Novel Dynamic Interpolation Strategy for Upper-Limb Rehabilitation Robot

Lizheng Pan[1], Aiguo Song[1,*], Guozheng Xu[2], Huijun Li[1] and Baoguo Xu[1]

[1]School of Instrument Science and Engineering, Southeast University, Nanjing, China

[2]College of Automation, Nanjing University of Posts and Telecommunications, Nanjing, China

Abstract: Focusing on providing stable and smooth robot-assisted exercises, this paper proposes a novel dynamic interpolation strategy to improve the robot movement performances. During the robot-assisted exercise, the designed control system dynamically employs appropriate interpolation method according to the physical state of the training impaired limb (PSTIL). The remarkable feature of this strategy is that it can make full use of the characteristics of different interpolation methods, which contributes to achieve better performances. Moreover, position-based impedance control is adopted to achieve the interaction compliance between the impaired limb of patient and robot end-effector. The results of experiments on 4-DOF upper-limb rehabilitation robot demonstrate the effectiveness and potentiality of the proposed method for achieving more stable and smoother robot-assisted exercises.

Keywords: Rehabilitation robot, Stability and smoothness, Dynamic interpolation, Impedance control

I. INTRODUCTION

Stroke is a leading cause of permanent disability, the third dominant cause of death, after heart disease and cancer in the aged society [1]. In general, stroke causes dysfunction to neural system and motor function, which results in a certain upper-limb impairment and motion disabilities. Fortunately, according to the neuronal plasticity theory, exercise treatment is helpful to regain extremity movement functions for people who have lost motion abilities because of suffering from stroke.

In recent decades, there is an increasing interest for clinical use of robotic systems to help patients recover from dysfunction after stroke [2]. Clinical outcomes have shown that intensive and repetitive robot-assisted movement exercises present a promising improvement of impaired-limb function movements [3]. To gain the maximal effectiveness, various control strategies, such as assistive control, challenge-based control and haptic simulation rehabilitation training, have been developed [4]. These developed strategies to some extent effectively stimulated the patient's active participation, supplied visual feedback and enriched the sensorial motor experience etc, which is helpful to increase the efficiency and effectiveness of therapy. But these control strategies paid little attention to the stability and smoothness of movement. However, due to the particularity of stroke patients, stability and smoothness of movement are very important for the robot-assisted exercises.

Interpolation method is usually adopted to execute the trajectory tracking in robotic application, which takes a significant role in the stability and smoothness of movement. Ref [5] adopted a parametric interpolation of the geometry in the operational space to improve the overall performances in positioning and path tracking. An interpolation method by combining third-order and fourth-order polynomials was present in [6], which implemented two quartic polynomials for the first and last segments of the trajectory, and cubic ones for other segments to generate smooth trajectory for good movement performance. The fuzzy-error interpolation technique which involves a fuzzy-inference system to estimate robot-pose errors, has been employed to improve the error estimation and compensation results for the target, and the simulation results showed that the fuzzy interpolation outperforms other popular interpolation methods (trilinear and cubic spline) [7]. Various fuzzy interpolation strategies have been rapidly developed and implemented in many academic and industrial fields in recent years; in essential, these strategies usually utilized a fuzzy-inference system to estimate robot-pose errors [7]. In addition, there are many interpolation methods have been developed or applied for a good movement performance, such as linear interpolation based methodology [8], polynomial based on Hermite cubic interpolation [9] and Lagrange interpolation [10], sample-based interpolation [11], B-spline interpolation [12]. However, all the mentioned literatures almost implemented single interpolation method to follow the trajectory or path tracking. In other words, the existing robot systems are rarely developed with an interpolation strategy which takes advantages of different interpolation methods.

