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Paper

A Bio-mimetic Rehabilitation Aid for Reaching Movements Using Time Base Generator*

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Abstract: In this paper, a new rehabilitation aid for reaching movements is proposed with an impedance-controlled robot using a Time Base Generator (TBG) model. The proposed system generates a bio-mimetic trajectory for the robotic aid, which has the same dynamic behaviors of a healthy operator. The robotic therapist assists trainee's movement based on the generated target trajectory with adaptation to the trainee's motor control capability. Also, a prototype system for upper-limb movements is constructed, and training experiments with a patient of *cerebellar ataxia* are performed to show the validity of the proposed robot-aided training system inspired by the biological motor control mechanism.

Keywords: 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 that can realize compliant motion exercise. Krebs *et al.* [4] 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. 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. Also, some robot-aided training approaches considering kinetic properties of movements have been proposed [5]–[7]. However, since these systems use the recorded data of movements by the healthy operator as a desired movement, it is difficult to provide compliant training considering individual differences among patients such as the physical feature and the joint motion range.

On the other hand, there have been many studies on the motor control mechanism of human arm [8]–[12]. For example, Morasso [8] 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" [9], "a minimum torque-change model" [10] and "a VITE model" [11]. 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.* [12] proposed a Time Base Generator (TBG) that 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.* [13], [14] applied the TBG to a motion-planning problem of a non-holonomic robot and a redundant manipulator. Then, Tanaka *et al.* [15] developed a trajectory generation method based on the artificial potential field approach (APFA) with the combination of the time scale transformation and the TBG. They had succeeded in generating a human-like hand trajectory on the nonholonomic constrained task [16].

In this paper, a new rehabilitation aid for reaching movements based on a biological motor control mechanism is proposed by using the TBG [17], [18]. The training system is constructed in such a way that a trainee operates an impedance-controlled robotic device during training, while

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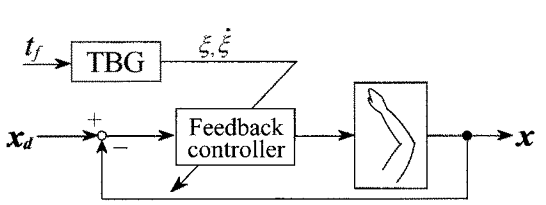


Fig. 1 Block diagram of the TBG model

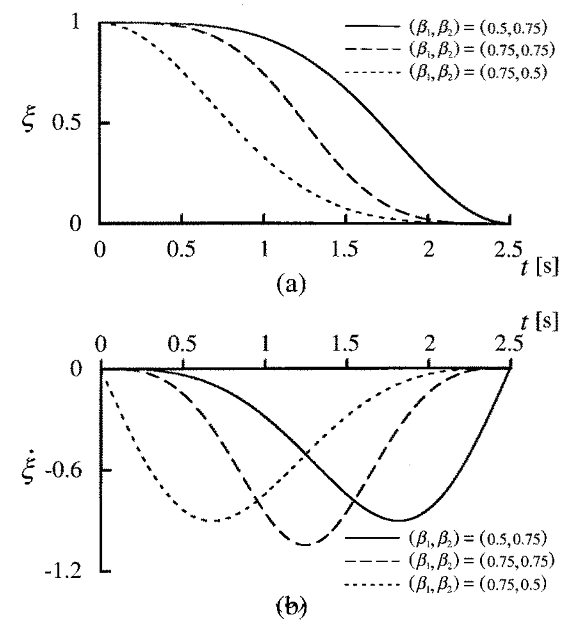


Fig. 2 Dynamic behavior of the TBG

the robot assists the trainee's movements with reference to a given target trajectory with adaptation to trainee's motor control capability. The target trajectory for a robotic aid is generated with the TBG based on the dynamic features of a healthy person's movements, so that the training considering dynamic behaviors can be provided to a trainee. The extent of assistant to the trainee can be adjusted in order to provide various training. Also, a prototype system for upper-limb movements is constructed, where two-dimensional motion training is possible.

This paper is organized as follows: First, the bio-mimetic trajectory generation method of robots using the TBG is explained in Section 2. Then, the bio-mimetic rehabilitation system using the TBG method for disabled motor control functions is proposed in Section 3. Finally, the validity of the proposed training approach is investigated through the training experiments with a patient of *cerebellar ataxia* in Section 4.

2. Bio-mimetic Trajectory Generation Method Using Time Base Generator

This section expresses a bio-mimetic trajectory generation method for robotic systems [15], [16]. The basic idea of the method is to compress a time scale of the controlled system with a TBG according to the specified convergence time in the actual time scale, and to design the asymptotic stabilizer for the time scaled system with an artificial potential field approach (APFA).

