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A Bio-mimetic Rehabilitation Aid for Human Movements using Mechatronic Technology

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Abstract

In this paper, a rehabilitation aid for reaching movements with an impedance controlled robot using a Time Base Generator (TBG) is proposed. A target spatio-temporal trajectory for the robot which has the same features as a healthy person has is generated by the TBG. During the training, a trainee is instructed to move the handle attached on the robot to a target position based on biofeedback information, and the robot assists him or her by tracking the given target trajectory. To show the validity of the proposed training approach for reaching movements, the training experiments are carried out with healthy persons whose joints of the upper limb are partly restricted by bandages.

Key Words: Rehabilitation, reaching movements, trajectory generation, impedance control.

1 Introduction

Robots have mainly been used as an effective industrial device for increasing productivity in factories. However, directing our attention to the current problems of medical welfare such as the undesirable social condition for handicapped people and the serious shortage in homecare in the coming aging-society, we expect naturally that an advanced type of robot that cooperates with a human or assists the daily life of a handicapped person should be developed in the near future.

Ordinary medical treatments, for motor functional disorder of the limbs, are carried out with some training implements through a dialog between patient and therapist. However, it is sometimes difficult to examine therapeutic effects through objective analysis. Moreover, without the therapist, the patient can not continue on with effective training.

Recently, a number of studies have been performed on a training and a rehabilitation system with robots, so as to improve the situations on medical welfare mentioned above. Especially, to support the joint motion exercise for prevention and improvement of joint contraction and muscle atrophy, the study on a Continuous-Passive-Motion (CPM) device, which moves the joints of the patient passively, has been actively performed. For instance, Sakaki et al. [1] and Okajima et al. [2] have developed the impedance-controlled CPM device which can realize compliant motion exercise. Also, Krebs et al. [3] have developed a training system for the upper limb movements through operating the end-effector of the impedance controlled robot according to a target pattern, such as a circle, shown in the computer display.

Meanwhile, there have been many studies on the mechanism of human arm movements [4]-[8]. For example, Morasso [4] measured reaching movements of the two-joint arm restricted to a horizontal plane, and found the common invariant kinematic features that a human usually moves his hand along a roughly straight path with a bell-shaped velocity profile from one point to another. As the explanation for the trajectory generation mechanism of human arm movements, many models have been proposed; for example, "a minimum jerk model" [5], "a minimum torque-change model" [6] and "a VITE model" [7]. The first and the second models assert that the underlying mechanism is a feedforward system, and the other deals it as a feedback. All of these models can generate hand trajectories in good agreement with experimental data. Also, Morasso et al. [8] proposed a Time Base Generator (TBG) which generates a time-series with a bell-shaped temporal profile, and showed that a straight and a curved hand trajectory can be generated by synchronizing a translational and a rotational velocity of the hand with the TBG signal. Furthermore, Tsuji et al. [9] [10] applied the TBG to the control of a non-holonomic robot and a redundant manipulator. Tanaka et al. [11] developed a trajectory generation method based on the artificial potential field approach with the combination of time scale transformation and the TBG.

The present paper proposes a rehabilitation aid for reaching movements that supports the training for dynamic behavior of the hand as well as spatial one, where the trajectory generated by the TBG with features of healthy persons is used as the target trajectory of a robotic aid. In the training with the proposed aid, a trainee moves the handle attached on an impedance controlled robot from a point to another, and the robotic aid assists trainee's hand movements so as to follow the given target trajectory. Also, a prototype for the motor control disorder is developed in this paper.

This paper is organized as follows: Section 2 describes a TBG based trajectory generation method. In section 3, a proposed rehabilitation aid with robot is explained in detail. Finally, the validity of the proposed system is shown through training experiments,

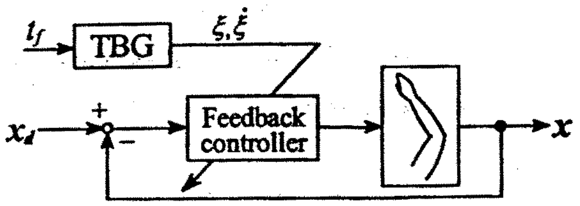


Fig.1 Block diagram of the TBG model

with subjects who are in good health, but joints of the upper limb are in bandages to partly restrict their arm motions.