*Address correspondence to this author at the School of Instrument Science and Engineering, Southeast University, China; Tel: +86-25-83793293; Fax: +86-25-83794158; E-mail: a.g.song@seu.edu.cn

Thus, in this paper, we develop a novel dynamic interpolation strategy to make good use of different interpolation methods achieving stable and smooth movement. How to move stably and smoothly is still desired for all application robots. In terms of rehabilitation robots, stable and smooth robot-assisted exercises can effectively avoid evoking the abnormal actions of the impaired limb during the training. Moreover, stable and smooth movement can make the subject enjoy the exercises with comfort and relax the muscle completely, which contributes to motivate the subject's participation and cooperation. In order to achieve smooth and stable movement exercises, firstly, the physical state of the training impaired limb (PSTIL) is evaluated in real time. Then, appropriate interpolation method is adopted by dynamic interpolation strategy according to the impaired-limb condition, which helps to improve movement performances. Finally, position-based impedance control is employed to achieve the compliance for the interaction between the impaired limb and the robot end-effector.

II. EVALUATION OF THE PSTIL

During the robot-aided rehabilitation exercise, the PSTIL is varying due to the pose-position change, forearm slight quiver, sudden twitch, abruptly severe tremor, external disturbance, and so on, which is partly subjected to the human control (another unresolved controller) [13]. In this work, we use features of the position and velocity tracking performance to evaluate the impaired-limb physical condition in real time. It includes two part work, an effective selected feature and evaluation of the PSTIL.

A. Feature Selection

As mentioned above, the PSTIL is dynamically variable during a rehabilitation programmes assisted by a robot, in a general sense, which works on the robotic control performance [13]. It means that the physical condition of the training impaired limb affects the tracking performances of position and velocity. Thus, the features of the position-velocity tracking errors correspond to the PSTIL to a certain extent.

The mean square error (MSE) is a measure of power of the signal in a sense, and is extensively used in practical application because of its good performance of practicability and effectiveness for real time control [14]. In this research, in order to obtain the features more effectively and instantaneously for practical application, subsection sliding MSE (SMSE) is adopted, which is expressed as

$$\begin{cases} \delta_k = \sqrt{\dfrac{\sum_{i=1}^{n}(\bar{x}_k - x_{k-i})^2}{n-1}} \\ \bar{x}_k = \dfrac{1}{n}\sum_{i=1}^{n} x_{k-i} \end{cases} \tag{1}$$

where, n is the number of sample data in the subsection, $\bar{x}_k$ is denoted the mean of k^{th} subsection, x_{k-i} is the value of $(k-i)^{th}$ sample data, and the δ_k is the corresponding feature of the k^{th} sample data.

B. Physical State Evaluation

Fuzzy logic reasoning is employed to evaluate the PSTIL, with double inputs and single output type. In order to make the assessment more effective and accurate, the inputs of the reasoning should include not only the extracted features with subsection SMSE but also the variation information of the tracking errors. The used inputs χ_p and χ_v are expressed as following.

$$\begin{cases} \chi_p = f_{ep} + k_p \bullet f(e_{\max}, e_{\min}) \\ \chi_v = f_{ev} + k_v \bullet f(e_{\max}, e_{\min}) \end{cases} \tag{2}$$

where f_{ep} and f_{ev} are the features of the position and velocity tracking errors respectively, $f(e_{\max}, e_{\min})$ is a function to display the information of the tracking error, k_p and k_v are ratios.

The corresponding output denoted with ρ reflects the PSTIL. During the fuzzification and defuzzfication, the inputs (χ_p and χ_v) and output (ρ) are defined as five fuzzy sets (NZ, ZE, PS, PM, PB), respectively, which is shown as in Figure **1**. One membership degree is obtained for each scaled input and membership function combination. Then, each combination of mapped inputs activates one control action according to the inference rule table for ρ (Table **1**). Figure **2** shows the overall input-output relationship of the fuzzy logic reasoning for the impaired-limb's physical state evaluation.