2.1 Time base generator

Figure 1 shows a control model of hand reaching movements using the TBG [12], where $\xi(t)$ is a non-increasing function of time. 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 $\boldsymbol{x}$ and a target position $\boldsymbol{x}_d$ is forced to synchronize with the TBG signal, so that a human hand can reach the target with a bell-shaped velocity profile at the specified time t_f.

The dynamics of ξ, considering generation of asymmetric bell-shaped profiles, is defined as follows [16]:

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

where the parameters γ and β_i $(i = 1, 2)$ are positive constants under $0 < \beta_i < 1$. The velocity profile of the TBG can be adjusted by changing β_i, while the convergence time t_f is calculated with the parameter γ and 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 γ in (1) 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 time histories of ξ 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 a velocity profile of the TBG signal can be regulated by changing β_i so that the asymmetric profile as well as the symmetric profile can be generated.

2.2 TBG built-in control laws

Generally, the kinematics of non-redundant robots can be described as

$$\dot{\boldsymbol{X}} = \boldsymbol{\Lambda}(\boldsymbol{X})\boldsymbol{U} \tag{4}$$

where $\boldsymbol{X}, \boldsymbol{U} \in \Re^n$ are the state variable vector and the input vectors of the system, respectively, and it is assumed that $\det \boldsymbol{\Lambda}(\boldsymbol{X}) \neq 0$.

The time scale compression of the system with the TBG can be realized by the time scale transformation [19] with the virtual time scale whose infinite time corresponds to a specified finite time t_f of the TBG in the actual time scale. Then, the relationship between actual time 't' and virtual time 'ν' is given by

$$\frac{d\nu}{dt} = a(t) \tag{5}$$

where the continuous function $a(t)$ is called a time scale function. In order to compress the time scale of the system with the TBG, the time scale function $a(t)$ is defined as

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

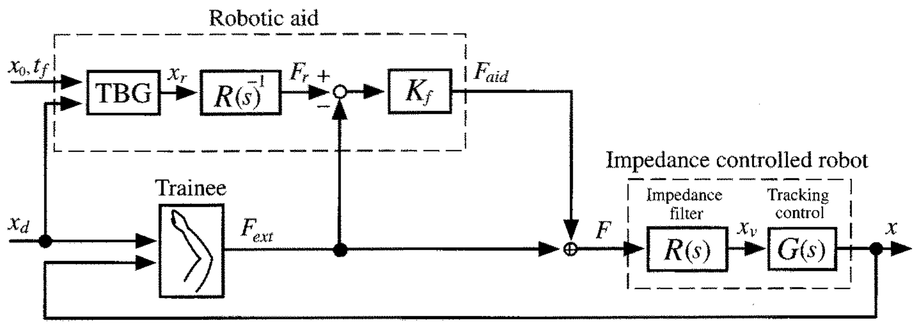


Fig. 3 Block diagram of the proposed rehabilitation aid

where p is a positive constant. From (5) and (6), the virtual time ν can be represented with respect to ξ as follows:

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

The parameter p can regulate the transformation of the time axis. The compressibility of the time axis becomes larger near the specified time as p decreases, while it becomes uniform in all the time as p increases. Generally, the stability and dynamic property of systems do not change in any time scale when a strictly monotone increasing function with respect to the actual time is used as the time scale function. It is obvious that the virtual time ν given in (7) never goes backward against the actual time t, so that the virtual time ν is used as a new time scale in time scale transformation of the original system (4) in order to derive the proposed controller.

Then, the system given in (4) can be rewritten in virtual time ν defined by (7) as follows:

$$\frac{d\boldsymbol{X}}{d\nu} = \frac{d\boldsymbol{X}}{dt}\frac{dt}{d\nu} = \boldsymbol{\Lambda}(\boldsymbol{X})\boldsymbol{U}_\nu \tag{8}$$

where

$$\boldsymbol{U}_\nu = \frac{1}{a(t)}\boldsymbol{U} \in \Re^n. \tag{9}$$

On the other hand, the APFA [13], [14] sets a potential function $V_X(\boldsymbol{X})$ which includes the minimum at a goal position $\boldsymbol{X}_d \in \Re^n$ in the task space. By applying a virtual attractive force to the goal position, the robot can reach the target in infinite time. An example of such a feedback controller $\boldsymbol{U}_\nu$ is given as

$$\boldsymbol{U}_\nu = -\boldsymbol{\Lambda}^{-1}(\boldsymbol{X})\left(\frac{\partial V_X}{\partial \boldsymbol{X}}\right)^T. \tag{10}$$

By inverse time-scaling from virtual time ν to actual time t for the feedback controller $\boldsymbol{U}_\nu$ designed by the APFA in virtual time ν, a feedback control law $\boldsymbol{U}$ in actual time t is derived as

$$\boldsymbol{U} = -a(t)\boldsymbol{\Lambda}^{-1}(\boldsymbol{X})\left(\frac{\partial V_X}{\partial \boldsymbol{X}}\right)^T. \tag{11}$$

With the derived controller $\boldsymbol{U}$, the system (4) in the actual time scale converges the equilibrium point at the specified time t_f.

