Engineering

Industrial & Management Engineering fields

Okayama University *Year* 1996

Application of rubber artificial muscle manipulator as a rehabilitation robot

Toshiro Noritsugu
Okayama University

Toshihiro Tanaka
Okayama University

Takashi Yamanaka
Bridgestone Corporation

Application of Rubber Artificial Muscle Manipulator as a Rehabilitation Robot

T.Noritsugu and T.Tanaka

Faculty of Engineering
Okayama University
Okayama, Tsushimanaka, 700,Japan

T.Yamanaka

Bridgestone Co.
Kodaira,Ogawahigashi,187,Japan

Abstract

The application of robot to rehabilitation has become a matter of great concern. This study deals with an exercise for restoration of function being one of important rehabilitation tasks. An exercise of single joint has already been achieved with some automatically controlled machines. Now, the multi-joint exercise becomes desirable, which requires the exercise robot with multi-degrees of freedom to generate more realistic motion pattern. This kind of robot has to be absolutely safe for human. A pneumatic actuator may be so effective for such a robot because of the flexibility from air compressibility that a rubber artificial muscle manipulator pneumatically driven is applied to construct the exercise robot with two degrees of freedom. Also an impedance control strategy is employed to realize various exercise motion modes. Further, an identification method of the recovery condition is proposed to execute the effective rehabilitation. Some experiments show the availability of proposed rehabilitation robot system.

1 Introduction

The number of human requiring the rehabilitation for the fracture of a bone and joint disease caused by traffic accident and cerebral apoplexy and so on will increase in the advancing aged society. For the exercise for restoration of function in the rehabilitation, some automatic recovery machines have already been used just for the relatively easy exercise [1]. For the complex exercise, a multi d.o.f manipulator is required. However, this kind of robots have not been well developed. Because they require essential functions such as safety and flexibility which are not common in general industrial robots. In this study, we take up a rubber artificial muscle actuator and apply a two d.o.f manipulator driven with this actuator to the rehabilitation robot for the exercise of the restoration of function. By introducing an impedance control scheme [2], several exercise motion modes can be uniformly realized. Through some experiments of trajectory tracking, compliance and damping control, the satisfactory control performance can be obtained.

Also an identification method of human arm parameters is proposed, which identifies the mechanical impedance of the arm to be used as an estimation index of the recovery by means of an adaptive identifier. The identification performance is experimentally investigated.

2 Construction of Control System

2.1 Experimental Manipulator System

This study deals with a two d.o.f manipulator for the restoration of human arms. Fig.1 shows the experimental rubber artificial muscle manipulator hung down against the gravity force, which has the arm length of L=410mm and L=385mm similarly to the human. Each joint is driven by rubber artificial muscle actuators (Rubbertuator from Bridgestone Co. in Japan). Joint angles θ_1, θ_2 and contact forces F_x, F_y are detected.

Fig.2 shows the experimental control system. The actuators are driven by 7 bits PCM digital control valves [3]. The control input U is an integer of $0 \leq U \leq 127$, U=0 corresponds to wholly exhausting and U=127 does wholly supplying. The supply pressure P_s is 550kPa.

2.2 Pressure Control System

The control performance of rubber artificial muscle actuator so strongly depends on the inner pressure response that the pressure should be controlled as rapidly and accurately as possible. The pressure control system shown in Fig.3 is constructed for each joint. The desired input pressures P_{rf} and P_{re} are generated from P_0 and dP, which are the reference pressure and the control pressure input, respectively. Subscripts f and e denote quantities of contracted and extended side, respectively. Also 1 and 2 correspond to arm 1 and 2. U_0 is the control input to PCM valve to generate P_0, determined from the static characteristic of valve.

2.3 Impedance Control System

In the X-Y coordinate shown in Fig.4, the position of arm end $\boldsymbol{X}=(x,y)^T$ and the contact force

IEEE International Workshop on
Robot and Human Communication
0-7803-3253-9/96 $5.00 ©1996 IEEE