III. REHABILITATION-ROBOT SYSTEM AND CONTROL METHOD

A. Rehabilitation Robot Setup

In this research, the upper-limb rehabilitation robot mainly consists of the Barrett WAM Arm, a 3-D force

Table 1: Fuzzy Reasoning Rules for ρ

χ_v	χ_p				
	NZ	**ZE**	**PS**	**PM**	**PB**
NZ	NZ	NZ	ZE	ZE	PS
ZE	NZ	ZE	PS	PS	PM
PS	ZE	ZE	PS	PS	PM
PM	ZE	PS	PS	PM	PB
PB	PS	PM	PM	PB	PB

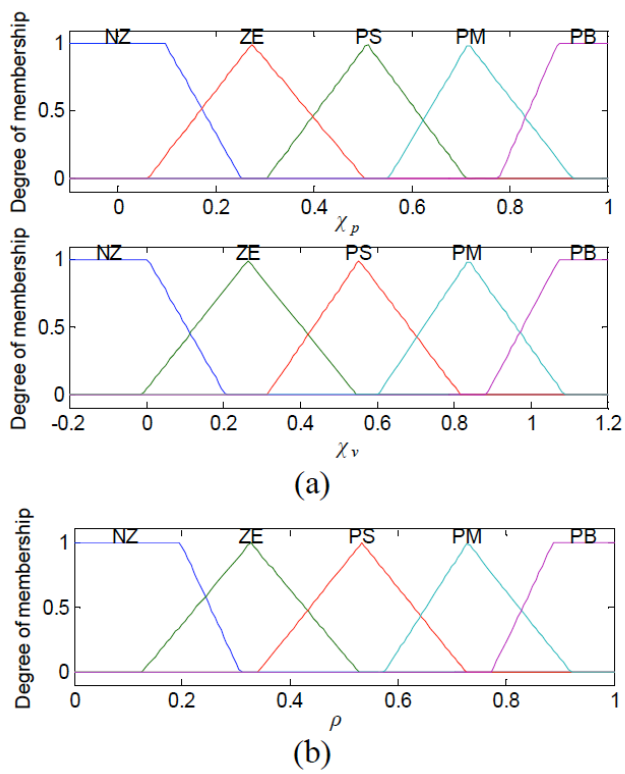


Figure 1: Input-output membership functions for fuzzy reasoning. (**a**) Input membership functions; (**b**) Output membership functions.

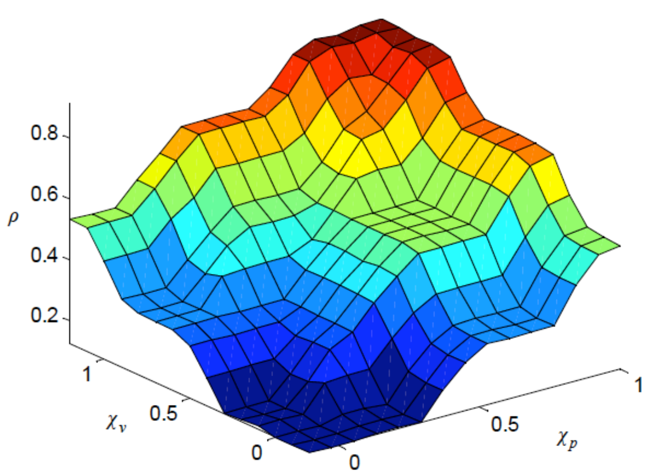


Figure 2: Input-output relationship surface map.

sensor, an arm support device, and an external PC offered by the Barrett Technology [15], as shown in Figure **3**. The standard WAM Arm is a four degree-of-freedom (DOF) manipulator with high back-drivability, and it can run in a wide 3-D workspace. Meanwhile, two control modules are supplied to monitor joint torque, velocity and voltage levels to the WAM, and to deal with emergency event. During the running, four driver motor angles can be measured to detect the position of every joint in real time, and the control torque can be set to provide the joint control. All the real-time communication between the external PC and the motor Pucks™ may be done *via* an internal high-speed CAN bus, a high-speed Ethernet cable or a wireless-Ethernet, and high-speed CAN bus communication was used in this research. In order to record the force between the impaired limb and the WAM end-effector, an improved 3-D force sensor [16] is designed and installed on the end-effector (Figure **3**), *via* a serial port to communicate with the extern PC. The arm support device can well support the impaired limb when doing passive exercises, and it can be installed on different sides for left or right impaired limb service.

