

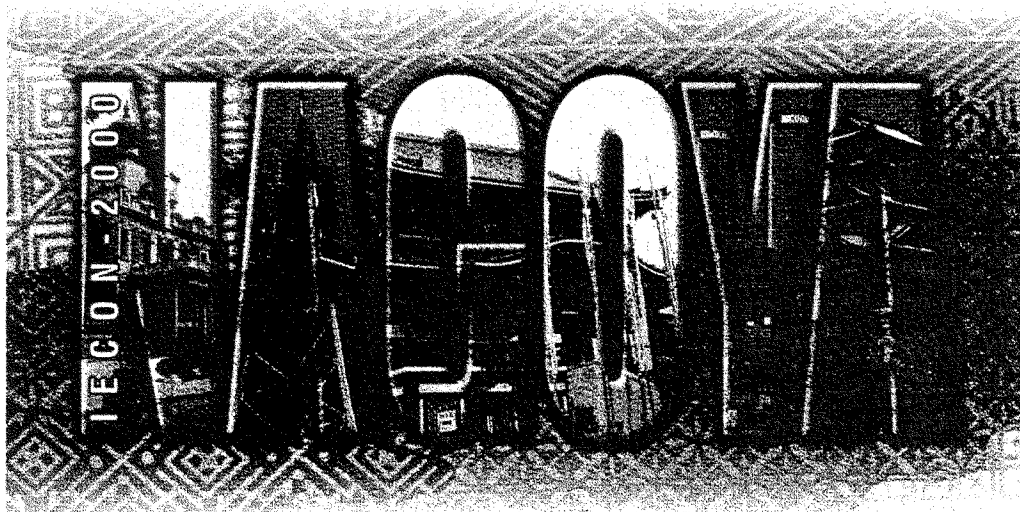
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# A Bio-mimetic Rehabilitation Aid for Motor Control Training using Time Base Generator

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## Abstract

*In this paper, a rehabilitation aid for reaching movements is proposed with an impedance controlled robot using a Time Base Generator (TBG). The TBG generates a target spatio-temporal trajectory for the robot, which has the same features as a healthy person has. In the proposed training, a trainee is instructed to move a handle attached on the robot to a target point based on biofeedback information, and the robot assists him or her according to trainee's motor control ability. To show effectiveness of the proposed training system, training experiments are carried out with healthy persons whose joints of the upper limb are partly restricted by bandages.*

**Key Words:** Rehabilitation, human movements, robot application, impedance control.

## 1 Introduction

Robots, in particular industrial robots, have been mainly used in limited environments where a robot does not need to consider about contact with a human. However, directing our attention to current problems of medical welfare such as undesirable social conditions for the handicapped and serious shortage in homecare in the coming aging-society, we naturally expect that robots will be able to cooperate with a handicapped person and assist his or her daily activities in the near future.

Ordinary medical treatments for motor functional disorder of extremities are carried out with some training apparatus through a dialog between a patient and a therapist. However, it is sometimes difficult to examine therapeutic effects objectively. Moreover, without the therapist, the patient cannot continue on effective training.

Recently, for the purpose of improving the present situation, a number of training and rehabilitation systems using robots have been developed. Especially, to support a joint motion exercise for prevention and improvement of joint contraction and muscle atrophy, studies on a Continuous-Passive-Motion (CPM) device [1], which moves joints of a patient passively, has

been actively performed. For instance, Sakaki et al. [2] and Okajima et al. [3] have developed the impedance-controlled CPM device which can realize a compliant motion exercise. Also, Krebs et al. [4] have developed a training system for upper limb movements through operating an end-effector of an impedance controlled robot according to a target pattern, such as a circle, shown in a computer display. However, in these previous training systems, it is difficult to offer efficient training for realizing a smooth motion like a healthy person because time-related characteristics of motion such as a velocity profile and a movement time are not used as a training goal.

On the other hand, there have been many studies on the motor control mechanism of human arm [5]-[9]. For example, Morasso [5] measured reaching movements of a 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 a starting point to a goal point. As an explanation for the trajectory generation mechanism of human arm, many models have been proposed: for example, "a minimum jerk model" [6], "a minimum torque-change model" [7] and "a VITE model" [8]. The first and the second models assert that the underlying mechanism is a feedforward control system, and the other deals it as a feedback. All of these models can generate the straight line trajectory in good agreement with experimental data by computer simulations.

