Performance Evaluation of a Novel Telerehabilitation System for the Elbow Joint Training

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Abstract – Except the network latency which limits the development of telerehabilitation systems for home-based rehabilitation, the loss of real contact feeling should also be addressed. In this paper, a novel telerehabilitation system is developed to recover the lost contact feeling. The system incorporates a human upper limb-like device (master device) for therapists’ use and an exoskeleton device (slave device) for patients’ use. The training process of passive training with the proposed system is introduced in this paper. On the patients’ side, a force sensor was used to detect the interaction force between the forearm and exoskeleton device. The interaction force can be reflected to therapists with master device which was designed with the SEA-based structure. The closed-loop interaction control method was used, thus the force feedback can be controlled by adjusting the deflection of elastic elements. The performance that the master device can generate variable impedances is evaluated. Moreover, motion tracking performance during passive trainings was tested under local network environment. The passive training is suitable for patients with severe impairments and poor motor function.

Index Terms – Telerehabilitation, Force feedback, Series Elastic Actuator, Exoskeleton device, Passive training.

I. INTRODUCTION

Human statistics annually report approximately 795,000 new or recurrent strokes [1]. Strokes may cause hemiparesis in subjects, resulting in impairment of the upper limb and disabilities in performing activities of daily living (ADL) in about 85% cases.

Upper extremity function is the most important ability performing various ADLs. For improving the upper extremity ability after a brain lesion, an early and intensive therapy approach is needed. Robot-aided therapy allows patients to receive a more effective and stable rehabilitation process [2]. Most existing robotic device can be separated into endpoint robots [3]-[4], cable suspensions [5], and exoskeletons [6]-[8]. However, the vast majority of rehabilitation robots may be used only at rehabilitation centers and need supervised assistance from qualified personnel [9]. Patients may face problems in continuing with rehabilitation, such as the inconvenience of going to the rehabilitation centers. Therefore, the patient demand for home-based rehabilitation is expected to increase.

On the other hand, caregivers usually do not have the ability to operate robotic devices like the qualified personnel. Therefore, a telerehabilitation system will be a logical step forward. With the telerehabilitation system, the patient can receive the assessment from therapists without visiting the rehabilitation centre. The therapists can adjust the appropriate parameters for training devices while their duties can be reasonably planned [10].

This kind of therapy is usually described as a bilateral system in which both the patient and the therapist interact with each other over the Internet through a shared virtual environment [11]. For instance, the Georgetown University ISIS Centre assembled two InMotion2 robots into a telerehabilitation test bed. Both the therapist and patient robots can independently interact with a virtual object. A sensed force calculated from the virtual object will be transmitted to the therapist and patient [12]. In our previous study, a telerehabilitation system with a commercial product (Phantom...
with that of human’s upper limb. Therefore, the therapist can accuracy kinematic parameters can be seen with the OpenGL- therapists can monitor the status of patients, while, a more master device while monitoring the status of patients over developed exoskeleton device is very light (1.5kg) for home the exoskeleton for training the patient. Most importantly, the performance. The conclusions and future works are given at importance of the haptic feedback was emphasized by Zampolini et al. [15] that the sensory input passively induced by the therapist is an important component in every rehabilitation technique; the traditional exercises should be considered as a standard during intensive rehabilitation [16]. Some researchers also attempted to provide the real contact feeling between the therapist and patient in telerehabilitation. For instance, the portable system designed by Park et al. [17] can detect both the joint angle and the torque on each side. They also proposed two methods for minimizing the effect of network latency, including a teach-and-replay control and a real-time control for fast movement and slow movement respectively. Different from it, we developed the device without using any force sensor, but the output impedance can be controlled with a position control method.

The exoskeleton device is superior to others on the respect that it can train the patient on each joint. Therefore, we used the exoskeleton for training the patient. Most importantly, the developed exoskeleton device is very light (1.5kg) for home use. In the Fig. 1, it can be seen that the therapist is operating a master device while monitoring the status of patients over web-camera and OpenGL-based model. Via the web-camera, therapists can monitor the status of patients, while, a more accuracy kinematic parameters can be seen with the OpenGL-based model. Since the structure of master device is similar with that of human’s upper limb. Therefore, the therapist can operate it directly according to their habits. On the patient’s side, the exoskeleton device is worn by patients on their impaired limbs. Two sides are communicated with the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol.

The remainder parts of this paper are organized as follows. In the part II, the system description of the telerehabilitation is given. In the part III, two important experiments are carried out for evaluating the system performance. The conclusions and future works are given at last.

