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Development of a Bilateral Rehabilitation Training System Using the Haptic Device and Inertia Sensors

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***Abstract* – According to the neuro-rehabilitation theory, passive, resistance and bilateral training are commonly applied for recovering the motor-function of stroke patient. Among them, bilateral training is proved to be an effective method for the hemiparesis that occupies most part of stroke patients. In this article, a novel system is proposed for providing the bilateral training with coordinative motion of two limbs. This system is developed for the elbow function recovery and the motion of two limbs is detected with two inertia sensors. A commercial haptic device (Phantom Premium) is adopted for providing a feedback with information of errors and how to correct them. Combined with a graphic interface which provides a visual feedback, the patient can adjust the two limbs to a coordinative motion. This system can perform the training to those patients with some muscle strength. However, usually the rehabilitation training is hierarchical and those patients with little muscle strength can even not lift their own limbs. Therefore, a light-weight exoskeleton device is applied and this device could provide partial assisting force, thus the patient can gradually adapt to the training. In this article, an issue about the effectiveness of feedback is discussed and verified with several contrast experiments.**

Index Terms – Haptic device, Exoskeleton device, Bilateral training, Upper limb rehabilitation, Feedback

I. INTRODUCTION

According to the statistics, approximately 795,000 people continue to experience a new or recurrent stroke (ischemic or hemorrhagic) [1]. In about 85% of cases, stroke causes hemiparesis in subjects, resulting in impairment of the upper limb and disabilities in performing activities of daily living (ADL).

Robotic therapy has been shown to increase the range of motion, strength, and agility of arm movements in chronic stroke patients, and many researches have focused on this research [2]-[6]. Researches have also noticed that virtual reality is effective for rehabilitation in recent years, some successful rehabilitation systems have been developed based on the virtual reality [7]-[8]. However, most of the existed rehabilitation robots are focus on the recovery of the affected limb only and this kind of trainings is called unilateral training. Since lots of tasks in the daily living need the coordination of two limbs, the bilateral upper limb training is important [9]. Some training systems have been developed for the bilateral training. Such as, the Virtual Reality Piano is a robotic and virtual environment system, and both of the arms and hands can be trained with the visual, auditory, and tactile feedback using a force reflecting exoskeleton [10]. The EXO-UL7 is a two-arm exoskeleton robot with 7 DoFs for each arm. In the bilateral mode, the desired joint angles are mirror symmetrically transmitted from the less impaired upper limb to the most impaired upper limb [11]. A novel upper extremity motor function rehabilitation system that can be manipulated by patients through a haptic device and an inertia sensor to perform a tracking task in virtual environment with coordination training of bilateral upper extremity is proposed [12]. Previous research also proved that the achievement of the goal of movement can be facilitated with feedback. The feedback needs to provide information on errors in movement and how to correct them by increasing the level of skill attained or by speeding up the learning process [13]. In our study, a commercial haptic device (Phantom Premium) is utilized for generating a desired force feedback. The feedback can provide the information on movement errors and the patient can correct their motion with the feedback. As a commercial product, Phantom Premium is easy to operate and set a desired torque in the horizontal and vertical plane. The elbow recovery training is built on the vertical plane, and the ability of flexion and extension can be trained. Motion of the two arms is calculated with the inertia sensor, and virtual task is rendered with the OpenGL environment. An exoskeleton device was also developed for those patients with little muscle strength which even make them difficult to lift their own limb [14]. The exoskeleton device can provide partial assistive force during the rehabilitation training, and this device is lightweight and compact (Fig.1). The force that provided by the Phantom and the exoskeleton device is different from the function. The exoskeleton applied in this system is a power assisting device, while, the Phantom main provide the feedback on movement error and how to correct the error. In this article, the subject with physical fitness is selected, so the exoskeleton device is not applied with the healthy subject. The principle of the impedance generating of the exoskeleton device is introduced in this article.

The remainder of this article is organized as follows. In the section II, the function of the exoskeleton device is mainly introduced including the control and structure design. In the section III, the training which is used for recovering the elbow function is introduced and several experiments are carried out.

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The performance of the proposed system is evaluated with the mean squared error between the affected and unaffected arm for each experiment. In the final section, the conclusion and future works are given.