Also, Morasso et al. [9] proposed a Time Base Generator (TBG) which generates a time-series with a bell-shaped velocity profile, and showed that not only a straight line trajectory but also a curved trajectory can be generated by synchronization of translational and rotational velocities of the hand with the TBG signal. Furthermore, Tsuji et al. [10] [11] applied the TBG to a motion planning problem of a non-holonomic robot and a redundant manipulator. Tanaka et al. [12] developed a trajectory generation

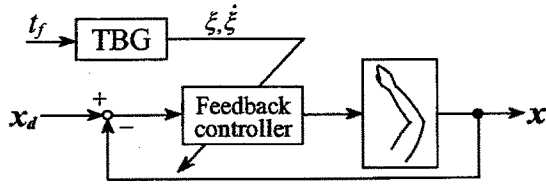


Fig. 1: Block diagram of the TBG model

method based on the artificial potential field approach with the combination of the time scale transformation [13] and the TBG.

Then, Tanaka et al. [14] have been proposed a rehabilitation aid for reaching movements with an impedance controlled robot using the TBG. The proposed robotic aid assists a trainee's movement so as to follow a target spatio-temporal trajectory generated by the TBG, which has the similar features to those of healthy person's hand trajectories. However, for more practical applications, it has been necessary to define an assistant quantity which can be adjusted according to trainee's motor ability. In the present paper, a new effective training system is developed by rebuilding the control system of the robotic aid proposed in [14].

This paper is organized as follows: Section 2 explains the artificial potential approach which built in a time scale transformation method using the TBG for control of a robot. In section 3, the outline of the prototype of the proposed training system is described. Finally, validity of the proposed system is shown through training experiments with subjects who are in good health, but restricted their arm motion partly by bandages.

## 2 Trajectory generation using time base generator

### 2.1 The TBG model

Figure 1 shows the block diagram of a human arm motion model using a Time Base Generator (TBG) [10] [11], where  $\xi(t)$  is a non-increasing function. The TBG generates a bell-shaped velocity profile satisfying  $\xi(0) = 1$  and  $\xi(t_f) = 0$  with the convergence time  $t_f$ .

The feedback controller in Fig. 1 outputs a command in such a way that an error between a current position  $x$  and a target position  $x_d$  is forced to synchronize in a TBG signal, so that a human hand can reach the target with a bell shaped velocity profile at the specified time  $t_f$ . However, the human arm movements on performing an ordinary work in a daily life are often affected by an environment so that the velocity profile often has some asymmetric distortion. Then, in this paper, a TBG considering the generation of asymmetric profiles [14] is used. The dynamics

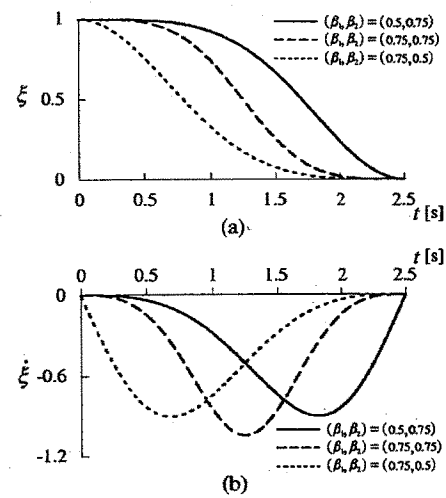


Fig. 2: Dynamic behavior of the TBG

of  $\xi$  is defined as follows:

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

where  $\gamma$  and  $\beta_i$  ( $i = 1, 2$ ) are positive constants under  $0 < \beta_i < 1$ . The temporal profile of the TBG can be adjusted by changing the parameters  $\beta_i$ . When  $\beta_1 = \beta_2$ , the dynamics reduce to the TBG proposed in [10] [11]. Then, the convergence time  $t_f$  can be calculated with the gamma function  $\Gamma(\cdot)$  as

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

Thus, the system converges to the equilibrium point  $\xi = 0$  in the finite time  $t_f$  if the parameter  $\gamma$  in (1) is chosen as

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

Figure 2 shows the time histories of  $\xi$  and  $\dot{\xi}$  using the parameters  $(\beta_1, \beta_2) = (0.75, 0.5)$ ,  $(0.75, 0.75)$  and  $(0.5, 0.75)$  with the convergence time  $t_f = 2.5$  [s]. It can be seen that the temporal profile of the TBG can be regulated by changing  $\beta_i$ , and the asymmetric velocity profile can be generated.