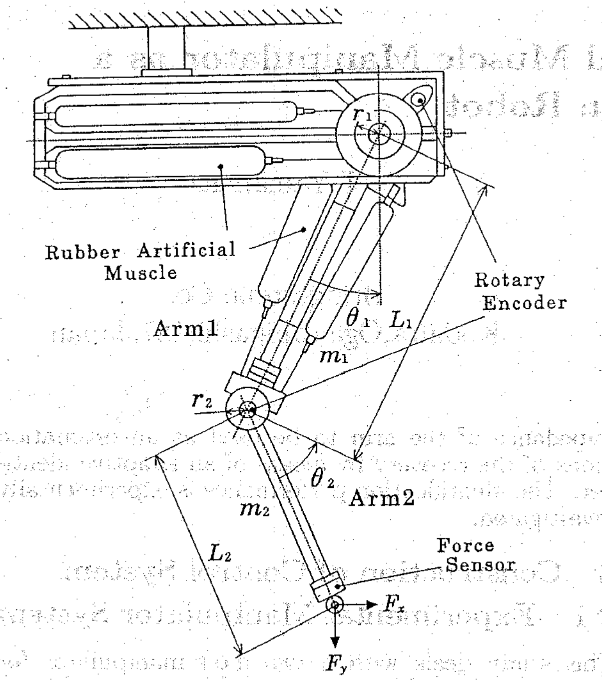


Figure 1 Rubber artificial muscle manipulator

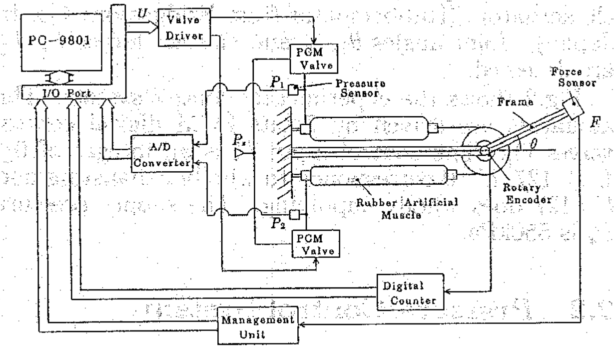


Figure 2 Experimental control system

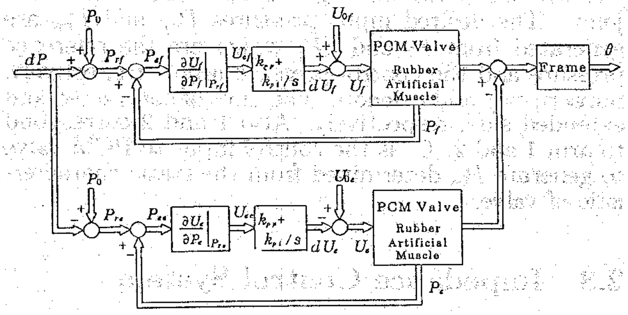


Figure 3 Pressure control system

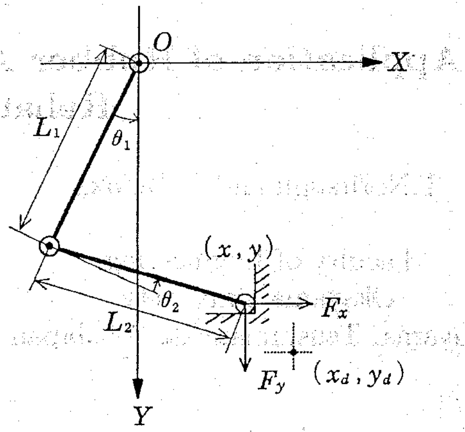


Figure 4 Model of manipulator contacting with object

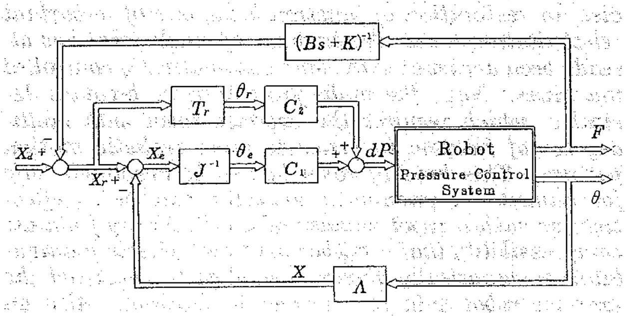


Figure 5 Proposed impedance control system

$\boldsymbol{F}=(F_x, F_y)^T$ are controlled to satisfy the following relation:

$$\boldsymbol{F} = \boldsymbol{B}(\dot{\boldsymbol{X}}_d - \dot{\boldsymbol{X}}) + \boldsymbol{K}(\boldsymbol{X}_d - \boldsymbol{X}) \qquad (1)$$

where $\boldsymbol{X}_d$ is the hypothetical desired position. $\boldsymbol{B}$=diag(b_x, b_y) and $\boldsymbol{K}$=diag(k_x, k_y) denote the desired damping and stiffness, respectively. Fig.5 shows the proposed impedance control system. If the inner position control loop ideally operates, $\boldsymbol{X}_r=\boldsymbol{X}$ is realized and the desired impedance described by Eq.(1) can be achieved [4].