The external PC runs with Ubuntu Linux system and the proposed control strategy is developed on it with a real-time module Xenomai to command the WAM-aided rehabilitation system. Meanwhile, a graphical user interface (GUI) is developed to display both the planed and actual trajectories on the screen, and to set the related control parameters, such as gravity compensation coefficient, training model, trajectory type, etc (Figure **3**). The GUI is developed using GTK, and the whole developed software of rehabilitation system is realized using C language with the Ubuntu Linux system in the external PC. In this research, a multi-thread method is adopted to manage all the system tasks, which is benefit for the real-time control.

B. Trajectory Interpolation

In joint space, so-called trajectory interpolation means to get the processing position for starting position and target position with certain interpolation method. Various interpolation methods have been developed to obtain good movement performance. In general, each interpolation method possesses its own characteristics and results in different effects on the movement performance.

The interpolation method which is so-called linear segments with parabolic blends (LSPB) is one of the

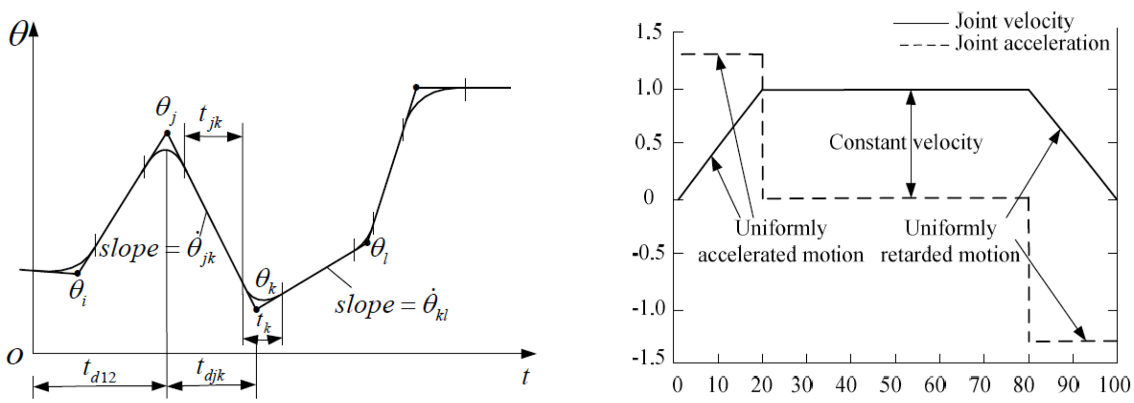
Figure 3: WAM Arm upper-limb rehabilitation robot setup.

extensively applied algorithms for its good performance and feasible realization. Employing this method, the desired trajectories are partitioned into certain segments and linear interpolation is used for the linear segment between two adjacent *via* points, while parabolic blending is used at the *via* waypoints [17], which is shown as in Figure **4**. The LSPB trajectory is such that the velocity is initially “ramped up” to its desired value and then “ramped down” when it approaches the goal position. The specific process to apply the LSPB was described in detail in [17]. To know more information about the LSPB, please refer to this literature.

In this research, we propose a dynamic interpolation strategy which selects the appropriate interpolation method to plan the trajectory tracking according to the PSTIL. Three interpolation methods, namely, LSPB, linear interpolation [8] and pulse linear interpolation, are employed to improve the movement performance by combining their individual characteristics. The LSPB is adopted as the primary interpolation method. However, linear or pulse linear interpolation is employed under small or large disturbances, respectively. Here, we provide some necessary introduction about the pulse linear interpolation which is used in this work.

The pulse linear interpolation is a method based on the linear interpolation, which is combined with a similar pulse variance. In this work, it is expressed as the following.

$$\begin{cases} \theta_{ki} = \theta_{lki} + \mathrm{sgn}(\theta_{lki} - \theta_a)\delta_k \\ \delta_k = \dfrac{|\theta_k - \theta_{k-1}|}{n_k} \end{cases} \tag{3}$$



(**a**) Interpolation trajectory planning

(**b**) Joint velocity and acceleration

Figure 4: Trajectory, velocity and acceleration with LSPB.

where θ_{lki} and δ_k are the i^{th} interpolation value by linear interpolation and variance for the subsegment connecting with k^{th} and $(k-1)^{th}$ waypoints, respectively, θ_a is the actual position, θ_k and θ_{k-1} are the values of k^{th} and $(k-1)^{th}$ waypoints, respectively, and n_k is the whole interpolation points for this subsegment.