### 2.2 Time scaled artificial potential field

Tanaka et al. [12] have developed a trajectory generation method for robots which can generate human-like trajectories by combining the time scale transformation using the TBG with the artificial potential approach (APFA). In this section, the trajectory generation method using the TBG model based on a human arm motion mechanism is explained.

Generally, the kinematics of robot can be described as

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

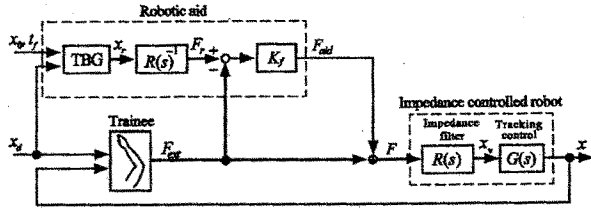


Fig. 3: Block diagram of a proposed rehabilitation aid

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

Here, we define virtual time  $\nu$  for time scaling the system. The relationship between actual time  $t$  and virtual time  $\nu$  is defined using a TBG signal  $\xi(t)$  with a positive constant  $p$  by

$$a(t) = \frac{d\nu}{dt} = -p \frac{\dot{\xi}}{\xi}, \quad (5)$$

where the continuous function  $a(t)$  is called the time scale function [12].

From (1) and (5), virtual time  $\nu$  can be derived as follows:

$$\nu = \int_0^t a(t) dt = -p \ln \xi(t). \quad (6)$$

It is obvious that virtual time  $s$  in (6) can be controlled by  $\xi$  and never goes backward against actual time  $t$ . Then, the system given in (4) can be rewritten in virtual time  $\nu$  defined (6) as follows:

$$\frac{dx}{d\nu} = \frac{dx}{dt} \frac{dt}{d\nu} = G(x)U_\nu, \quad (7)$$

where

$$U_\nu = \frac{1}{a(t)}U \in \mathbb{R}^n. \quad (8)$$

On the other hand, the APFA [10] [11] sets a potential function  $V(x)$  which includes the minimum at the goal position  $x_d$  in the task space. Then, by applying a virtual attractive force to the goal position, the robot can reach the target. By using inverse time-scaling from virtual time  $\nu$  to actual time  $t$  for the feedback controller  $U_\nu$  designed by the APFA in virtual time  $\nu$ , the feedback control law  $U$  in actual time  $t$  is derived as

$$U = -a(t)G^{-1}(x) \frac{\partial V}{\partial x}. \quad (9)$$

By using the derived controller  $U$ , the system (4) in the actual time scale can be stable to the equilibrium point at the specified time  $t_f$ . That is, the generation of spatio-temporal trajectories from the initial position to the target position becomes possible.

In this paper, utilizing the generated trajectory with the designed controller in (9), a rehabilitation aid for a therapeutic treatment of the motion exercise is constructed.

### 3 Rehabilitation training for motor control using TBG

#### 3.1 Impedance controlled robotic aid

Figure 3 shows the block diagram of a proposed rehabilitation aid. In the training, a trainee moves a handle position  $x \in \mathbb{R}^n$  of an impedance controlled robot from an initial point  $x_0$  to a target point  $x_d$  by applying the hand force  $F_{ext} \in \mathbb{R}^n$  to the robot. On the other hand, in order to make the trainee's hand follow a target trajectory  $x_r \in \mathbb{R}^n$  generated by the TBG, the robotic aid assists a trainee's movement with an assistant force  $F_{aid} \in \mathbb{R}^n$  which is produced on the basis of  $x_r$ .