The rubber artificial muscle has so little damping that the satisfactory continuous trajectory control is not easy to be obtained with an usual feedback control. Then a two degrees of freedom control with a feedforward compensation is constructed. C_1 and C_2 are PI and PD controller, respectively. Both the disturbance suppression characteristic and the tracking property can be independently specified by C_1 and C_2. The proportional gain of C_2 are determined from the relation between pressure and displacement of the rubber artificial muscle actuator measured considering the gravity effect. $\boldsymbol{\Lambda}$, $\boldsymbol{J}$ and $\boldsymbol{T}_r$ denote the transformation between each variables.

This impedance control system operates as an usual position control system under the not contacting condition of $\boldsymbol{F}=\boldsymbol{0}$. The smaller the desired stiffness $\boldsymbol{K}$ becomes, the faster the control system can respond but the less the stability becomes. The large desired damping $\boldsymbol{B}$ can improve the stability.

2.4 Application to Restoration Exercise

There are many kinds of exercises for the restoration of function in the rehabilitation. Some of them can be carried out with a robot manipulator instead of a medical trainer. The following motion modes have been defined for the exercise with robot.

(1)Isometric mode:The robot arm receives the force from the patient at the stationary state. This mode can be achieved by means of the extremely high impedance and the constant $\boldsymbol{X}_d$.

(2)Isokinetic mode P(Passive):The arm operates at the constant speed in spite of the force from the patient. This mode is used for the exercise of reinforce or extension of movable region of the muscle, which can be achieved by setting $\boldsymbol{X}_d$ as a ramp signal. The safety for the patient having only the small muscular strength can be secured by setting the low desired impedance.

(3)Isokinetic mode A(Active):The patient tries to move the arm at the constant speed, being exerted the reaction force proportional to the arm speed. This mode can be obtained from the damping control specified by $\boldsymbol{B}$, where $\boldsymbol{X}_d$ is constant and $\boldsymbol{K}=\boldsymbol{0}$.

(4)Isotonic mode:The arm gives the patient the constant force to increase the muscular strength. This mode can be realized with the force control achieved by setting $\boldsymbol{K}$ and $d\boldsymbol{X}=\boldsymbol{X}_d$ -$\boldsymbol{X}$ at constant.

3 Results of Restoration Exercise

3.1 Compliance Control

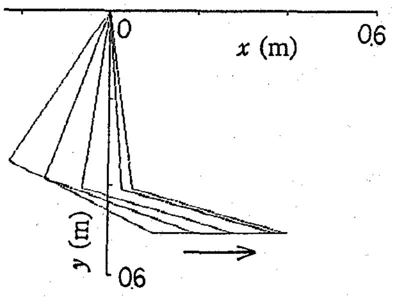
Fig.6 shows the response of contacting trajectory control where $k_x=k_y=1000$N/m, $\boldsymbol{B}=\boldsymbol{0}$. The arm contacts with the object wall at y=0.53m. The desired speed in the X direction $\dot{x}$=30mm/s and y_d=0.54m. Although the desired force F_y shown by the dotted line calculated by Eq.(1) does not become a completely straight line, both the desired compliance and tracking speed can be realized with the satisfactory accuracy.

3.2 Motion Mode for Restoration

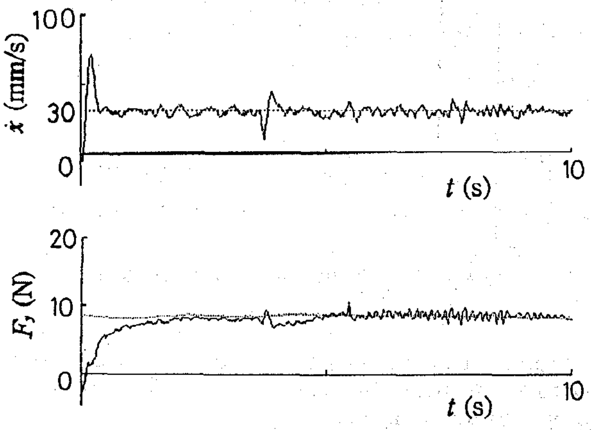
Assuming the exercise by means of the straight line trajectory, the human puts load on the end-effector as shown in Fig.7. Each motion mode is achieved in only the X direction. In the Y direction, the usual compliance control is executed.