C. Control Method

Upper-limb rehabilitation robot is applied to assist the neural injuries to improve their motion function with rehabilitation movement programmes. Due to the formed connective tissue and local circulation obstruction after stroke, the impaired limb is more susceptible to injury. Therefore, the suitable compliant behavior between the rehabilitation robotic end-effector and impaired limb is one of the primary considerations in designing control system, especially to the physically interactive rehabilitation robot. A well-established framework to manage this task was given by impedance control [18], which is inherently a model-based approach. In this work, the position-based impedance control is adopted to design the control system.

The aim of an impedance controller is to establish a mass-damper-spring relationship between the position and the force [19]. The desired impedance equation of the rehabilitation robot can be represented by

$$\Delta F = M_d \Delta\ddot{X} + B_d \Delta\dot{X} + K_d \Delta X \tag{4}$$

$$\Delta X = X_d - X \text{ , } \Delta\dot{X} = \dot{X}_d - \dot{X} \text{ , } \Delta\ddot{X} = \ddot{X}_d - \ddot{X}$$

where M_d, B_d, K_d are desired inertia, damping and stiffness matrix, respectively, X_d, X are the desired and actual position of the rehabilitation manipulator, $\dot{X}_d$, $\dot{X}$, $\ddot{X}_d$, $\ddot{X}$ are velocity and acceleration correspondingly.

Here, the impedance controller is adopted to achieve the interactive compliance, and then the position controller with proportional-integral-derivation (PID) algorithm is applied to execute the position tracking. Considering the gravity compensation for the robot itself and arm support, and combining the PID position control, the eventual control torque of robot joint is expressed by

$$\tau_c = K_P(\theta_d - \theta) + \int K_I(\theta_d - \theta)dt + K_D(\dot{\theta}_d - \dot{\theta}) + \tau_{compensation} \tag{5}$$

where K_P, K_I, K_D are the gain parameters of PID controller, respectively, $\theta_d, \theta, \dot{\theta}_d, \dot{\theta}$ are the desired-actual position and velocity of the robotic links, respectively, $\tau_{compensation}$ is the gravity compensation torque.

In this research, a dynamic interpolation strategy is proposed to improve the movement performances. We aim to investigate whether the proposed dynamic interpolation contributes to supply with smooth movement training or not. The issue on how to effectively protect the impaired limb under sudden twitch or other emergency in real time is not discussed here, and we have focused on this issue in our previous research [20]. The overall control system block diagram for position-based impedance control with dynamic interpolation strategy is shown as in Figure **5**. The dynamic interpolation mechanism provides an appropriate interpolation method to plan the trajectory tracking, according to the evaluating PSTIL. The impedance controller and PID position