II. SYSTEM DESCRIPTION

Passive training and active training are two important training methods for recovering the motor function of stroke patients. The passive exercise is suitable for patients with severe impairments and poor motor function [18]. Usually, in the initial stage of the rehabilitation process, the patient cannot move autonomously, therefore, the device should promote a desired motion pattern. Compared with the passive training, the active training is suitable for weak patients [19]. In a one-to-one condition, the therapist can directly assist the patient in performing tasks. The exerting resisting/assisting force and the skill depend on the therapist’s experience. However, if the therapist and the patient are located at different places, the therapist cannot directly sense the condition of the patient, resulting in many difficulties. In this paper, we main introduce the telerehabilitation system for passive training with force feedback. On therapists’ side, the trade-off between generating and receiving the pressure of arm movements are happened on different training modes (passive or active).

A. Exoskeleton device (slave device) for patient’s use

As a home-based exoskeleton device, the device was assembled for a light-weight and compact structure (Fig. 2). Especially, for avoiding the unwanted translational force in elbow joint, two passive Degree of Freedom (DoF) mechanisms were designed for constant alignment between the user’s elbow and robot axes. However, applying both active and passive modalities with only one system became difficult. In detailed, the passive training requires the exoskeleton device to have a relatively high joint impedance, whereas the fundamental requirement of the active training is that the device should provide a near-zero impedance. Here, the impedance is defined as (1), which represents how much the device resists motion when adding an extra force:

$$z(w) = f(w) / v(w)$$  \( (1) \)

where \( z(w) \) is the motor impedance, \( f(w) \) means the resistive force, and \( v(w) \) is the velocity. However, the dynamic of the device became one of the barriers to achieve high impedance accuracy and precision. Different from the commercial products, such as Phantom Premium, Phantom Omni etc. the device became non-backdrivable after introducing a large reduction ratio gearhead. Admittance control can ignore the backlash and tip inertia. However, a high accuracy force sensor is needed since the input of the controller is the interaction force. The force sensor may induce noisily control signal even advanced filtering methods are adopted. Therefore, the non-backdrivable problem was solved by building an elastic contact between the forearm and device.
Thus, the output impedances can be controlled by adjusting the length of the elastic element. By using this control method, the device can generate needed assisting/resisting force. The detailed control method can be found in [20]. The kinematic analysis can be found in [21].

During the telehealth rehabilitation, the force feedback from patient to therapist is important value to ensuring the safety of patients as well as performing an effective training. However, the forearm is always closely contact with the device which induces the difficulty to detect the interaction force. Although the Surface Electromyography (sEMG) which reflects the muscle activities can be used for calculating the interaction force with Hill model, the dynamic motion of the forearm will influence the accuracy [22]. Instead, we added a force sensor (TEDEA Model 1006, total error within 0.0067% of R.O.) under the device. The displacement of the force sensor and the contact plate between the forearm and sensor are shown in Fig. 3. During the data recording, we used an AD board to sample the magnified data with a sample frequency of 1000Hz. This method can be used to detect the suddenly increased force for avoiding the danger happens such as spasm. However, this method cannot be used for admittance control since we cannot get a high-precision control signal.

![Fig. 3 Displacement of the force sensor and contact plate](image)

**B. Human upper limb-like device (master device)**

As mentioned above, the therapist can operate a master device to perform rehabilitation training to patients who are located at home. The prototype of the master device is shown in Fig. 4. The principle of the force sensing part is similar with that of the Series Elastic Actuator (SEA). That is to say, by controlling the deflection of the elastic part, the master device can vary the output impedance [23]. Specifically, SEAs realize low reflected inertia, high shock tolerance with high energy-storage capacity, and accurate and stable force control [24]. The newly proposed design measures the elastic element deflection. A long steel bar is installed on the motor shaft parallel to the elastic element for magnifying the deflection and measuring it at the extreme part. The signal-to-noise ratio was effectively reduced with this method [23]. The master device was designed to meet several requirements. 1) The dimensions of the device should approximate those of a human limb (TABLE I). 2) The therapist should receive the sensation of lifting a human limb. 3) The training action performed by the exoskeleton device on the patient. Therefore, the master device must detect the additional force exerted by the therapist, which is typically resistive for active training. 4) When the force imparted by the exoskeleton device to the patient exceeds the tolerated force, the master device can suddenly increase the force feedback or stiffness, allowing the therapist to appropriately change the force.

This paper main discuss the performance during the passive training. Thus, the master device main detect the motion from therapists. Also, when the patient experiences pain, the resistance of the master device can suddenly increase, and the therapist can appropriately adjust the force to avert danger. For not preventing the motion of therapists, during the passive training, the output impedance of the device should be adjusted as near-zero. Actually, during active training, the force-sensing mechanism can also measure the extra force exerted by the therapist. Therefore, the force-sensing mechanism is the most crucial component of the master device. Notably, the proposed force-sensing mechanism is superior to traditional force sensors, which are expensive and noisy. The contactless angle sensor which can provide the minimum sensation of impedance to the user was selected. The designed force structure fixes the angle sensor and also changes the deflection toward the rotation angle.

