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Robot assisted rehabilitation of the arm after stroke: prototype design and clinical evaluation

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Abstract Robot assisted rehabilitation training is a promising tool for post-stroke patients' recovery, and some new challenges are imposed on robot design, control, and clinical evaluation. This paper presents a novel upper limb rehabilitation robot that can provide safe and compliant force feedbacks to the patient for the benefits of its stiff and low-inertia parallel structure, highly backdrivable capstan-cable transmission, and impedance control method in the workspace. The "assist-as-needed" (AAN) clinical training principle is implemented through the "virtual tunnel" force field design, the "assistance threshold" strategy, as well as the virtual environment training games, and preliminary clinical results show its effectiveness for motor relearning for both acute and chronic stroke patients, especially for coordinated movements of shoulder and elbow.

Keywords rehabilitation robot, passive training, active training, force feedback, impedance control

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1 Introduction

Stroke has become the second cause of death over the world, according to statistics from WHO (world health organization). Above 80% of stroke survivors, on the other hand, have certain kinds of movement disorders [1], which seriously affect their independence in ADLs (activities of daily living), thus need further medical intervention after surgery. Motor impairment after cerebrovascular accident can recover to some extent after receiving long term and high intensity rehabilitation training as a consequence of brain plasticity. While the conventional manual therapy is a huge physical burden on therapists, robot assisted rehabilitation is believed to be a better solution in some respects. Additionally, robots can be programmed and easily be used to record details of interest during training, which provides references for timely and quantitative performance evaluation, rehabilitation medical research.

Different from versatile industrial manipulators, rehabilitation robot emphasizes more on its inherent safety and compliant interaction features than on the manipulation accuracy. An ideal rehabilitation

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robot should be able to replicate good features of a human therapist's hand, which is lightweight and soft, at the same time it can sense patients' gentle residual voluntary force, and provide assistance in a compliant manner [2].

The current rehabilitation robot controllers have two training modes in general, i.e., passive training and active training. While passive training is readily implemented using sophisticated motion controllers, where patients are carried passively by the robot to move following a desired trajectory. Active training is proved to be more effective than passive training for brain recovery, but harder to implement [3,4]. The major challenge is the accurate detection of patients' motion intention reflected by their unpredictable voluntary force, and the robot assistance should exactly satisfy their needs (i.e., the principle of "assist-as-needed", AAN) [5]. More assistance permits post stroke patients to finish the task easily, but also promotes their slackness and dependence on the robot; less assistance requires more active contributions, but possibly hurts their motivations and active engagement.

Besides the control algorithm, the dynamic characteristics of different robot designs also affect the final control performance, especially the system safety and force transparency when the patient interacting with a virtual environment. Firstly, the reflected inertia of the robot at the end-effector should be small, as a large inertia may cause serious damages to the patient, and also affects the interaction transparency. Secondly, the actuation and transmission systems should be smooth and highly back-drivable such that even severe stroke patients can actively move the robot using their residual force, and the robot can provide smooth and compliant assistance, which is necessary for the implementation of active training [6].

This paper presents a novel upper limb rehabilitation robot, which aims to implement the AAN-type active training for post stroke patients by both the robot design and the assistance controller design, and the clinical trial and evaluation methods are also studied. This robot is a 2-DOF haptic interface, which has a five-bar parallel mechanical structure, thus has stiffer joints and lower inertia links than serial type robot. The torques of two joint motors are transmitted to the links through a novel capstan-cable system, which is highly backdrivable and has no backlash compared to gear box, and all these features are beneficial to the feedback transparency in virtual interaction. On the control method, different from the simple passive training controller and basic impedance controller, we build a high-level assistance controller other than the low-level impedance controller. This controller features a "virtual tunnel" force field and the "assistance threshold" strategy, where the robot only provides assistance when the patient deviates too much from the "virtual tunnel", and only when the patient actively starts moving and lags behind the reference. Based on the high transparency mechanical design, the "Assist-As-Needed" controller, as well as the visual feedback by the virtual environment training games, the patient who has nerve injury after stroke has more motivation and more active engagement to move, and the clinical trial results validate this robot design.

2 Upper limb rehabilitation robot design

In order to provide compliant force feedbacks based on the patient's movement performance, we have developed a rehabilitation robot named CASIA-ARM which adopts the end-effector structure, and its technical specifications are listed in Table 1. As shown in Figure 1, this robot has a five-bar parallel structure, where the two base joints are actuated by DC motors, and other three joints are passive. This design has several benefits: this parallel robot has a closed link structure, thus normally stiffer than serial robots [7]; all the joints connecting with moving links are passive, thus have smaller inertia reflected at the end-effector, which benefits both the patient's safety and the interaction transparency in rehabilitation training. Different from the direct drive design of MIT-MANUS [8], this robot is actuated by smaller DC motors with a capstan-cable transmission system, where the steel wires are wrapped around the motor shaft sleeves and the transmission wheels, which is highly backdrivable and has no backlash. To ensure safety of the patient, the motor torques are limited by the drivers, and the detection of large accelerations through the encoders will switch off the motor driver outputs and two electromagnetic brakes are switched on immediately. For more details of the mechanical design and kinematic analysis, please refer to [6].