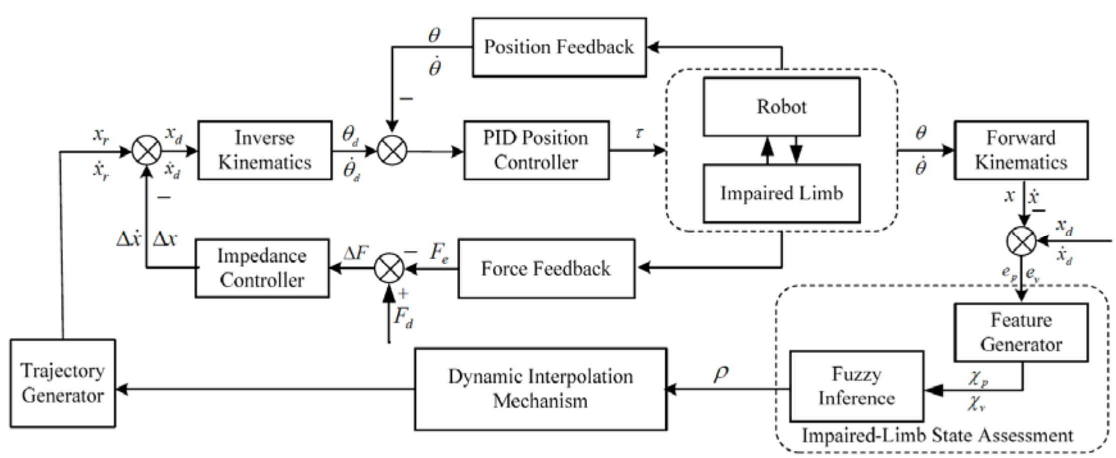


Figure 5: Control system block diagram for WAM Arm rehabilitation robot.

controller are implemented to achieve the trajectory tracking.

IV. RESULTS

A. Experiment Scheme

To verify the effectiveness of the proposed method, the shoulder extension/flexion movement trajectories were predefined in horizon plane. In the exercise, the upper-limb movable range expressed in the WAM Arm's world coordinates was defined as 0.45 rad in flexion and −0.45 rad in extension (*XOY plane*), with 18.1s for each session.

A healthy adult male volunteer was inducted to deliberately come into being different PSTIL (without, small or large disturbance) during the rehabilitation exercise, to demonstrate the comparisons of control performance with LSPB, linear, pulse linear and dynamic interpolation method. The volunteer was asked to simulate the each type physical state as much as possible with the same action and at the same position. In order to avoid the occasional influence to the experiment results, the volunteer was asked to do massive simulation exercise firstly, moreover, each experiment was carried out for five times. The eventual outcome was expressed with the average of the 5-time results.

According to the practical application of the system, the parameters of the PID controller were set as following: $K_{Ph} = 300, K_{Ih} = 0.5, K_{Dh} = 1.5$, and the parameter n in SMSE was set 10. The domains of the input-output variables for fuzzy reasoning of impaired-limb physical state evaluation were defined as $\chi_p \in [-0.1, 1.0]$, $\chi_v \in [-0.2, 1.2]$, $\rho \in [0, 1.0]$.

B. Control Performances

In this paper, the PSTIL was defined with three cases, i.e., without disturbance, small and large disturbances. During the experiments, the subject was conducted to deliberately exert small and large disturbances for a short time in the first and second training sessions, respectively. The movement performances with different interpolation methods were studied. In the horizontal shoulder extension/flexion exercise respecting to the third joint of the WAM, the joint position error (for tracking performance) and corresponding control torque (for stability and smoothness) were recorded and demonstrated as in Figures **6** and **7**, respectively. The management of proposed dynamic interpolation strategy was demonstrated for small and large disturbance conditions, respectively, in Figure **8**.

It is obvious in Figure **6** that the pulse linear interpolation method presents the best performance in terms of the position tracking errors. However, control torque with pulse linear method is easy-to-volatility, which is obviously seen in Figure **7**. The proposed dynamic interpolation strategy shows better