The dynamics of the impedance controlled robot can be described as

$$M\ddot{x} + B\dot{x} + K(x - x_0) = F_{ext} + F_{aid}, \quad (10)$$

where  $M \in \mathbb{R}^{n \times n}$ ,  $B \in \mathbb{R}^{n \times n}$ ,  $K \in \mathbb{R}^{n \times n}$  denotes the inertia, the viscosity and the stiffness matrix of the end-effector, respectively. 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 reduces 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. In the system, the target force  $F_r$  is calculated with the following equation:

$$F_r = M\ddot{x}_r + B\dot{x}_r + K(x_r - x_0). \quad (11)$$

Then, the assistant force  $F_{aid}$  for the robotic aid in the training is defined with the trainee's hand force  $F_{ext}$  and the target force  $F_r$  as follows:

$$F_{aid} = K_f(F_r - F_{ext}), \quad (12)$$

where  $K_f = \text{diag.}(k_{f1}, k_{f2}, \dots, k_{fn}) \in \mathbb{R}^{n \times n}$  is the assistant gain matrix for regulating an assistant quantity in the training under  $0 \leq k_{fi} \leq 1$  ( $i = 1, 2, \dots, n$ ). When  $K_f = I$  or when the trainee can generate the target force trajectory  $F_r$ , the dynamics of robot handle follows the given target spatio-temporal trajectory. By adjusting  $K_f$  to each trainee, the training considering trainee's motion characteristics can be realized.

Figure 4 shows the block diagram of the robot control part, where  $x_v \in \mathbb{R}^n$  is the desired position, and  $x^* \in \mathbb{R}^n$  the equilibrium point of the stiffness of robot. The impedance filter computes the robot's desired position  $x_v$  from the control input  $F$  which is the sum of hand force  $F_{ext}$  and assistant force  $F_{aid}$ . Then,  $x_v$  arrives at the tracking control block that works to minimize the error between  $(x, \dot{x})$  and  $(x_v, \dot{x}_v)$  by adjusting the feedback control gains  $K_p$ ,  $K_v$ ,  $K_a$ .

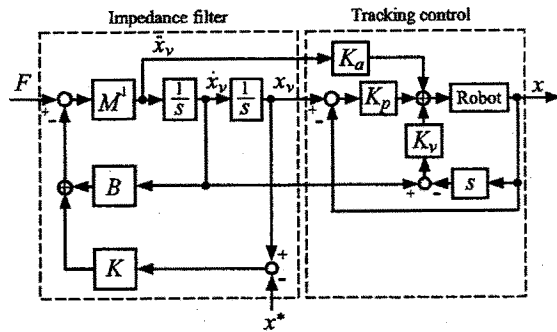


Fig. 4: Impedance control of a robot in the training system

## 4 Experiments

### 4.1 Prototype of training system

Figure 5 shows the prototype of a TBG based rehabilitation aid. The system is composed of an impedance-controlled robot for applying force to a trainee's hand, a computer for robot control and signal processing, and a display which indicates training information to the trainee. The robot is composed of two linear motor tables with one degree of freedom (Nihon Tomson Coop., maximum force  $\pm 10$  [kgf]; and Nihon Seikou Coop., maximum force  $\pm 40$  [kgf]), which are placed orthogonally in order to carry out the two-dimensional hand motion exercise. During 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: Nihon Tomson Coop., 1.0 [ $\mu\text{m}$ ]; and Nihon Seikou Coop., 1.0 [ $\mu\text{m}$ ]).

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

To show effectiveness of the proposed training system, experiments were carried out with subjects by using the prototype. In order to simplify the discussion, the motion direction of hand was limited to the  $x$  axial direction (See Fig. 5).

### 4.2 Bio-mimetic trajectory generation using TBG

The kinematics of a human hand towards the  $x$  direction can be described as

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

where  $\dot{x}$  denotes the velocity of the hand, and  $u$  the control input.