The TBG built-in controller can generate a smooth trajectory with characteristics of human movements, and can control kinetic properties such as the movement time and the velocity profile by adjusting the TBG parameters without any change of the form of the designed controller.

3. Bio-mimetic Rehabilitation Aid for Reaching Movements

A bio-mimetic rehabilitation aid using the TBG method is proposed in this section. The system can provide training exercises of reaching movements considering smoothness with adaptation to trainee's motor control capability.

3.1 Control system

Figure 3 shows the block diagram of a proposed rehabilitation aid in the n-dimensional reaching movements. In the training, a trainee moves a handle position $\boldsymbol{x} \in \Re^n$ of an impedance controlled robot from an initial point $\boldsymbol{x}_0 \in \Re^n$ to a target point $\boldsymbol{x}_d \in \Re^n$ by applying the hand force $\boldsymbol{F}_{ext} \in \Re^n$ to the robot. On the other hand, in order to make the trainee's hand follow a target trajectory $\boldsymbol{x}_r \in \Re^n$ generated by the TBG, the robotic aid assists trainee's movements with an assistant force $\boldsymbol{F}_{aid} \in \Re^n$ which is produced on the basis of $\boldsymbol{x}_r$.

The dynamics of the impedance controlled robot can be described in the n-dimensional task space as

$$\boldsymbol{M}_e\ddot{\boldsymbol{x}} + \boldsymbol{B}_e\dot{\boldsymbol{x}} + \boldsymbol{K}_e(\boldsymbol{x} - \boldsymbol{x}_e) = \boldsymbol{F} \tag{12}$$

$$\boldsymbol{F} = \boldsymbol{F}_{ext} + \boldsymbol{F}_{aid} \tag{13}$$

where $\boldsymbol{M}_e \in \Re^{n\times n}$, $\boldsymbol{B}_e \in \Re^{n\times n}$, $\boldsymbol{K}_e \in \Re^{n\times n}$ denotes the diagonal matrix with respect to the inertia, the viscosity and the stiffness of the end-effector; and $\boldsymbol{x}_e \in \Re^n$ the equilibrium point of the stiffness of the robot. Regulating the impedance parameters $\boldsymbol{M}_e$, $\boldsymbol{B}_e$, $\boldsymbol{K}_e$, an operating load of the handle to a trainee can be changed. For example, with the stiffness $\boldsymbol{K}_e = \boldsymbol{0}$ [N/m], the motion during the training reduces to reaching movements. On the other hand, when $\boldsymbol{K}_e \neq \boldsymbol{0}$ [N/m], the pulling motion of the handle against the spring can be considered as muscle training. In the system, the target force $\boldsymbol{F}_r$ is calculated with the following equation:

$$\boldsymbol{F}_r = \boldsymbol{M}_e\ddot{\boldsymbol{x}}_r + \boldsymbol{B}_e\dot{\boldsymbol{x}}_r + \boldsymbol{K}_e(\boldsymbol{x}_r - \boldsymbol{x}_e). \tag{14}$$

Then, the assistant force $\boldsymbol{F}_{aid}$ for the robotic aid in the training is defined with the trainee's hand force $\boldsymbol{F}_{ext}$ and the target force $\boldsymbol{F}_r$ as follows:

$$\boldsymbol{F}_{aid} = \boldsymbol{K}_f(\boldsymbol{F}_r - \boldsymbol{F}_{ext}) \tag{15}$$