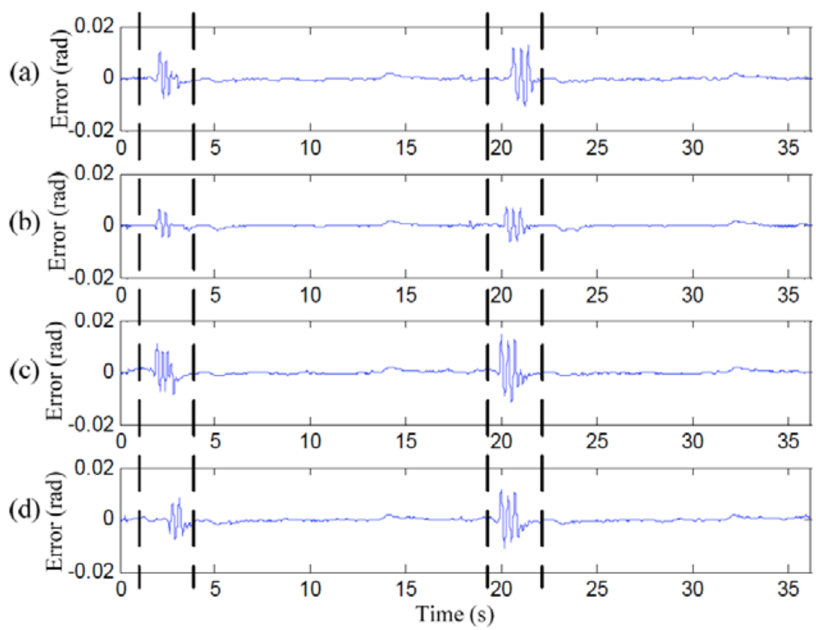


Figure 6: Position tracking errors with different interpolation methods. (**a**) Linear, (**b**) Pulse linear, (**c**) LSPB, (d) Dynamic interpolation.

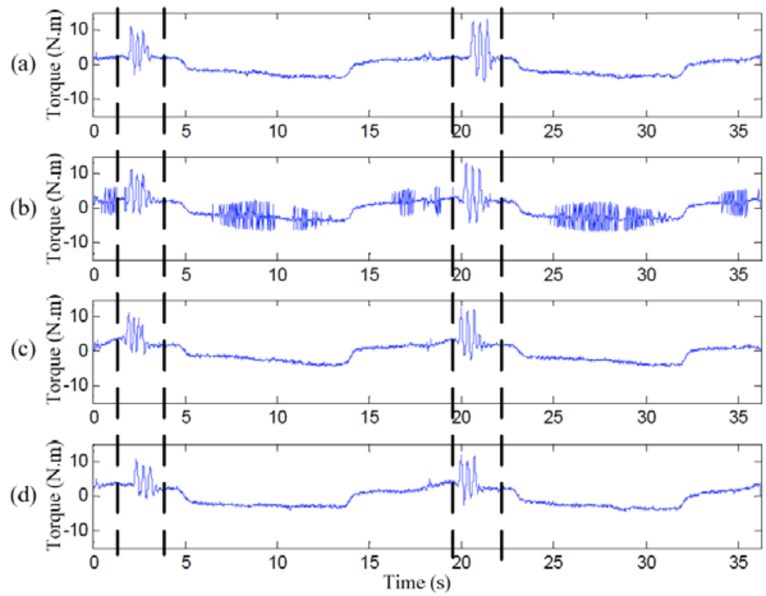


Figure 7: Control torques with different interpolation methods. (**a**) Linear, (**b**) Pulse linear, (**c**) LSPB, (**d**) Dynamic interpolation.

performances than the one of the LSPB, whichever in position tracking (in Figure **6**) or movement stability (in Figure **7**), clearly demonstrated during the period with small or large disturbances. It is evident in Figure **8** that the control system dynamically employed different interpolation methods to planning the trajectory during the disturbance conditions. In Figure **8b**, the pulse linear method is employed more frequently during forepart than during hint-part under large disturbance condition, which is different from the small disturbance condition. Moreover, comparing Figure **8a** and **b**, the pulse linear method is apt to be adopted under large disturbance condition. It demonstrates that the designed dynamic interpolation strategy can make full use of different interpolation to improve movement performance effectively.

The data of the tracking errors and control torques was further analyzed to demonstrate the movement performances with different interpolation methods. Two performance indices, the maximum of the absolute error (MAE) and the sum of absolute error (SAE) of the trajectory tracking errors, were adopted to evaluate position tracking performances. Moreover, three cases, i.e., maximum absolute torque (MAT), maximum absolute rate of the torque (MART) and MART during 0.1s, were considered to analyze the movement stability and smoothness of the control performance. The outcomes of the tracking errors and control torques are present in Tables **2** and **3**, respectively. In terms of tracking performance comparison, it included three parts, namely, exclusive disturbance, small and large disturbance segments. Note that, by comparing the evaluating indices, the pulse linear method