Table 1 Technical specifications of CASIA-ARM

Item	Characteristic
DOF	2
Actuation	2 DC motors
Sensors	2 rotary encoders
Range of joint motion	80°–220°, −40°–100°
Workspace	500 mm × 416 mm
Motor torque	∼ 450 mNm
Reduction ratio	20:1
Force capability	>32.8 N

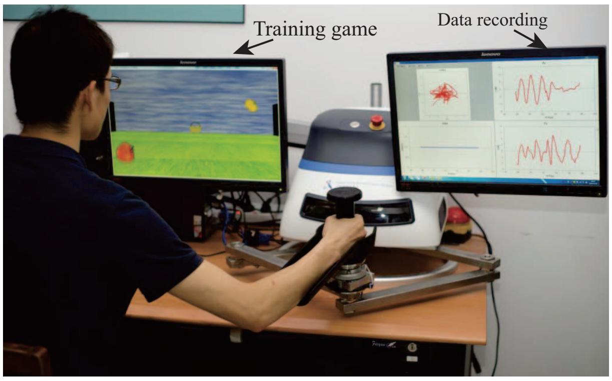

Figure 1 (Color online) Training scenario using CASIA-ARM, where the patient is directed to catch the moving objects in the virtual environment with the robot's assistance.

As shown in Figure 2, the robot is coupled with the patient at the end-effector as a human-robot system. This system has two DOFs, but has four active inputs (two robot active joints and two human joints: shoulder and elbow), thus it is a redundantly actuated parallel mechanism. We have analyzed the dynamics model of the robot in [9]. As the robot has small inertia and friction, and moves slowly during rehabilitation training, its force feedback capability can be obtained approximately by static force analysis. The static force output at the end-effector can be obtained as below:

$$F = J(\theta_1,\ \theta_2)^{-\mathrm{T}}[nT_{m1},\ nT_{m2}]^{\mathrm{T}}, \tag{1}$$

where T_{m1}, T_{m2} are torques of two joint motors, n is the reduction ratio, and $J(\theta_1, \theta_2)$ is the Jacobian matrix dependent on joint angles (θ_1, θ_2) (the expression of the Jacobian matrix associated with the two angles can be found in [9]), thus the force output capability is uneven within the workspace. As shown in Figure 3, the force outputs at a certain position are constrained within a parallelogram (the four vertexes correspond to four different configurations of two motor maximal torque outputs: $[-\max|T_{m1}|, -\max|T_{m2}|]$, $[-\max|T_{m1}|, \max|T_{m2}|]$, $[\max|T_{m1}|, -\max|T_{m2}|]$ and $[\max|T_{m1}|, \max|T_{m2}|]$, and the maximum reflected force in all directions is defined by the maximum radius of the parallelogram's inscribed circles shown in Figure 3, which is 32.8 N by simulation.

3 Implementation of active training controller

As shown in Figure 1, with the aid of this robot, the patient can easily moves his/her hand in the horizontal plane using residual muscle force to complete the training games displayed on the screen, and the gravity of the affected arm is supported by the robot. As patients cannot control their arms as will, the robot should play a role in guiding, assisting, and erecting the movement.

The active training also has two submodes: active assist mode and active resist mode, which are appropriate for severe and moderate patients, respectively. In the active assist mode, the robot provides

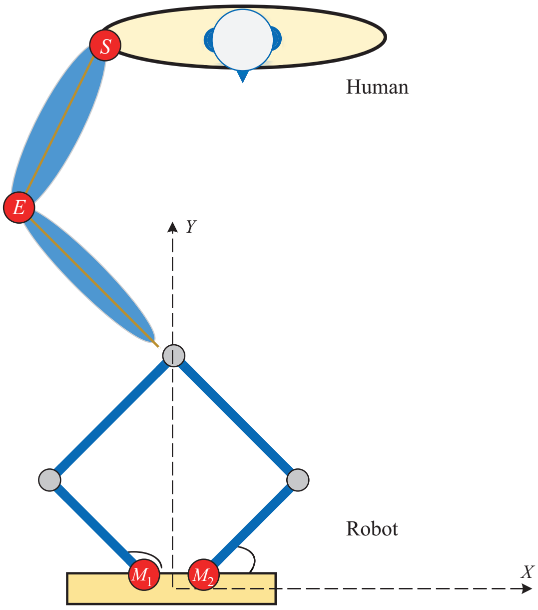

Figure 2 (Color online) Demonstration of the human-robot system, where M_1 and M_2 are the robot's joint motors, and S and E denote the patient's shoulder and elbow joints, respectively.