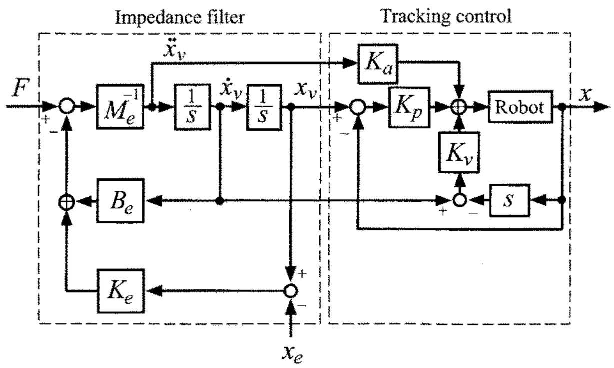


Fig. 4 Impedance control of a robot in the training system

where $\boldsymbol{K}_f = \mathrm{diag}\,({}^1k_f, {}^2k_f, \cdots, {}^nk_f) \in \Re^{n\times n}$ is the assistant gain matrix for regulating an assistant quantity in the training under $0 \le {}^ik_f \le 1$ $(i = 1, 2, \cdots, n)$. At ${}^ik_f = 0$, no robotic assistance is given to the trainee. On the contrary, the maximum robotic assistance is given at ${}^ik_f = 1$, so that the hand force of a trainee is canceled and the target force is ordered to the training device.

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

3.2 Bio-mimetic trajectory generation for robotic aid

The proposed training system generates a bio-mimetic target trajectory for the robotic aid using the TBG method described in the previous section.

The kinematics of a human hand in the n-dimensional task space can be represented as

$$\dot{\boldsymbol{x}} = \boldsymbol{u} \tag{16}$$

where $\dot{\boldsymbol{x}} = ({}^1\dot{x}, {}^2\dot{x}, \cdots, {}^n\dot{x}) \in \Re^n$ denotes the vector of a hand velocity, and $\boldsymbol{u} = ({}^1u, {}^2u, \cdots, {}^nu) \in \Re^n$ the vector of a virtual control input for the hand movement which arises from the motion of arm joints.

By time-scaling from actual time t to virtual time ν defined in (7) for the system (16), the system in the virtual time scale can be rewritten as

$$\frac{d\boldsymbol{x}}{d\nu} = \frac{1}{a(t)}\boldsymbol{u}. \tag{17}$$

By applying the TBG based method with the following potential function V_x as

$$V_x = \frac{1}{2}\boldsymbol{x}^T\boldsymbol{x} \tag{18}$$

the feedback controller $\boldsymbol{u}$ for the system (16) can be designed by

$$\boldsymbol{u} = -\frac{1}{2}a(t)\boldsymbol{x} = \frac{p}{2}\frac{\dot{\xi}}{\xi}\boldsymbol{x}. \tag{19}$$

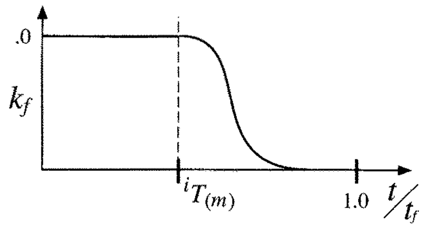


Fig. 5 Assistant gain planning

Substituting the controller (19) into (16), the following differential equation can be derived for each component variables ${}^ix$ as

$$\frac{{}^i\dot{x}}{{}^ix} = \frac{p}{2}\frac{\dot{\xi}}{\xi}. \tag{20}$$

Solving the above differential equation for ${}^ix$, the dynamic behavior of the hand in the i-th coordinate is represented by

$${}^ix = {}^ix_0\xi^{\frac{p}{2}} \tag{21}$$

where ${}^ix_0$ is the initial hand position. It can be seen that the hand behavior ${}^ix$ synchronizes with the TBG. Because of $\lim_{t\to t_f}\xi(t) = 0$, ${}^ix$ can reach the target point at the specified time t_f.

The target trajectory $\boldsymbol{x}_r$ for the robotic aid is generated by using (21) with regulating the TBG parameters β_1, β_2 and the movement time t_f based on the measurements of healthy subject's movements. Also, a reasonable target trajectory for each trainee can be generated via modulating these parameters according to his/her physical features and motion range of joints.

3.3 Robotic assistance

In the developed system, the various robot-aided training can be offered by adjusting the assistant gain ${}^ik_f$ in (15) during the training.

For instance, setting ${}^ik_f = 1$ during the training, the robotic therapist assists trainees movements with the desired force profile ${}^iF_r$, so that trainee's hand follows the target trajectory ${}^ix_r$. This training mode is effective for teaching the normal smooth movement to the trainee.