2 Trajectory generation using time base generator

2.1 The TBG model

Figure 1 shows a block diagram of a Time Base Generator (TBG) model [9] [10], where $\xi(t)$ is a non-increasing function called TBG generates a bell-shaped velocity profile satisfying $\xi(0) = 1$ and $\xi(t_f) = 0$ with the convergence time t_f.

The motor controller in this model generates a command signal to synchronize the error between a current position x and a target position x_d with a TBG signal, so that the hand can reach the target with a bell shaped velocity profile at the specified time t_f. However, the human movements on performing an ordinary work in a daily life is often affected by the environment. Therefore, the velocity profile often has some asymmetric distortion. In order to generate such an asymmetric profile as well as a bell shaped one, a new TBG is proposed in this paper.

The dynamics of ξ is defined as follows:

$$\dot{\xi} = -\gamma \xi^{\beta_1}(1-\xi)^{\beta_2}, \tag{1}$$

where γ and β_i $(i = 1, 2)$ are positive constants under $0 < \beta_i < 1$. The temporal profile of the TBG can be adjusted by changing the parameters β_i. When $\beta_1 = \beta_2$, the dynamics reduce to the TBG proposed in [9] [10]. Then, the convergence time t_f can be calculated with the gamma function $\Gamma(\cdot)$ as

$$t_f = \int_0^{t_f} dt = \frac{\Gamma(1-\beta_1)\Gamma(1-\beta_2)}{\gamma\Gamma(2-(\beta_1+\beta_2))}. \tag{2}$$

Thus, the system converges to the equilibrium point $\xi = 0$ in the finite time t_f if the parameter γ is chosen as

$$\gamma = \frac{\Gamma(1-\beta_1)\Gamma(1-\beta_2)}{t_f\Gamma(2-(\beta_1+\beta_2))}. \tag{3}$$

Figure 2 shows the time histories of ξ and $\dot{\xi}$ under the parameter $(\beta_1, \beta_2) = (0.75, 0.5)$, $(0.75, 0.75)$, $(0.5, 0.75)$ with the convergence time $t_f = 2.5$ [s]. It can be seen that the temporal profiles of the TBG is regulated by changing β_i.

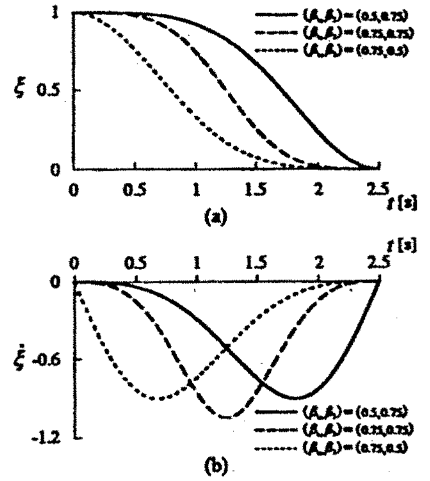


Fig.2 Dynamic behavior of the TBG

2.2 Time scaled artificial potential field

Tanaka et al. [11] have developed a trajectory generation method for robots based on the artificial potential field approach (APFA), with the combination of a time scale transformation and a time base generator (TBG) [8]. Then, it was applied to reproduce the primitive human trajectory of the hand with non-holonomic constraints. In this section, the TBG based trajectory generation method is explained.

The kimenatic system of robot can be described as

$$\dot{x} = G(x)U, \tag{4}$$

where $x \in \Re^n$ is a position vector of robot; $U \in \Re^n$ is an input vector; and it is assumed that det $G(x) \neq 0$.

Here, we define virtual time s for time scaling the system. The relationship between actual time t and virtual time s is given by

$$\frac{ds}{dt} = a(t), \tag{5}$$

where the continuous function $a(t)$ called the time scale function [12] is defined with the TBG as follows:

$$a(t) = -p\frac{\dot{\xi}}{\xi} \tag{6}$$

with a positive constant p.

From (5) and (6), virtual time s can be derived as follows:

$$s = \int_0^t a(t)\, dt = -p \ln \xi(t). \tag{7}$$

It is obvious that virtual time s in (7) can be controlled by ξ and never goes backward against actual time t.