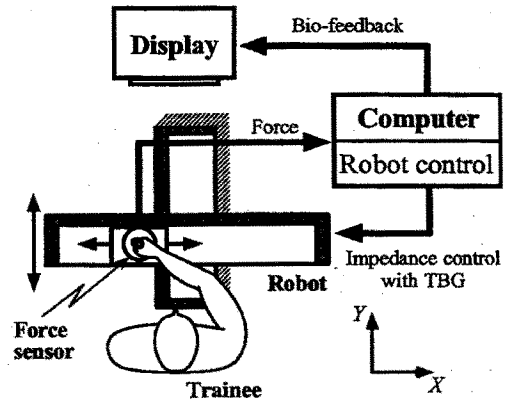


Fig. 5: Prototype of a training system

By time-scaling from actual time  $t$  to virtual time  $\nu$  for the system (13), the system in  $\nu$  can be written as

$$\frac{dx}{d\nu} = \frac{1}{a(t)}u. \quad (14)$$

For the system (14), the following potential function  $V_\nu$  with the equilibrium point  $x_\nu^* = 0$  is defined:

$$V_\nu = \frac{1}{2}x_\nu^2. \quad (15)$$

From (9), the feedback controller  $u$  for the system (13) can be designed as

$$u = -\frac{1}{2}a(t)x. \quad (16)$$

Substituting the controller (16) into (13) with (5), the following differential equation can be derived as

$$\frac{\dot{x}}{x} = \frac{p\xi}{2\xi}. \quad (17)$$

Solving the above differential equation for  $x$ , the dynamic behavior in the  $x$  coordinate of the hand is represented by

$$x = x_0\xi^{\frac{p}{2}}, \quad (18)$$

where  $x_0$  is the initial point of the hand. It can be seen that the hand behavior  $x$  synchronizes with the TBG signal. Then, since  $\lim_{t \rightarrow t_f} \xi(t) = 0$ , the hand can reach the target point at the specified time  $t_f$ .

In the experiment, a target trajectory for robotic aid is generated by (18) with the regulation of the TBG parameters  $\beta_1, \beta_2$  and the movement time  $t_f$  according to a healthy person's trajectory.

### 4.3 Typical trajectory of a healthy person

The proposed rehabilitation aid for reaching movements uses trajectories with features of healthy person's movements as target trajectories for training.

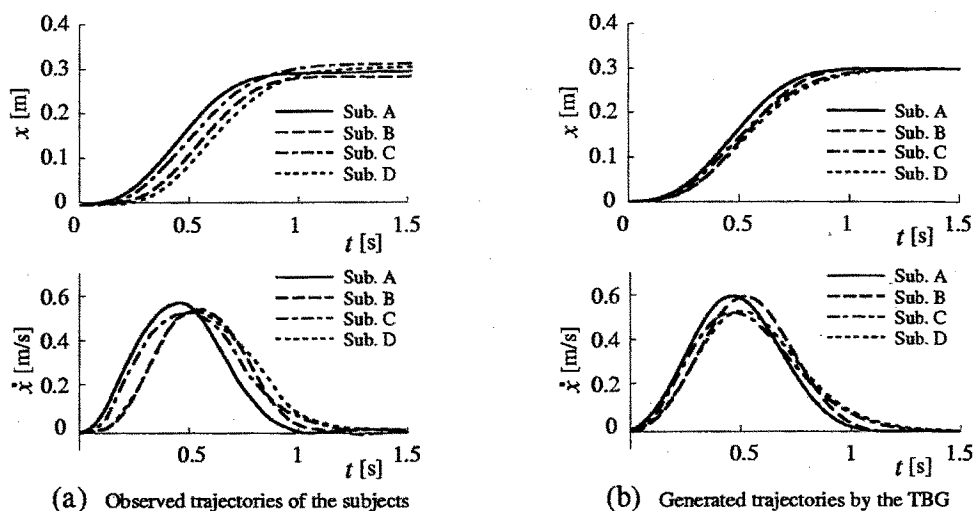


Fig. 6: Typical trajectories of the healthy persons and modeled trajectories with the TBG under  $(M, B, K) = (1.5 \text{ [kg]}, 30 \text{ [Ns/m]}, 0 \text{ [N/m]})$

First, in order to reveal what kind of hand trajectories a healthy person generates, trajectory generation experiments were carried out with healthy and skillful persons (four male university students).