When ${}^ik_f$ is changed during the training as shown in **Fig. 5**, the robot makes the trainee's movement follow the target trajectory until a decreasing time ${}^iT_{(m)}$, and the training loads are gradually increasing afterward. With this time-varying assistance, the robot aid can teach the timing of movements to the trainee. Then, in repeated exercises such as several round point-to-point movements, it is expected that the suitable time-related schedule of assistant quantity for the trainee is designed via adjusting ${}^iT_{(m)}$ by the following renewal rule:

$${}^iT_{(m)} = \eta\,{}^iJ_{(m-1)} + (1-\eta)\,{}^iT_{(m-1)} \tag{22}$$

with the following training performance of the $(m$-1)-th trial ${}^iJ_{(m-1)}$ $(m = 1, 2, 3 \cdots)$

$${}^iJ_{(m-1)} = \begin{cases} E & (0 \le E \le 1) \\ 1 & (E > 1) \end{cases} \tag{23}$$

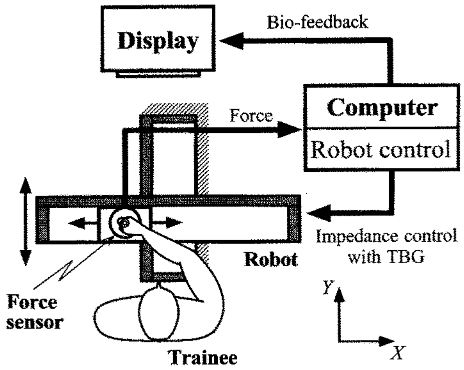


Fig. 6 Prototype of a training system

$$E = \frac{\int_0^{t_f} |^i x_r(\tau) - {}^i x(\tau)| d\tau}{\int_0^{t_f} |^i x_r(\tau)| d\tau} \tag{24}$$

where $0 \leq {}^iT_{(m)} \leq 1$, ${}^iT_{(0)} = 0$ and $0 \leq \eta \leq 1$. ${}^iT_{(m)}$ is much dependent on the last training performance as η becomes larger, while ${}^iT_{(m)}$ is defined by considering past results as η becomes smaller.

The programmed robotic assistance may encourage the trainee in his/her training, and suggest a new training method. Next section describes experiments of the proposed robot-aided training approach with a constructed prototype system for upper-limb movements.

4. Training Experiments

4.1 Apparatus

Figure 6 shows the prototype of the proposed rehabilitation aid using the TBG. The system is composed of an impedance-controlled robot for applying compliant 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 ±10 [kgf]; and Nihon Seikou Coop., maximum force ±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 [μm]; and Nihon Seikou Coop., 1.0 [μm]).

The trainee is asked to move the handle from a point to another, 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. After a set of trials, the training information is reported to the trainee in order to show his/her movements and problems.

4.2 Modeling of normal movements with TBG

The developed 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 in operating the impedance controlled robot, trajectory generation experiments were carried out with healthy and skillful persons (four male university students). In the following discussion, the motion direction of hand is limited to the x axial direction (see Fig. 6). In the experiments, the subjects were instructed to move the handle to the target point at a starting sign of a countdown with three seconds. The distance between the initial point and the target is 0.3 [m].

Figures 7 and **8** show typical examples of the observed spatial trajectories and the velocity profiles of the hand, where the robot impedance parameters were set as (M_e, B_e, K_e) = (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]). It can be observed from Fig. 7 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. 8, 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.

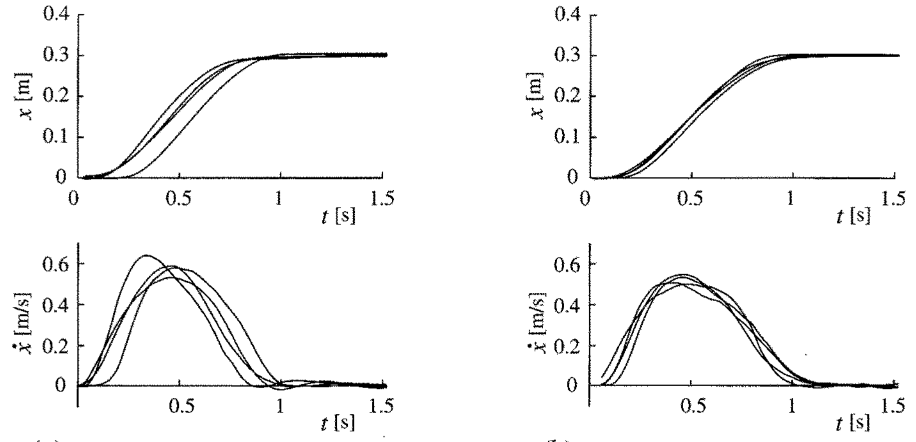
On the other hand, **Fig. 9** shows the trajectories generated by using the bio-mimetic controller with TBG in (19) under the mechanical impedance parameter (M_e, B_e, K_e) = (1.5 [kg], 30 [Ns/m], 0 [N/m]), (3.0 [kg], 60 [Ns/m], 0 [N/m]). The TBG parameters β_1, β_2 and the movement time t_f were estimated by the non-linear regression analysis with the observed trajectories in Fig. 8. Comparing Fig. 8 and Fig. 9, it can be seen that the generated trajectories are similar to the healthy person's. Also, adaptively modified trajectories according to trainees can be easily produced by changing the TBG parameters if needed.