The system given in (4) can be rewritten in virtual time s defined (7) as follows:

$$\frac{dx}{ds} = \frac{dx}{dt}\frac{dt}{ds} = G(x)U_s, \tag{8}$$

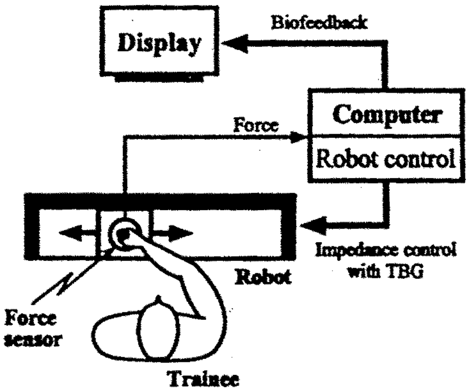


Fig.3 Prototype of a training system

where

$$U_s = \frac{1}{a(t)}U. \tag{9}$$

On the other hand, in the APFA [9] [10], the goal is represented by an artificial attractive potential field which depends on the defined potential function $V(\boldsymbol{x})$ in the task space. The potential function $V(\boldsymbol{x})$ has the minimum value $V(\boldsymbol{x}_d) = 0$ at the target point $\boldsymbol{x}_d$, so that the trajectory to the target can be generated by tracking a unique flow-line of the gradient field through the initial position. By using the inverse time-scaling from virtual time s to actual time t for the feedback controller $\boldsymbol{U}_s$ designed by the APFA, the feedback control law $\boldsymbol{U}$ in actual time t is derived as

$$U = -a(t)G^{-1}(\boldsymbol{x})\frac{\partial V}{\partial \boldsymbol{x}}. \tag{10}$$

With the derived controller U, the system (4) in the actual time scale can be stable to the equilibrium point at the specified time t_f.

In this paper, we propose a rehabilitation aid for a therapeutic treatment of the motion exercise using the generated trajectory with the designed controller in (10).

3 Rehabilitation training for reaching movements using TBG

3.1 Training system

Figure 3 shows the prototype of a TBG based rehabilitation aid. The system is composed of an impedance-controlled robot for applying force to the trainee's hand, a computer for robot control and signal processing, and a display which indicates the training information to the trainee. The linear motor table with one degree of freedom is used as a robot (Nihon tomson coop., maximum force ±10 [kgf]). During the training, hand force generated by the trainee is measured by a six-axis force/torque sensor (BL Autotec Co'Ltd., resolution: force x and y axes: 0.05 [N], z axis: 0.15 [N], torque: 0.003 [Nm]) attached on the handle of robot. Also, the handle position is measured by an encoder built in the linear motor table (resolution: 2 [μm]).

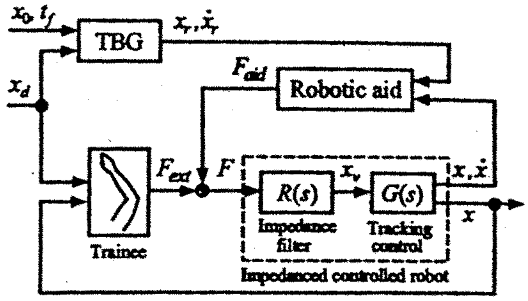


Fig.4 Block diagram of the proposed rehabilitation aid

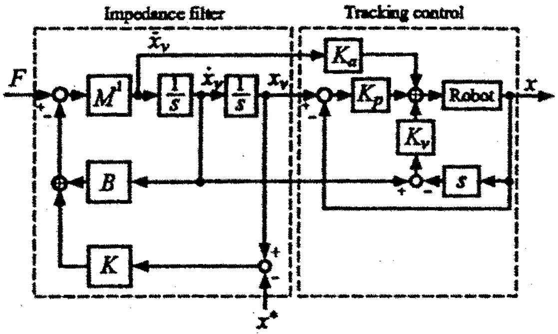


Fig.5 Impedance control of the robot in the training system

In the training, the trainee moves the handle from a point to another as depicted in the display, and the robotic aid works to support trainee's hand movements so as to follow a target spatio-temporal trajectory, which has the similar features of a healthy person's.