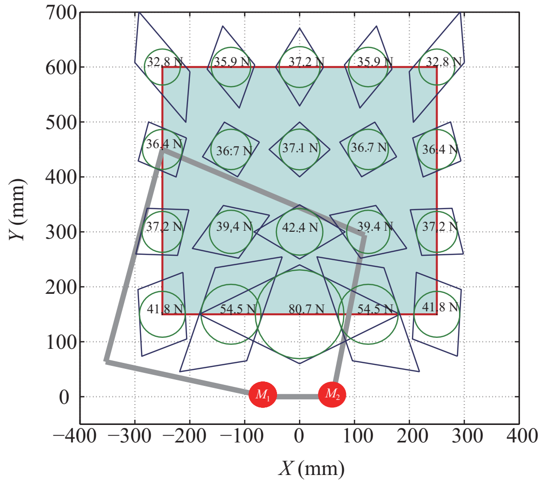

Figure 3 (Color online) Reflected force at the end-effector over the workspace, where the force feedback capabilities at 20 positions over the workspace are depicted by parallelograms.

assistance only when patients lag behind the desired trajectory, while patients are loaded with more resistance based on their position and velocity in the active resist mode.

The active training controller of CASIA-ARM is implemented in two levels: a high level controller and a low level controller. The high level controller implements the AAN principle and motion trajectory planning, and regulates the low level impedance controller. For the trajectory planning, taking reaching movement training as an example, the normal time-dependent trajectory has a form as below:

$$\frac{x(t)-x_i}{x_d-x_i}=\frac{y(t)-y_i}{y_d-y_i}=10(t/\tau)^3-15(t/\tau)^4+6(t/\tau)^5, \tag{2}$$

where (x_i, y_i) and (x_d, y_d) are coordinates of the starting point and ending point, respectively, and τ is the total movement time. Obviously, the trajectory of (2) corresponds to a straight line in the workspace, and the 5-order polynomial form guarantees the smoothness of position, velocity, acceleration, jerk.

The tolerance of patients' movement variation is also incorporated into the high level controller, and also takes the reaching movement training along X axis as an example:

$$\begin{aligned} F_x &= \begin{cases} -k_x\left(x-x_{\rm ref}\right)-b_x\dot{x}, & x_{\rm th}<x<x_{\rm ref}, \\ 0, & x<x_{\rm th} \text{ or } x>x_{\rm ref}, \end{cases} \\ F_y &= \begin{cases} -k_y\left(|y|-|y_{\rm wall}|\right)-b_y\dot{y}, & |y|>w_{\rm wall}, \\ 0, & |y|<w_{\rm wall}, \end{cases} \end{aligned} \tag{3}$$

where F_x, F_y are the robot assistance/resistance in the forward and perpendicular directions, respectively.

The stiffness along the forward direction k_x is set smaller than that in the perpendicular direction k_y, and thus the movement along the forward direction depends more on the patient's voluntary efforts. Besides, there is a deviation tolerance $w_{\rm wall}$ in the vertical direction, i.e., two elastic walls are built to prevent the patient from deviating too far away from the desired path, which gives freedom for patients exploring within the "tunnel", and was proved to be beneficial for motor relearning [10]. To further motivate patients' active engagement, the robot assistance is only imposed when patients move beyond a threshold $x_{\rm th}$ from the starting point by themselves. Compared with the existing error-based assisting

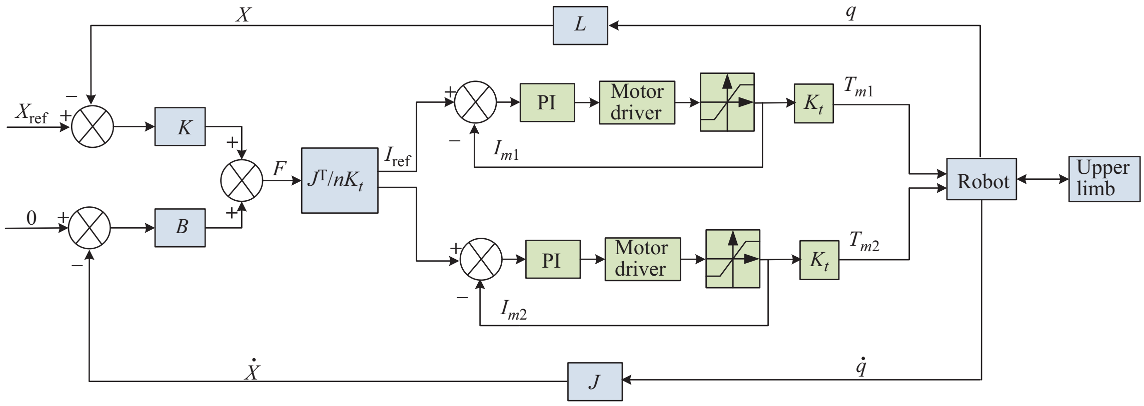

Figure 4 (Color online) Structure of the low level controller of CASIA-ARM, where the joint torques are regulated through inner motor current control loop, K_t represents the motor torque constant, $q = (\theta_1, \theta_2)$ is the joint space variable, and I_{m1} and I_{m2} represent the motor currents.