4.3 Rehabilitation training

The validity of the proposed training approach was demonstrated with a patient of *cerebellar ataxia* (a middle-aged woman), who has difficulty in making smooth movements because of poor coordination of the limbs [20]. In the experiments, the patient was asked to make two round point-to-point movements from the initial position to the goal synchronized with the starting sign from the display where three circles are used to count down three seconds until the start of movements. Each trial of stroke movement was conducted within 3 [s], after that, the handle automatically moved to the goal point within 2 [s]. Also, the mechanical impedance parameters were set as (M_e, B_e, K_e) = (1.5 [kg], 20 [Ns/m], 0 [N/m]).

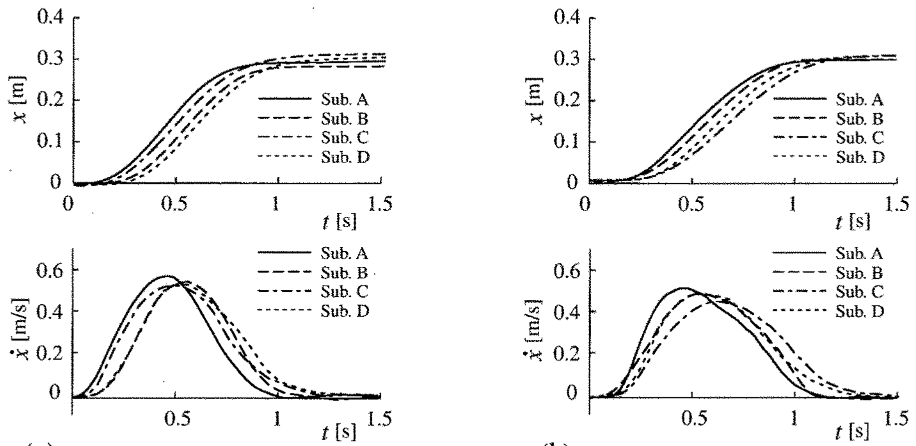
First, training experiments with the regulation of the assistant quantity during the training are shown in **Figs. 10, 11** and **12**, where (a), (b), (c) and (d) show the time histories of the hand position x, the hand velocity $\dot{x}$, the assisted forces F_{aid} and the assistant gains ${}^xk_f$, respectively. The fine solid line in each figure denotes the target trajectory (${}^xx_r$, ${}^x\dot{x}_r$, ${}^xF_r$), where the stroke length is L_s = 0.2 [m] and the movement time is t_f = 0.95 [s].

Figure 10 shows the generated trajectories with the different constant assistances under ${}^xk_f$ = 0, 0.5, 1.0. It can



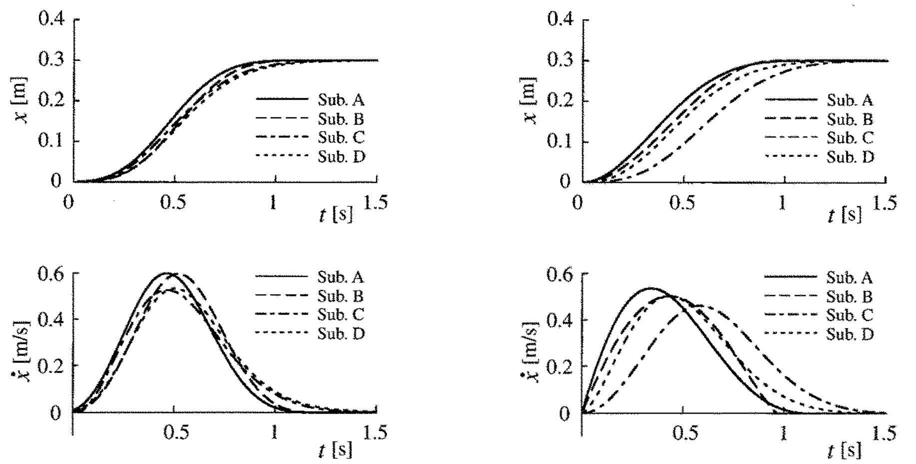
(a) $(M_e, B_e, K_e) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m]$)$ (b) $(M_e, B_e, K_e) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m]$)$

Fig. 7 Generated trajectories by the subject A under the different impedances



(a) $(M_e, B_e, K_e) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m]$)$ (b) $(M_e, B_e, K_e) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m]$)$