### II. EXPERIMENTS AND RESULTS

#### A. Motion tracking test with local network communication

As shown in Fig. 1, the position tracking performance was evaluated. The network latency is not the main issue discussed in this paper, thus two sides were communicated with TCP/IP under a local network environment. During the telehealth rehabilitation, network latency main induce unsafety. In our proposed system, we designed the exoskeleton device with a clutch-like mechanism for avoiding the dangerous. This experiment was to verify whether the motion of therapists can be transmitted to patients’ side. And we selected a typical PID algorithm to keep the exoskeleton device tracking the motion.

<table>
<thead>
<tr>
<th>SPECIFICATIONS OF THE MASTER DEVICE</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm</td>
<td>200</td>
<td>65 (outer)</td>
<td>Plastic</td>
</tr>
<tr>
<td>Upper limb</td>
<td>170</td>
<td>76 (outer)</td>
<td>Plastic</td>
</tr>
<tr>
<td>Elastic element (Linkage bar)</td>
<td>80</td>
<td>5</td>
<td>Steel (E = 206 Gpa)</td>
</tr>
<tr>
<td>Long steel bar</td>
<td>270</td>
<td>4</td>
<td>Steel</td>
</tr>
</tbody>
</table>

![Fig. 4 Prototype of the master device (a human upper limb-like device)](image)
of the master device. The $e(t)$ can be written as (3), in which the $\partial_1$ is the motion of the therapist, while the $\partial_2$ is the rotation angle of the exoskeleton device recorded with encoder. The parameters ($K_p$, $K_i$ and $K_d$) were experimental decided. The time consumption was recorded synchronous for each data, and the sampling frequency of the sensor for recording the motion of therapists was 1000Hz. Generally speaking, there are four steps to perform the passive training. 1) The therapist wears the exoskeleton device and adjusting the rotating centre of forearm in accordance with that of the device. 2) Confirm the IP address, build the communication with Socket, and check the function of web camera 3) Adjust the output impedance of the master device as zero. 4) The therapist can start the training, while the exoskeleton device will track the motion.

The experimental result for evaluating the tracking performance is shown in Fig. 5. The subject (patient) was requested to relax while following the motion from the master side. The red line represents the rotational angle of the exoskeleton device, and the black line represents that of the therapist. We also recorded the time consumption as shown in Fig. 6. The vertical axis represents the time consumption for one-way data delivery and the maximum time consumption in this test was approximately 15ms. During this test, the patient responded no obviously uncomfortable, and the motion of the exoskeleton device was smooth.

\[ v(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t) \]  
(2)

\[ e(t) = \partial_1 - \partial_2 \]  
(3)

**B. Force feedback of the master device**

The closed-loop interaction control method [25] was applied to the master device. The output impedance of the master device can be controlled by adjusting the deflection of elastic elements. We selected the rotation angle of the master device $\alpha$ and the deflection angle of the elastic element $L_i$ as the inputs of the controller. When the therapist operates the device, the load force $F_i$ imposes a deflection $L_i$ on elastic elements as shown in (4) where the $K_i$ is relative to the selected elastic elements.

\[ L_i = F_i / K_i \]  
(4)

And the desired rotation angle of the motor $X_{md}$ with respect to desired rotation angles $\alpha$ is calculated as (5).

\[ X_{md} = \alpha + F_i / K_i \]  
(5)

After adding the virtual impedance model, we can obtain the (6), where $K_i$ and $B_i$ are the desired coefficients.

\[ F_i = K_i \alpha + B_i \dot{\alpha} \]  
(6)

Therefore, at last, by replacing the (6) with (5), we can obtain the (7).

\[ X_{md} - \alpha = \frac{K_i \alpha + B_i \dot{\alpha}}{K_i} \]  
(7)
In this paper, a novel telerehabilitation system for passive training with force feedback is introduced, especially the mechanical design and control method. The control method and kinematic analysis of the exoskeleton device were introduced in our previous study. The closed-loop interaction method of the master device is introduced and the two experiments are carried out for proving that we can control the output impedance in this paper. The interaction force between the forearm and exoskeleton device can be detected with a force sensor installed on the exoskeleton device. A more accurate interaction force will be calculated in our future work. We also did a test for evaluating the tracking performance under TCP/IP communication. In the future, the time delay will be considered. A more effective telerehabilitation system will be developed in our future work with more clinical tests.

ACKNOWLEDGMENT

The research is partly supported by National Science Foundation of China (61375094), Key Research Program of the Natural Science Foundation of Tianjin (13JCZDJC26200), National High Tech. Research and Development Program of China (No. 2015AA043202), and JSPS KAKENHI Grant Number 15K2120.

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