The rest of this section describes the control system of the proposed aid and the target trajectory generation with the TBG.

3.2 Impedance controlled robot

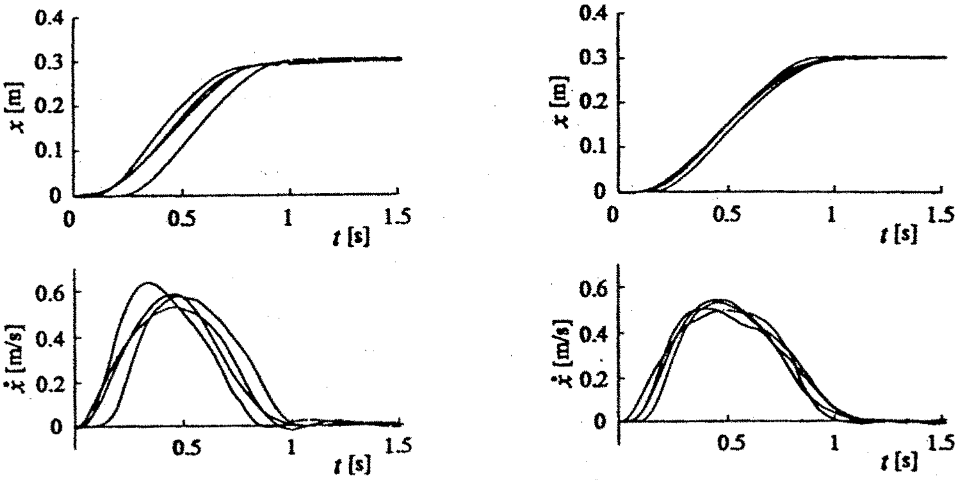
Figure 4 shows the control system of the proposed rehabilitation aid, where x_0 and x_d denote the initial and target positions of the handle, respectively; x_r the target trajectory generated by the TBG based method; F_{ext} the operational force generated by an operator; and F_{aid} the supporting force generated by the robotic aid according to the error between trainee's behavior (x, $\dot{x}$) and target trajectory (x_r, $\dot{x}_r$).

Here, the supporting force F_{aid} is defined as

$$F_{aid} = B_a(\dot{x}_r - \dot{x}) + K_a(x_r - x), \tag{11}$$

where B_a denotes the position feedback gain and K_a the velocity feedback. These gains can be regulated to change the level of assistance according to the trainee's disorder.

Figure 5 shows the block diagram of the robot control part, where x_v is the desired position; x^* the equilibrium point of the stiffness of robot; M the inertia of the end-effector; B the viscosity; and K the stiffness.



(a) $(M, B, K) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m]) (b) $(M, B, K) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m])

Fig.6 Generated trajectories by the subject A under the different robot impedances

The impedance filter computes the robot's desired position x_v from the operational force F_{ext}. Then, x_v arrives at the tracking control block that works to minimize the error between $(x, \dot{x})$ and $(x_r, \dot{x}_r)$ by adjusting the feedback control gains K_p, K_v, K_a.

Under this control scheme, the transfer function of the impedance-controlled robot is given by

$$R(s) = \frac{1}{Ms^2 + Bs + K}. \qquad (12)$$

Regulating the impedance parameters M, B, K, an operating load of the handle to a trainee can be changed. For example, with the stiffness $K = 0$ [N/m], the motion during the training leads to reaching movements. On the other hand, when $K \neq 0$ [N/m], the pulling motion of the handle against the spring can be considered as muscle training.

3.3 Bio-mimetic trajectory generation with TBG

In the training with the prototype, the degree of freedom of the hand movements is one, so that its kinematics can be written as

$$\dot{x} = u, \qquad (13)$$

where $\dot{x}$ is the velocity of hand, and u the control input. For this system, the following potential function V so as to design a feedback controller is defined:

$$V = \frac{1}{2}x^2. \qquad (14)$$

From (10), the feedback controller u based on the potential function V (14) can be derived as

$$u = -\frac{1}{2}a(t)x. \qquad (15)$$

Under this control input, the following dynamics of hand is realized:

$$x = x_0\xi^{\frac{\beta}{2}}. \qquad (16)$$

It can be seen that the dynamics of hand movements is "synchronized" with the TBG because x is proportional to the $\frac{\beta}{2}$th power of ξ.

