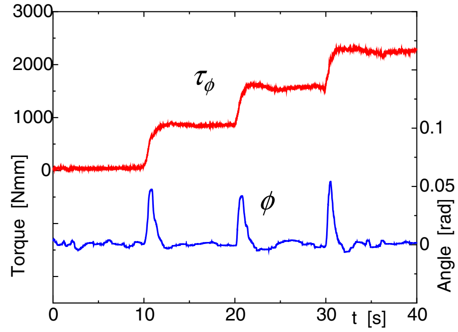
IV. EXPERIMENTAL REHABILITATION MOTION

There are several exercise modes in a rehabilitation. A control performance on an each rehabilitation exercise is verified experimentally in the following.

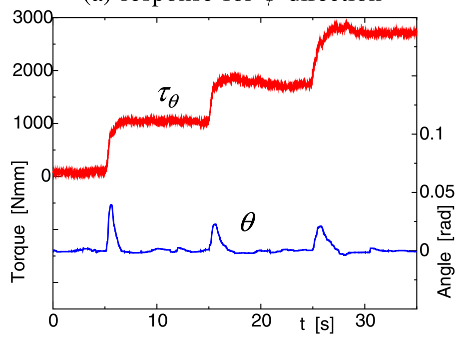
A. isometric exercise

Isometric exercise is often implemented in an initial period of rehabilitation. It is a motion requiring a muscle to contract without changing its length. In order to realize isometric exercise on a manipulator, manipulator is required to behave like a rigid wall. In a position based impedance control system, it corresponds to the case of setting an impedance as infinity, which is equivalent to the case of carrying out just a positioning control system.

Fig.6 shows the results of isometric exercise. Human holds a bar on the manipulator as shown in Fig.2 (c) and

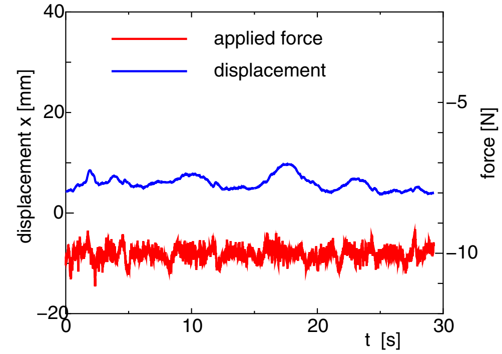


(a) response for ϕ direction

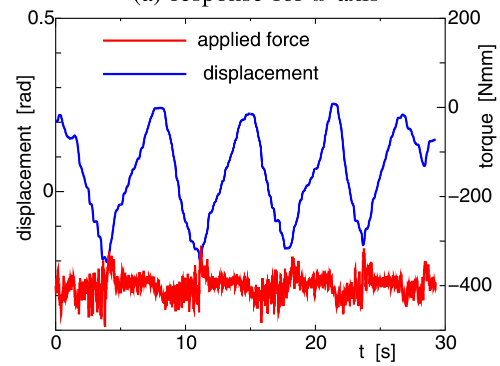


(b) response for θ direction

Fig. 6. isometric exercise



(a) response for x axis



(b) response for ψ axis

Fig. 7. isotonic exercise

apply a step like torque. Figure (a) and (b) corresponds to the motion of flexion(ϕ) and radial flexion(θ) as shown in Fig.3, respectively.

In pneumatic servo system, the servo stiffness in dynamic frequency range is not so large due to the air compressibility(off course the steady state servo stiffness is ∞ since it is 1 type control system). Consequently impulsive angle deviation is confirmed at the moment of changing an applying torque but the displacement angle in steady state is kept to be 0, which means the purpose of isometric exercise is achieved.