Isokinetic mode P

Fig.8 shows the response being subjected to the load force from the human, which demonstrates the speed control performance of the arm. Where, k_x =500N/m, k_y=1000N/m, $\boldsymbol{B}=\boldsymbol{0}$ and $\dot{x}_d$=30mm/s. The reaction force agrees with the desired value calculated by Eq.(1) in spite of the direction of force.



(a) Arm configuration of every 3 seconds



(b) Speed and contact force

Figure 6 Contacting trajectory control

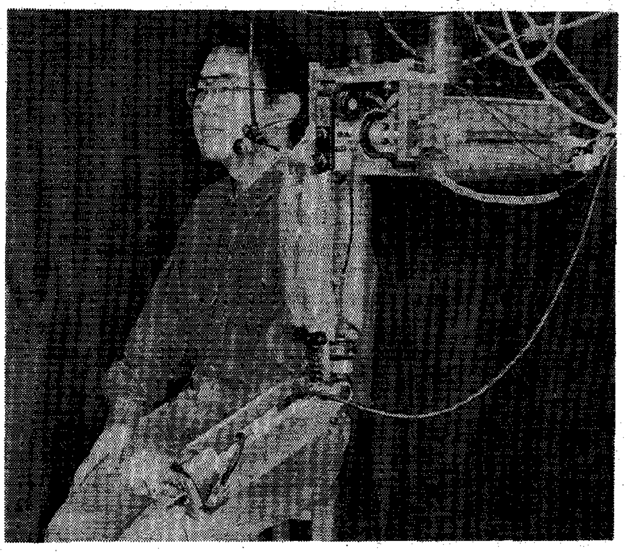


Figure 7 Overview of experimental setup

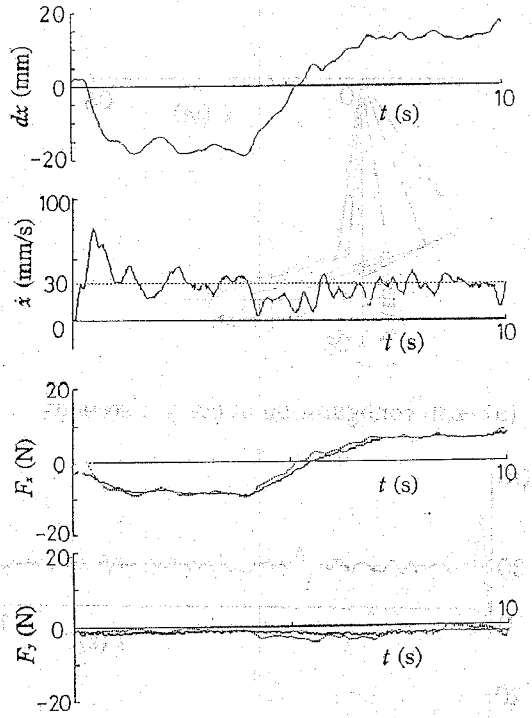


Figure 8 Isokinetic motion mode P

Further, the arm moves at the nearly desired speed in average. In the Y direction, the force from the weight of human hand appears.

Isotonic mode

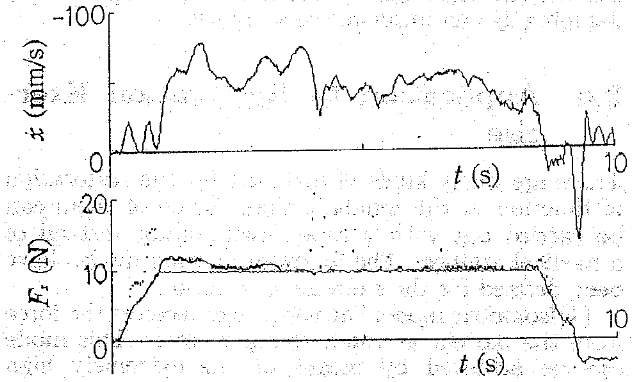
Fig.9 shows the force response when the human moves the arm at the various speed. Where k_x=2000N/m, k_y=1000N/m, B=0, dx=0.005m, so that the desired force in X direction is 10N. Before the force reaches the desired force, the usual compliance control is executed based on fixed x_d. When the force exceeds the desired value, x_d is changed to keep dx constant. At the moment the force decreases under the desired value, x_d is fixed at that momentary value. Fig.10 shows the response for the small desired force of 1N, where k_x=1000N/m, dx=0.001m. The satisfactory force control performance can be obtained over the wide force range.