Consequently, a target trajectory for robotic aid in the training can be generated by (16) with the regulation of the TBG parameters, β_1, β_2, t_f, according to a healthy person's trajectory.

4 Experiments

4.1 Typical trajectory of healthy persons

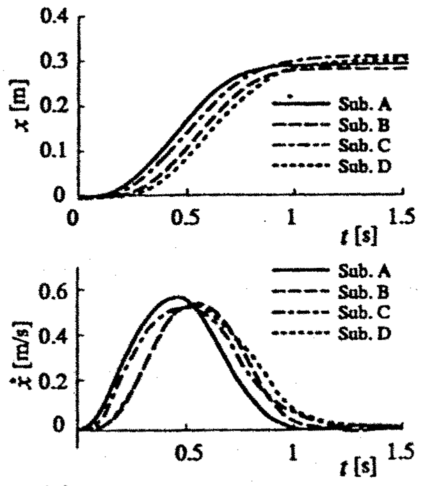
The proposed rehabilitation aid for reaching movements uses the trajectory with features of the healthy person's movements as the target trajectory for the robotic aid. First, in order to reveal what kind of hand trajectories a healthy person generates, the trajectory generation experiments were carried out with the healthy and skillful persons (four male university students).

Figures 6, 7 show typical examples of the observed spatial trajectories and the velocity profiles of the hand, where the robot impedance parameters were set as $(M, B, K) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m]) and (1.5 [Kg], 30 [Ns/m], 0 [N/m]) under $(K_a, K_v, K_p) = (0.0$ [Ns^2/m], 100 [Ns/m], 675 [N/m]). In the experiments, the subjects were instructed to move the handle to the target point which is 0.3 [m] away from the initial.

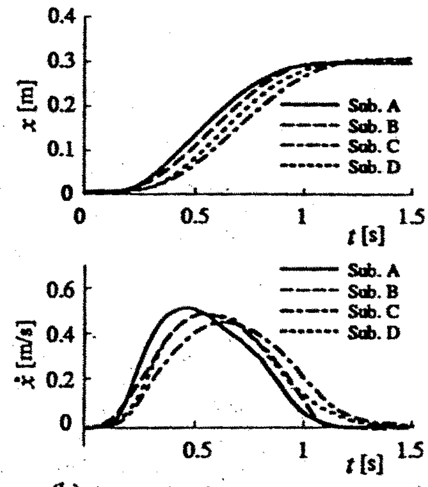
It can be observed from Fig. 6 that the subject A generates the single-peaked velocity profiles, and the motion duration to the target tends to be longer as the load of hand is larger. The same features can be seen in the generated trajectories by all subjects as shown in Fig. 7, although there are small differences between the subjects. Through the observation of reaching movements, it is shown that the skillful person can generate the stable trajectory with a single-peaked velocity profile during the operation of the impedance controlled robot.

4.2 Target trajectory for a robotic aid

In the previous section, the trajectories of a healthy person on manipulation of the robot were measured.



(a) $(M, B, K) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m])



(b) $(M, B, K) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m])

Fig.7 Generated trajectories by the subjects under the different robot impedances

Next, we attempt to reproduce the trajectories which have similar features of the observed trajectories using the TBG method.

Figure 8 shows the trajectories generated by the TBG based method with the mechanical impedance parameter $(M, B, K) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m]), (3.0 [Kg], 60 [Ns/m], 0 [N/m]). The TBG parameters β_1, β_2 and the movement time t_f were estimated by the non-linear regression analysis with the observed trajectories in Fig. 7. It can be seen from Fig. 7 and Fig. 8 that the generated trajectories are similar to the healthy person's.

4.3 Rehabilitation training of motor control

In order to show the validity of the proposed rehabilitaion aid for reaching movements, the experiments with the subjects (two male university students) were carried out by using the generated tratectory with the TBG. The subjects were healthy but unpracticed in operating the system, and their wrist and elbow joints were in bandages to partly restrict arm movements.