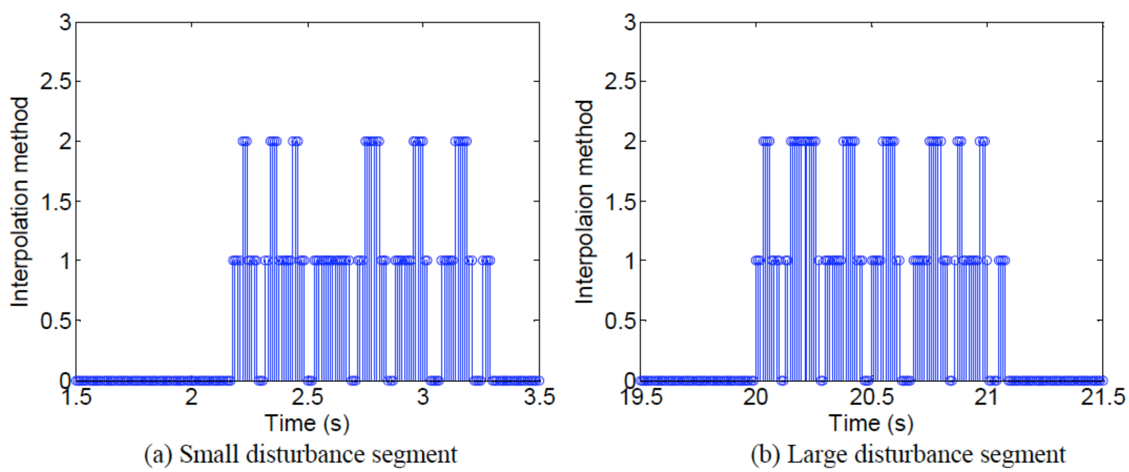


Figure 8: Management with dynamic interpolation strategy. ('0', '1' and '2' denote LSPB, linear and pulse linear, respectively).

Table 2: Position Tracking Performance Comparison

Method	Position tracking (rad)					
	Exclusive disturbance segments		Small disturbance segment		Large disturbance segment	
	MAE	SAE	MAE	SAE	MAE	SAE
Linear	0.002135	1.4167	0.010762	0.51978	0.012954	0.82595
Pulse linear	0.001592	1.0318	0.0062345	0.28699	0.0075015	0.47091
LSPB	0.001805	1.378	0.011144	0.72372	0.014481	0.94948
Dynamic	0.0018315	1.3776	0.0084096	0.48574	0.011735	0.88922

Table 3: Control Torque Performance Comparison

Method	Torque change (N.m, N.m/s)		
	MAT	MART	0.1s MART
Linear	13.197	308.75	164.21
Pulse linear	13.608	831.41	142.14
LSPB	12.974	277.32	122.38
Dynamic	12.039	276.84	107.18

performs best in position tracking, while worst in torque stability (MAT=13.608, MART=831.41, 0.1s MART=142.14) which means that it is difficult to work with very satisfied smoothness. The dynamic strategy presents better movement performance (trajectory tracking, stability and smoothness) than the LSPB, which can obviously seen from the analyzed results with MAE and SAE for position tracking and MAT, MART and 0.1s MART for control torque. Overall, dynamic interpolation strategy can take advantages of each employed method, and perform a better movement performance under disturbances.

V. CONCLUSIONS

This paper proposes a novel dynamic interpolation strategy to improve the movement performance for upper-limb rehabilitation robot. The designed control system dynamically selects appropriate interpolation method to plan trajectory according to the evaluated PSTIL, which can make good use of the characteristics of different interpolation methods. Moreover, position-based impedance control is adopted to achieve the compliance during rehabilitation exercises. Employing dynamic interpolation, the robot carried out the rehabilitation training with better movement performances in position tracking as well as stability and smoothness, in particular, under certain disturbance conditions. Our tests with a healthy subject demonstrated the effectiveness and practicability of the proposed control strategy based on dynamic interpolation. Moreover, the proposed strategy is promising to be implemented in other fields for improving the robot movement performances.

In the current stage, we just demonstrated a plane exercise. In future work, we will predefine some spatial trajectories and develop effective decision-making mechanism for dynamic interpolation strategy to execute compounding movement exercises with better movement performance.

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