Isokinetic mode A

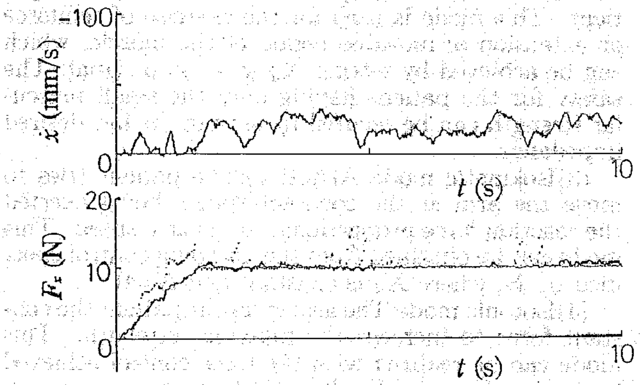
Fig.11 shows the response of damping control to realize the isokinetic mode A. Where b_x=300Ns/m, k_y=1000N/m, k_x=b_y=0, and the arm is moved by the human hand. The force satisfactorily coincides with the theoretical one over the wide range of arm speed. Fig.12 shows the accuracy of damping control, which illustrates the realization of accurate damping control for the isokinetic motion mode A.

4 Identification of Human Parameters

An effective rehabilitation requires to identify the recovery condition of patients by using an appropriate estimation index. In this study, a mechanical impedance of human arm is proposed to be employed as the estimation index. Also, the rubber artificial muscle manipulator is used for the purpose of simultaneously executing both the restoration exercise and



(a) Fast motion



(b) Slow motion

Figure 9 Isotonic motion mode

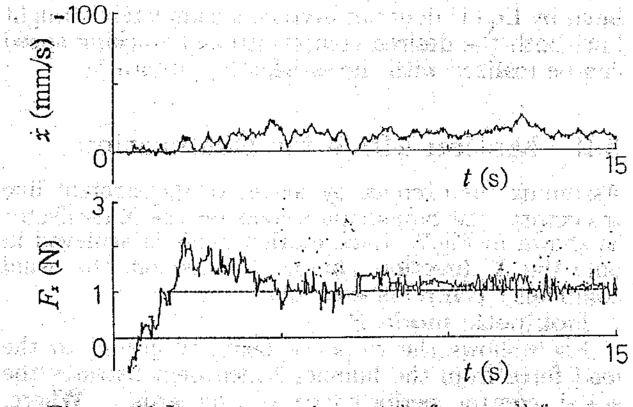
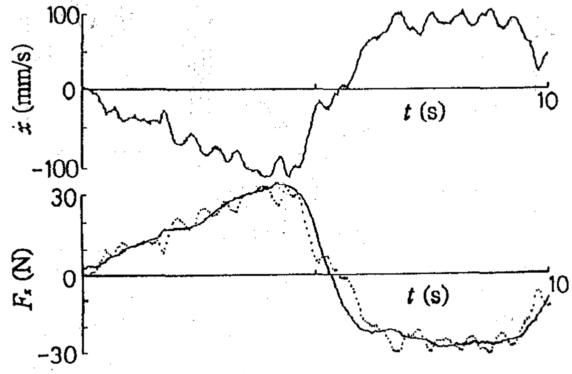
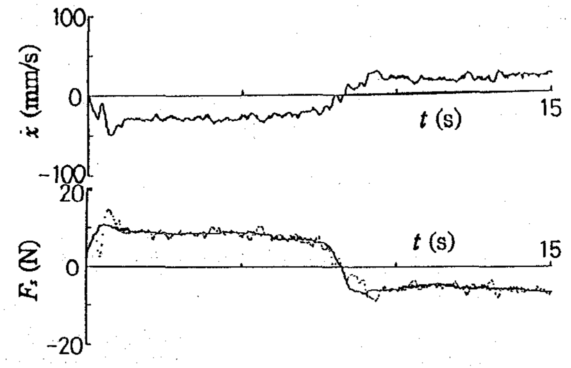