methods, the "virtual tunnel" force field and "assist-threshold" control strategy give the patient more freedom to relearn movement skills, and the robot only provides assistance when necessary. This novel design of a high-level adaptive strategy with a low-level impedance controller is an implementation of the "Assist-As-Needed" clinical principle, which emphasizes on the patient's active engagement and appropriate feedback, and has been proven to be more effective than passive training [11].

The low level controller based on impedance control method [12] is shown in Figure 4, and the robot assistance is determined by the trajectory error and velocity in the workspace, where L represents the robot kinematics, X is the end-effector position, J is the Jacobian matrix, $K = \text{diag}(k_x, k_y)$ and $B = \text{diag}(b_x, b_y)$ are the stiffness and damping matrix, respectively. In the low level controller, two motor drivers work in the current control mode, and the torque reference T_m is obtained by projecting the desired force F at the end-effector into the joint space.

As the low-level controller is built based on the impedance control method, the stability of the system should be analyzed to guarantee the safety of the patient. According to previous research [13], for a haptic interface that has fixed sampling period and physical damping, there is a limit to the stiffness K maintaining the stability, and the virtual damping B contributes to stability. As the explicit expression of maximum K is hard to obtain, the exact value of maximum K for our robot is found to be approximately 5000 N/m through trial and error. During rehabilitation training, however, the stiffness is always set under 1000 N/m, thus the robot's stability and the patient's safety can be guaranteed.

4 Clinical trial and evaluation

Two questions about the robot applicability should be addressed: whether the above robot design and control methods can reduce motor impairment, and whether robotic therapy is more effective than conventional therapy. To this end, between June 2016 and September 2016, a randomized controlled trail was conducted, and we enrolled 24 patients who had motor impairment after stroke ($<$ 6 months: 12 cases; $>$ 6 months: 12 cases).

All patients were randomly assigned (12:12) to receive robotic (experimental group) or conventional therapy (control group), and had no significant difference between groups in scores on the upper extremity section of the Fugl-Meyer assessment (FMA-UE). Both groups received routine therapy, and an additional robotic therapy was provided to the experimental group, at least 20 min every time, five times a week for 4 weeks (total 20 sessions), and an equal duration of conventional training was given to the control group. For either group, professional assessors tested patients immediately before and at the end of the trial.

The baseline characteristics and FMA-UE scores of each group are listed in Table 2, where all calculations were done with SPSS, and we used a significance level of 0.05 for all analyses. Both groups

Table 2 Baseline sample characteristics and FMA-UE outcomes[a)]

	Case	Sex	Age (year)	Before trial	After trail	Z	p	Change
Robotic therapy	12	M(10)F(2)	46.1±15.8	27.6±10.7	37.9±10.5	−3.063	0.002	10.3±6.3
Conventional therapy	12	M(9) F(3)	46.9±10.1	26.2±6.0	32.8±7.0	−3.064	0.002	6.7±3.1
Z	–	–	–	−0.289	−1.245	–	–	–
p	–	–	–	0.772	0.213	–	–	–

a) Mann-Whitney U-test is used to analyze data in the same group, and Wilcoxon rank-sum test is used to analyze data between groups.

had significant gains in FMA-UE scores, and changes were higher in patients assigned to robotic therapy than in those assigned to conventional therapy, but no significant differences were found between the two groups. These results proved the effectiveness of robot assisted rehabilitation therapy, which is consistent with early results [14]. On the other hand, though the robot therapy shows no significant gains than the conventional therapy, patients had shown more interests in this new method, and called for more advanced and sophisticated rehabilitation robots.

5 Discussion

This paper presents the design and control method of a novel upper limb rehabilitation robot, which has good interaction performance and clinical outcomes. The design of parallel structure and capstan-cable transmission system has small reflected inertia and friction at the end-effector, which is beneficial to both safety and compliant interaction between the robot and patients. The high level controller implements the AAN training principle and trajectory planning functionality, and the low level controller guarantees accurate and compliant assistance of the robot through the impedance control method in the workspace. Finally, the preliminary clinical trial results show the effectiveness of the robotic therapy, and our future work will focus on optimal robot assistance strategies and robot-based evaluation methods.

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Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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