Figure 9 shows the spatio-temporal trajectories generated by the subject and the time courses of the supporting forces F_{aid} by the robotic aid with the different gains such as (B_a [Nm/s], K_a [N/m]) = (0, 0), (25, 20), (50, 100), (100, 200) under the robot impedance parameter $(M, B, K) = (1.5$ [Kg],30 [Ns/m], 0 [N/m]). In the experiment, the target trajectories shown by the fine lines in Fig. 9 (a), (b) were used as the target ones x_r, $\dot{x}_r$ for the robotic aid.

It can be observed from Fig. 9 that the trainee's spatio-temporal trajectories becomes more similar to the trajectory of the healthy person shown in Fig. 6, 7, as the support of robotic aid increases.

5 Conclusions

In this paper, the rehabilitation aid for reaching movements using the TBG has been proposed. Then, the prototype for a physically handicapped person in motor functional disorder has been developed with the impedance controlled robot. The training experiments were carried out with the subjects whose joints of the arm are partly restricted, and the validity of the proposed method was shown.

However, there are several problems for developing a practical system, such as the safety of system and an algorithm of parameter adjustment of the robotic aid according to the level of tranee's disorder. Future research will be directed to extend the system function so as to set impedance parameters according to the tranee.

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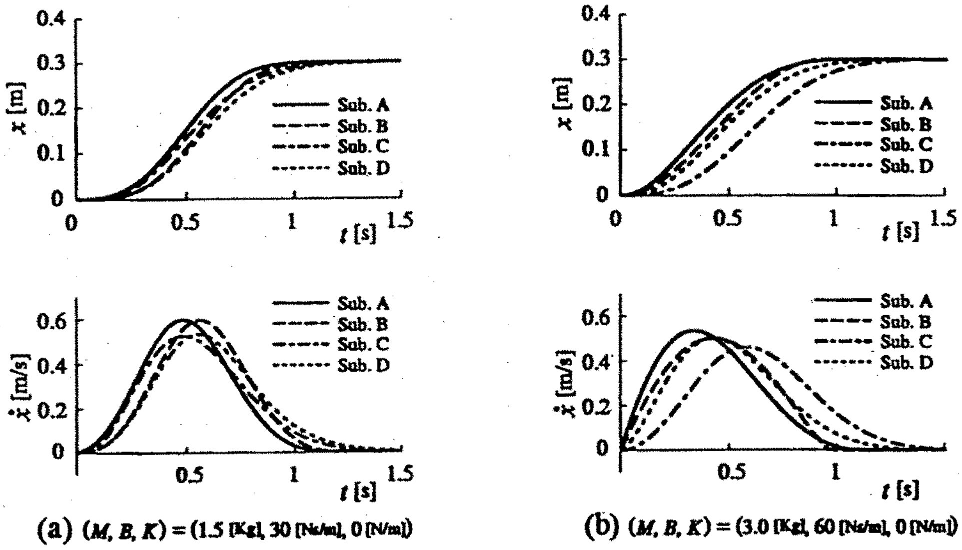

Fig.8 Target trajectories generated by the TBG for the robotic aid

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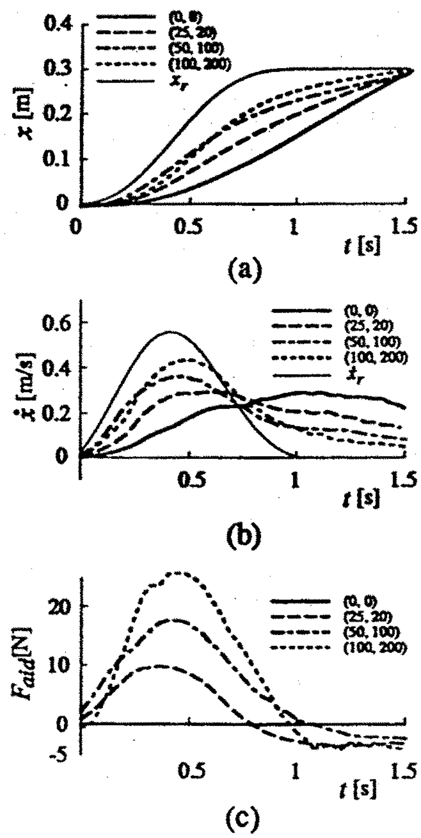

Fig.9 Generated trajectories by the subject whose some joints of the upper limb are restricted by bandages