Figure 10 Isotonic motion mode for small force



(a) Fast motion



(b) Slow motion

Figure 11 Isokinetic motion mode A

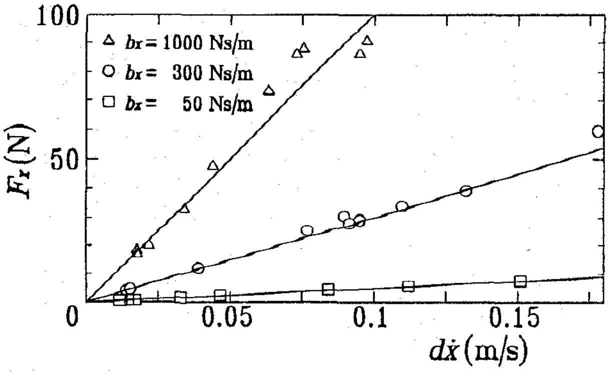


Figure 12 Accuracy of damping control

the identification of recovery condition. In the system shown in Fig.7, the manipulator oscillates the human arm through the grip in the vertical X-Y plane. The human arm is modeled by an impedance model, of which unknown impedance parameters described in X-Y coordinate are identified by means of an adaptive identifier.

4.1 Impedance Model

A human arm is modelled as an impedance model as follows, of which parameters are identified.

$$\boldsymbol{F}_h = \boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{B}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} \qquad (2)$$

$$\boldsymbol{M}=\begin{bmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \end{bmatrix}, \boldsymbol{B}=\begin{bmatrix} B_{xx} & B_{xy} \\ B_{yx} & B_{yy} \end{bmatrix}, \boldsymbol{K}=\begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}$$

are inertia, damping and stiffness matrices, respectively, described in the X-Y coordinate. $\boldsymbol{F}_h^T = [F_{hx} \ F_{hy}]$ is a passive reaction force from the arm. Other force not included in $\boldsymbol{F}_h$ is also considered as a disturbance in the model. The plant model to be identified is given by

$$\boldsymbol{F} = \boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{B}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} + \boldsymbol{F}_a = \boldsymbol{P}\boldsymbol{\zeta} \qquad (3)$$

where $\boldsymbol{F}^T = [F_x \ F_y]$ is the output from the plant model,detected with the force sensor. $\boldsymbol{F}_a^T = [F_{ax} \ F_{ay}]$ corresponds to the disturbance including an active force generated by the human. $\boldsymbol{P}^T = [\boldsymbol{P}_x \ \boldsymbol{P}_y]$ and $\boldsymbol{\zeta}$ are a parameter matrix and a state variable vector, respectively, shown as

$$\boldsymbol{P}_x = [M_{xx} \ M_{xy} \ B_{xx} \ B_{xy} \ K_{xx} \ K_{xy} \ F_{ax}] \qquad (4)$$

$$\boldsymbol{P}_y = [M_{yx} \ M_{yy} \ B_{yx} \ B_{yy} \ K_{yx} \ K_{yy} \ F_{ay}] \qquad (5)$$

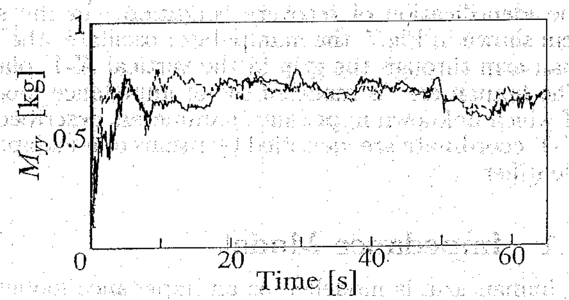
$$\boldsymbol{\zeta}^T = [\ddot{x} \ \ddot{y} \ \dot{x} \ \dot{y} \ x \ y \ 1] \qquad (6)$$

The mechanical impedance parameters are identified as components of parameter vectors $\boldsymbol{P}_x$ and $\boldsymbol{P}_y$ by using an usual adaptive identifier.