Fig. 8 Generated trajectories by the subjects under the different impedances



(a) $(M_e, B_e, K_e) = (1.5$ [Kg], 30 [Ns/m], 0 [N/m]$)$ (b) $(M_e, B_e, K_e) = (3.0$ [Kg], 60 [Ns/m], 0 [N/m]$)$

Fig. 9 Bio-mimetic trajectories generated by the TBG for the robotic aid

be observed from Fig. 10 that the trainee's spatio-temporal trajectories become closer to the desired trajectory measured from the healthy operator as the assistant quantity $^{x}k_f$ increases. In particular, in the case of $^{x}k_f = 1.0$, the robot instructed the patient how to move her hand for smooth movements by applying the desired force profile to the handle. On the other hand, Fig. 11 shows the generated trajectories with the time-varying assistances under the decreasing times $^{x}T_{(m)} = 0.2$, 0.6. It should be noticed that movements of the patient agree with the desired movement until $^{x}T_{(m)}$, while the error between those movements are increasing thereafter. It indicates that the training consid-

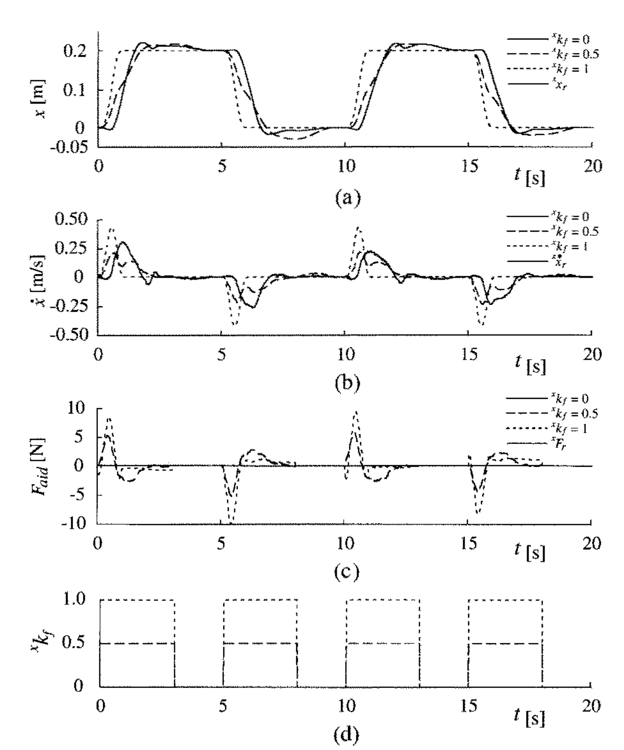


Fig. 10 Generated trajectories with the different constant robotic assistances

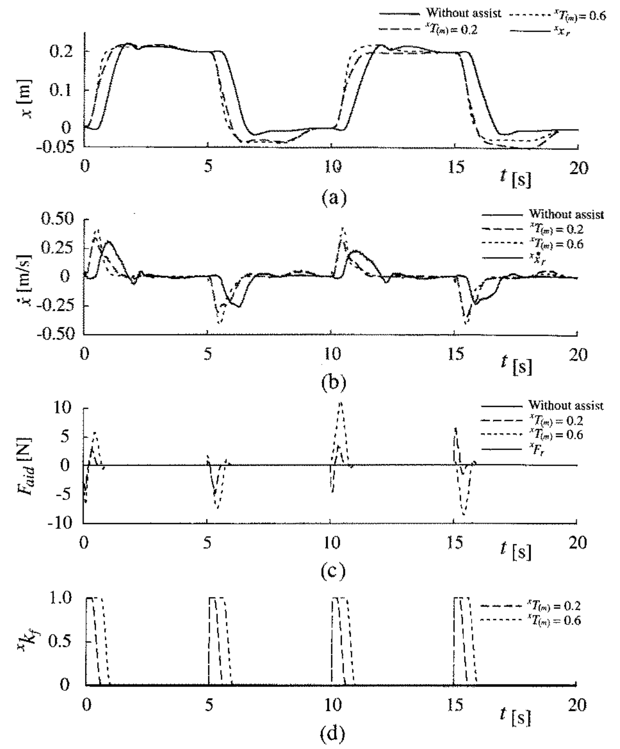


Fig. 11 Generated trajectories with the different time-varying robotic assistances

ering the start timing of movements had been provided by means of the time-varying robotic assistance. Then, Fig. 12 shows the results where the decreasing time $^xT_{(m)}$ was automatically renewed by (22) under the parameter η = 0.5. The time schedules of robotic assistance were designed according to the patient's movements of past trials. As trials go on, it is expected that the suitable assistant gain profile can be obtained according to motor control capability of the trainee. Through the training experiments, it was confirmed that the developed system can provide the training considering dynamic behaviors according to the training aim and the patient by regulating the gain of robotic assistance ^ik_f in (15).