B. *isotonic exercise*

Isotonic exercise is a rehabilitation motion where a constant tension torque is applied to the wrist joint regardless of a wrist motion. In order to realize this motion on a manipulator, $H_r(s)$ is chosen as described in Eq.(8) so that the right hand side in Eq.(7) may follow the reference force/moment $F_r(s)$.

$$H_r(s) = G_r(s)^{-1}\{I_{mp}^{-1}(s)F_r(s) + H(s)\} \qquad (8)$$

Fig.7 (b) shows the results of isotonic exercise in terms of supination/pronation motion under the condition that a constant tension torque of 400 Nmm is applied for ψ axis. As mentioned at a section of “Introduction”, in a rehabilitation of a wrist joint which has an active motion, it is important to give tension force continuously along the direction of forearm shown by an arrow in Fig.1 in order to prevent a friction between angle bones. Therefore an isotonic exercise along x axis with constant force of 10 N is executing simultaneously, whose result is shown in figure (a).

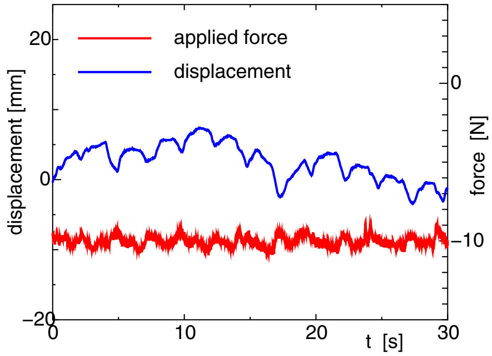
In both figures, blue and red lines correspond to the response of displacement and applied force for each axis, respectively. In spite of the sinusoidal motion for ψ direction, it is confirmed that human(patient) feels almost the reference torque of 400 Nmm under the condition of constant tension force for x axis. This is one of the features of multiple D.O.F parallel manipulator.

C. *passive isokinetic exercise*

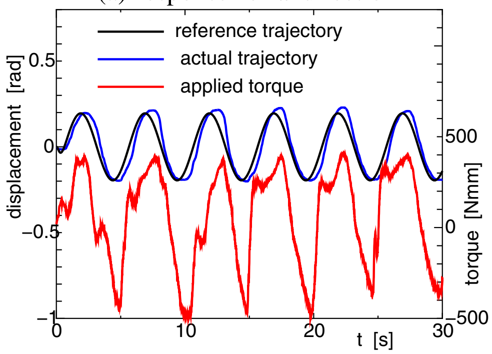
The isokinetic exercise is classified into 2 types, passive and active. In a passive isokinetic exercise, wrist joint is forced to move at constant angular velocity regardless of their applying force/torque. If the direction of motion agrees with that of applied force, it is called concentric contraction and the contrary case is called eccentric contraction. This passive isokinetic exercise is done by implementing a position control system on a manipulator with setting a reference position $H_r(s)$ as dynamic trajectory.

Fig.8(b) shows the results of concentric contraction in terms of supination/pronation motion under the condition that a sinusoidal function with 5 s period is set to $H_r(s)$ for ψ axis. In this exercise too, an isotonic exercise for x axis with reference force of 10 N is executed as shown in figure (a) for a prevention of bone friction, simultaneously.

Fig.9 shows the same experimental results with Fig.8 except that exercise motion is changed to an eccentric one, namely the direction of applied torque is opposite of that



(a) response for x direction



(b) response for ψ direction

Fig. 8. isokinetic exercise (concentric contraction)

of wrist motion. In both Fig.8 and Fig.9, a black line shows the desired trajectory, $G_r(s)H_r(s)$. In the case of eccentric motion, the displacement is slightly out of its reference trajectory but passive isokinetic exercise can be confirmed to be done through both of Fig.8 and 9.

D. active isokinetic exercise

The active isokinetic exercise is a motion where human generates wrist motion with constant angular velocity actively. In order to realize this rehabilitation motion, a damping control is implemented on a manipulator.