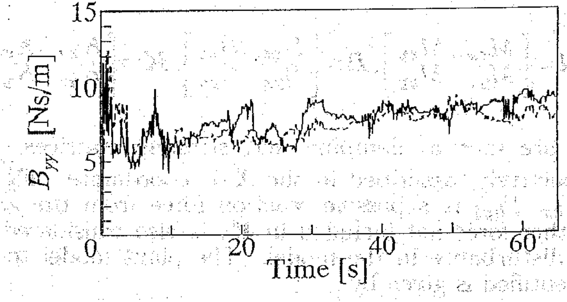
4.2 Results of Identification

Fig.13 shows the impedance parameters identified twice for the identical person. The inertia and the damping have almost same values at twice. On the contrary, there is much difference between two trials. That means the stiffness can sensitively reflect the change in the condition of human arm.

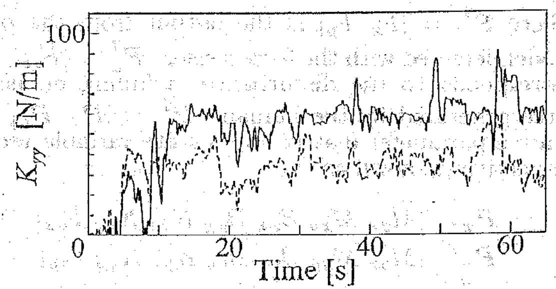
Fig.14 shows the result when the human consciously apply the force in the positive Y direction 33 seconds after. The identified values of F_{ay} confirms the validity of the term of $\boldsymbol{F}_a$ in Eq.(3). Further, the result of K_{yy} agrees with the fact that the human arm becomes hard when it generates the force. The identified values of inertia and damping have remained almost constant. The results show the availability of the stiffness to estimate the condition of the human arm.



(a) Inertia

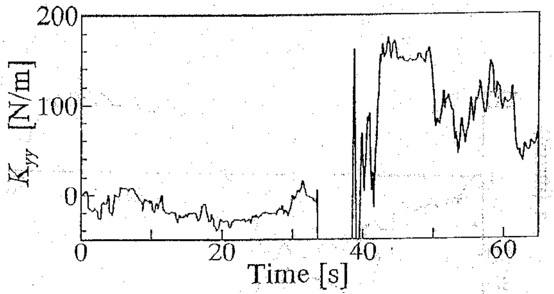


(b) Damping

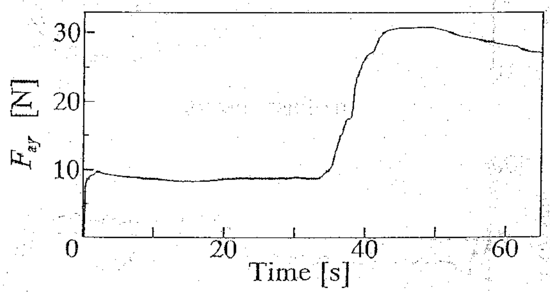


(c) Stiffness

Figure 13 Identified impedance parameters



(a) Stiffness



(b) F_{ay}

Figure 14 Identification of conscious force

5 Conclusion

The rehabilitation robot requires not so highly accurate control performance but the complete safety and flexibility for the human. From a such point of view, this study has applied the rubber artificial muscle actuator to the exercise robot for restoration of the function. We have proposed the unified control approach to realize the important motion modes for the restoration, based on the impedance control strategy. Through some experiments the proposed control approach has been proved to be effective. Also the availability of this actuator to the rehabilitation robot has been confirmed.

Further, an identification method of the human arm parameters has been proposed to estimate the recovery condition of the arm, which identifies the mechanical impedance of the arm by means of an adaptive identifier. Experiments have confirmed the effectiveness of the proposed approach.

The integration between the restoration exercise and the identification is the next important issue, where the mechanical impedance may be a common significant estimator.

References

[1] Y.Doi, "Exercise Apparatus for Restoration of Function," *Journal of the Society of Biomechanisms*, Vol.17, No.2, pp.99-105, 1993.

[2] N.Hogan, "Stable Execution of Contact Tasks using Impedance Control," *Proc. IEEE Int.Conf.on Robotics and Automation*, pp.1047-1054, 1987.

[3] T.Noritsugu and T.Wada, "Microcomputer Controlled PCM Digital Pneumatic Servo System," *Transactions of the Society of Instrument and Control Engineers*, Vol.25, No.3, pp.253-259, 1987.

[4] D.A,Lawrence, "Impedance Control Stability Properties in Common Implementation," *Proc.IEEE Int.Cof.on Robotics and Automation*, pp.1185-1190, 1988