It should be noted that the proposed training system can regulate time-related properties of the target trajectory such as the movement time and the velocity profile according to motion ability of a trainee by using the TBG parameters. Selecting reasonable dynamic properties of the employing target trajectory enables to reduce the influences coming form individual differences among patients.

Finally, a brief example utilizing this feature is shown in **Fig. 13**. The exercises were investigated with the movement time t_f = 2.0 [s] under the different constant assistances by ^xk_f = 0, 0.5, 1.0. It can be seen that the dynamic properties of patient's movements were closed to that of the desired movement as the robotic assistance increases. If a generated trajectory becomes close to the normal one, it can be expected that the motor capability will be improved.

5. Conclusions

In this paper, the TBG method was applied to develop the bio-mimetic rehabilitation aid for disabled motor control function with the impedance-controlled robot. By utilizing the modeled trajectory with TBG, which has dynamic features of normal movements as the training target, the robotic aid can offer effective training considering smoothness of movements and can also teach the normal movement to the trainee. Then, the validity of the proposed training approach was experimentally confirmed with the prototype device.

However, there are some points that should be improved for real application of the proposed bio-mimetic robotic rehabilitation aid, such as how to avoid excessive assistance for a trainee, and how to find an appropriate target trajectory according to a trainee of wide degree of motor control disorder. Future research will be directed to cope with these problems and also consider what kind of robotic-aided training should be provided by this system.

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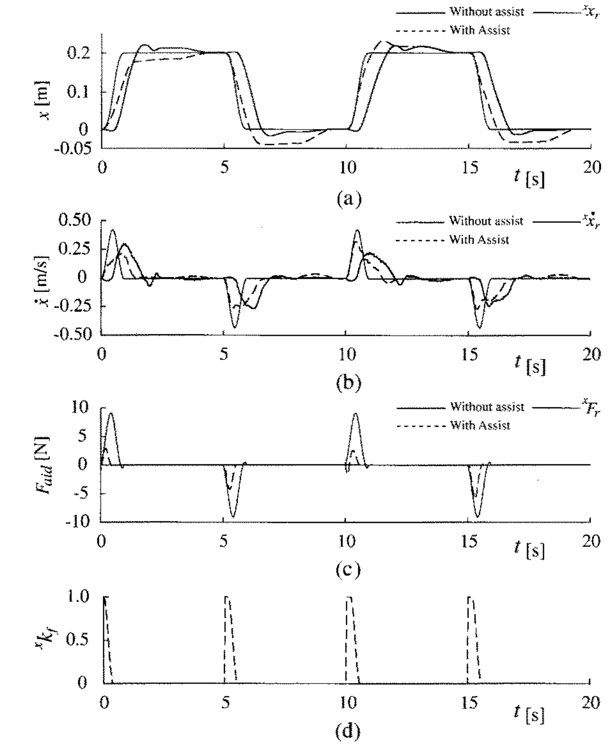

Fig. 12 Generated trajectories with the automatically adjusted robotic assistances

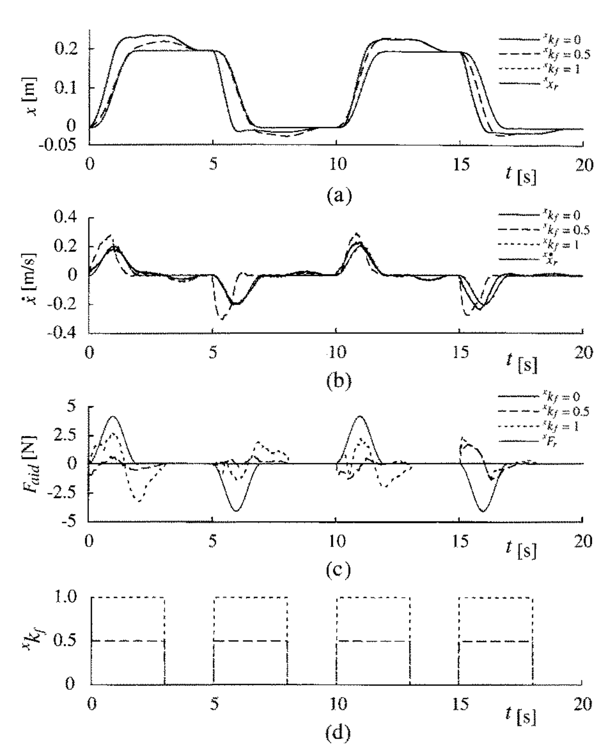

Fig. 13 Generated trajectories with slow movement ($t_f = 2$ [s])

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