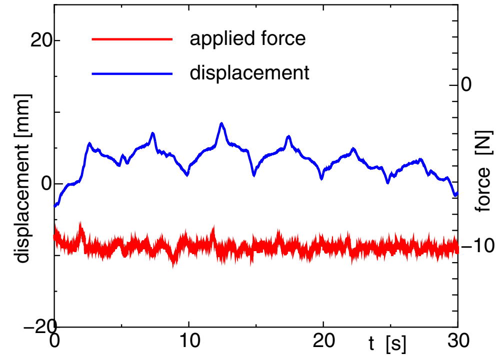
Fig.10 (b) shows the results of active isokinetic exercise in terms of supination/pronation motion, where black dot corresponds to the desired trajectory $\dfrac{F_h(s)}{B_t s}, B_t = 3\mathrm{Nms/rad}$. The actual trajectory shown by blue line almost agree with desired one(black dot), which show that the damping control is achieved. In this exercise too, an isotonic exercise for x axis with reference force of 10 N is executed simultaneously as shown in figure (a).

E. Estimation of wrist impedance

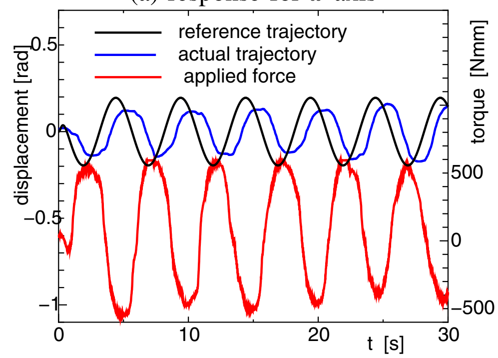
In order to evaluate the effectiveness of rehabilitation exercises, estimation of wrist impedance become significant. We suppose that wrist impedance, for example in the case of ϕ, is expressed as

$$\tau_\phi = B_\phi \dot{\phi} + K_\phi \phi + \tau_{\phi 0} \tag{9}$$

where B_ϕ,K_ϕ and $\tau_{\phi 0}$ is viscous coefficient, stiffness and free torque, respectively. We also assume that the wrist

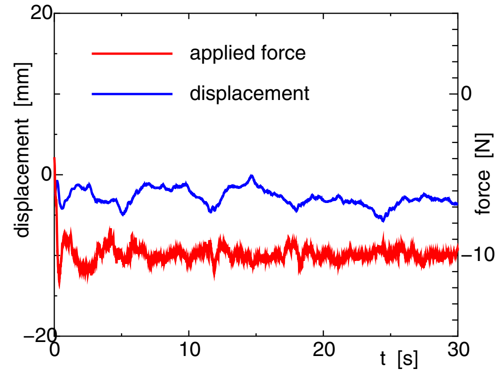


(a) response for x axis

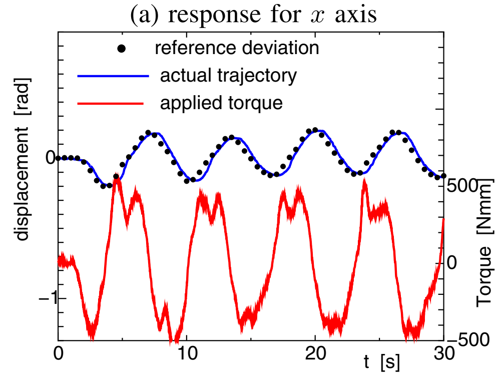


(b) response for ψ axis

Fig. 9. Passive isokinetic exercise (eccentric contraction)