Figures 6 (a) shows typical examples of the observed spatial trajectories and the velocity profiles of the hand, where the robot impedance parameters were set as  $(1.5 \text{ [Kg]}, 30 \text{ [Ns/m]}, 0 \text{ [N/m]})$ . In the experiments, the subjects were instructed to move the handle to the target point which is  $0.3 \text{ [m]}$  away from the initial.

It can be observed from Fig. 6 (a) that the subjects generates the single-peaked velocity profiles although there are small differences among the subjects. Through the observation of reaching movements, it is shown that a skillful person can generate a stable trajectory during the operation of the impedance controlled robot.

#### 4.4 Modeling of human hand trajectory with TBG

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

Figure 6 (b) shows the trajectories generated by the TBG based method with the mechanical impedance parameter  $(M, B, K) = (1.5 \text{ [Kg]}, 30 \text{ [Ns/m]}, 0 \text{ [N/m]})$ . The TBG parameters  $\beta_1, \beta_2$  and the movement time  $t_f$  were estimated by the non-linear regression analysis with the observed trajectories in Fig. 6 (a). It can be seen that the generated trajectories are similar to the healthy person's as shown in Fig. 6.

In the training, the robotic aid assists trainee's hand movements by using the trajectories generated by the TBG based method.

#### 4.5 Rehabilitation training for upper limb movement

In order to show validity of the proposed rehabilitation aid for reaching movements, experiments with subjects (three male university students) were carried out by using the generated trajectory 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 7 shows the spatio-temporal trajectories generated by the subjects and the time courses of the assisting forces  $F_{aid}$  by the robotic aid with the different assistant gains ( $K_f = 0, 0.25, 0.5, 1.0$ ). In the experiment, the target trajectories shown by the fine lines in Fig. 7 (a), (b) were used as the target ones  $x_r, \dot{x}_r$  for the robotic aid, and the robot impedance parameter was set at  $(M, B, K) = (1.5 \text{ [Kg]}, 30 \text{ [Ns/m]}, 0 \text{ [N/m]})$ .

It can be observed from Fig. 7 that the trainee's spatio-temporal trajectories becomes closer to the trajectory of the healthy person shown in Fig. 6 (a), as the assistant gain of robotic aid increases.

#### 5 Conclusions

In this paper, the rehabilitation system for motor control disorder using the TBG has been proposed. The robotic aid in the system can regulate the assistant quantity according to the trainee's motor ability. Then, the prototype for reaching movements has been developed with the impedance controlled robot. Also, through the training experiments with the subjects whose joints of the arm are partly restricted, the validity of the proposed method was shown.

Future research will be directed to consider how

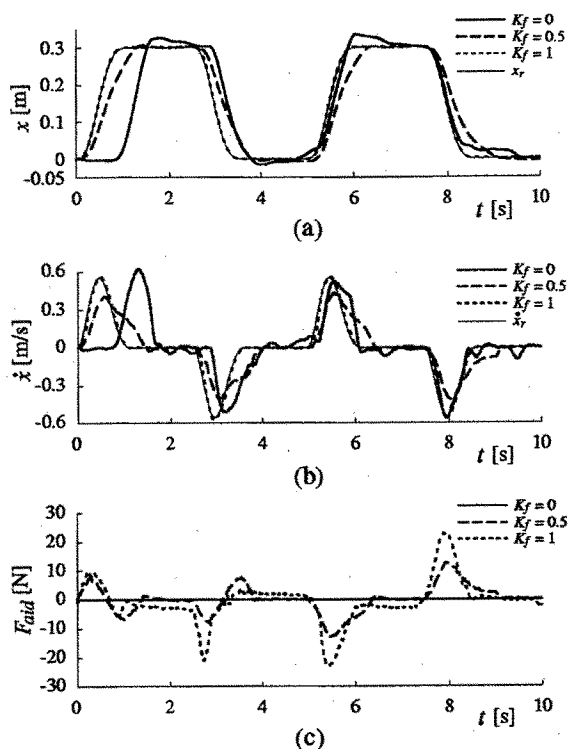


Fig. 7: Generated trajectories by the subjects with robotic assistance

much and when the robot should assist each trainee during training, and also will analyze the training effectiveness with handicapped patients for developing a practical system.

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