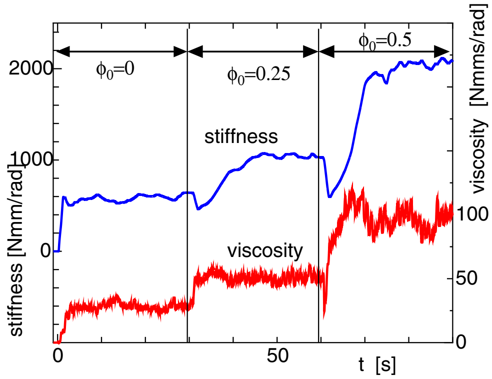


(a) response for x axis

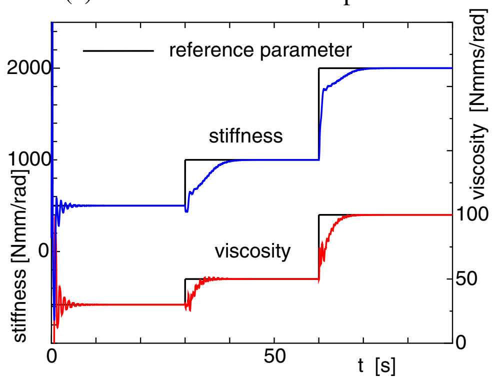


(a) response for ψ axis

Fig. 10. Active isokinetic exercise



(a) estimation of wrist impedance



(b) estimation of wrist model impedance

Fig. 11. Estimation performance of wrist impedance

impedance get larger according to the wrist angle gets closer to its limitation. Then the wrist impedance at 3 angle parts are investigated. Fig.11 (a) shows the results of estimation of wrist impedance for flexion/extension motion(around ϕ axis). Positioning control is implemented on manipulator with its reference of $\phi_r = \phi_0 + 0.1\sin(2\pi/1.0t)$, where ϕ_0 is set as $\phi_0 = 0$ rad(0s $\leq$ t $<$ 30s), $\phi_0 = 0.25$ rad(30s $\leq$ t $<$ 60s), $\phi_0 = 0.5$ rad (60s $\leq$ t $<$ 90s). The wrist impedance parameters are estimated by using recursive least square method[7]. Seeing from the figure wrist impedance get larger as a wrist angle close to the limitation. Fig.11 (b) shows the same result with figure (a) except that it estimate the parameter not of the actual human wrist but of that of the wrist impedance model described in Eq.(9), where each parameter is set by considering the result of figure (a) as B_ϕ=25 Nmms/rad K_ϕ= 500 Nmm/rad $(0 \leq t < 30)$,B_ϕ=50 K_ϕ= 1,000 $(30 \leq t < 60)$,B_ϕ=100 K_ϕ= 2,000 Nmm/rad $(60 \leq t \leq 90)$. In steady state the parameters are estimated well, which shows the effectiveness of estimation of human wrist shown in the figure (a). Embedding these estimation function into the rehabilitation exercise is left as future work.

V. Conclusion

In this study, we have introduced a pneumatic parallel manipulator in order to develop a rehabilitation equipment of human wrist joint from a view that a parallel manipulator's feature of multiple degrees of freedom is suitable for complex wrist motion. An impedance control system is constructed on a manipulator to implement several rehabilitation exercises.

Basic control performances for several rehabilitation exercises are experimentally verified, which show the effectiveness of the proposed control system.

An acquisition and realization of a series of motion and force pattern required for an actual rehabilitation exercise and the embedding of the proposed impedance parameter estimation function into the rehabilitation motion are the matter to be settled at present.

Acknowledgment

This work is partially supported by Okayama Foundation of Science and Technology. Authors express their gratitude.

References

[1] Physical therapy white paper, Japan Physical Therapy Association Ed., 2002

[2] *T. Noritsugu, T.Tanaka*, Application of Rubber Artificial Muscle Manipulator as a Rehabilitation robot, *IEEE/ASME Trans. on Mechatronics, vol.2 No.4 pp.259-267,1997*

[3] *T. Kikuchi, J.Furusho and K.Oda*, Development of Isokinetic Exercise Machine Using ER Brake, *Proc. of the 2003 IEEE ICRA, pp.214-219*

[4] *K. Koyanagi, J.Furusho, U.Ryu and A.Inoue*, Development of Rehabilitation System for the Upper Limbs in a NEDO Project, *Proc. of the 2003 IEEE ICRA, pp.4016-4021*

[5] *D.Stewart*, A platform with Six Degrees of Freedom, *Proc. Inst. Mechanical Engineers,180-15,371/386,1965*

[6] *M.Takaiwa and T. Noritsugu*, Development of Pneumatic Human Interface and Its Application to Compliance Display, *J. of Robotics and Mechatronics, vol.13 No.5 pp.472-478 2001*

[7] *T.Soderstrom and P. Stoica*, System Identification, *Prentice Hall, Chap.9, 1989*