II. THE FUNCTION OF THE EXOSKELETON DEVICE

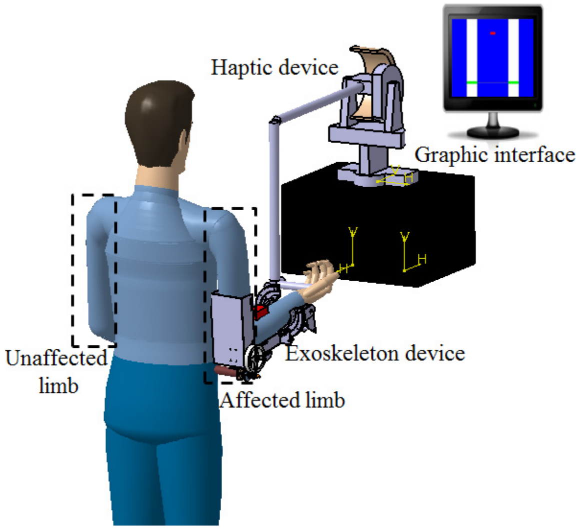

Fig.1 Bilateral training for recovering the elbow function

The conceptual graphic of the bilateral training for recovering the elbow function is shown in Fig.1. The exoskeleton device is worn by the affected limb for providing some power assist. The weight that the exoskeleton provides is decided by the need of the patient. The signal can come from the biological signal and it can receive some benefits on the real time adjustment of the weight [15]-[17]. The exoskeleton device (Fig.2) allows an ergonomic physical human-robot interface, so this device has a convenient wearing and comfortable interaction [18]-[19]. Two passive DoFs mechanisms in the elbow joint allow the constant alignment between the user's elbow and robot axes during movement. And the translational forces can be avoided which main caused from the joint misalignment between the robot and human joints. The security problem is also considered for the device design. The axle sleeve of the elbow motor is connected to the helical capstan shaft due to the friction by adjusting the outer thumbnut. Therefore, the helical capstan shaft will apart from the motor shaft when overload. In the actuated DoFs of elbow joint, power derived from motors is transmitted to a drive pulley through stainless steel wire ropes which can not only provide enough torque for passive training, but also decrease the backlash which is usually found in geared mechanisms. And the rotational velocity is decreased via high ratio gearheads (231:1). The exoskeleton device has enough bandwidth and power to realize the desired positioning performance with the desired high impedance (the impedance is the relationship between the velocity and force). However for the proposed bilateral training, the exoskeleton device should provide partial assisting force for the affected limb and not influence the function of the haptic device. It is necessary to minimize the interaction force between the user and the exoskeleton so that the device can follow the motion of the user and provide properly partial assisted force by increasing the power of motor. Nevertheless, the high ratio gearheads induces the device non-backdrivable which induces the impedance control difficult to use. And the admittance controlled systems detect the force commanded by the operator, thus the high accuracy force detection and a high dynamic response are demanded. This issue has been solved, facilitating both low- and high-impedance control modes [14]. The working principle of the proposed control method is related to the Series Elastic Actuation (SEA) [20]. The important difference with standard SEA is the utilization of a cable transmission and the detachment of the power source from the robot frame.

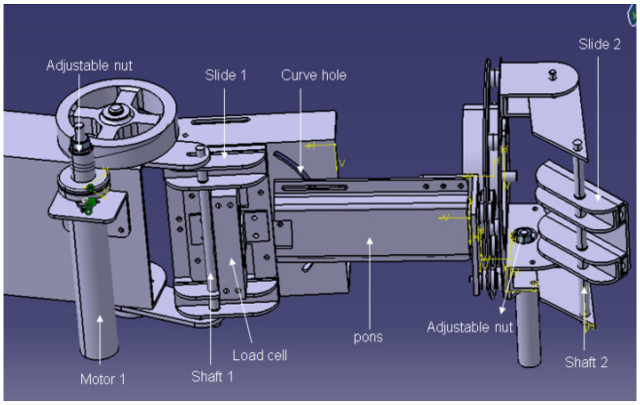

Fig.2 The exoskeleton device (Lower view)

An experiment was carried for verifying the performance of the proposed control method. By changing the friction with the clamp nut of the exoskeleton device, the shaft sleeve of the elbow motor can apart from the grooved pulley, so that the elbow motor will not provide the power to the robot frame through the cable transmission. A force sensor (FS03, Honeywell) (Fig.3) was added between the forearm and the elastic belt for detecting the interaction force during the flexion motion. The activity of the biceps muscle which plays a key role during the flexion motion was detected with sEMG (Surface Electromyography). sEMG signal was collected using bipolar surface electrode which is 12mm long and located 18mm apart. The sampling rate was 1000Hz with differentially amplified (gain 1000) and common mode rejection (104dB). The collected sEMG was then filtered with high-pass frequency using 10Hz and reconstructed with RMS value. A contrast experiment was carried out. In the first situation, the grooved pulley was apart from the shaft sleeve without using the clamp nut. In this case, the motor did not provide the power to the robot frame. A volunteer with physical fitness was requested to flex his forearm while the

MTx can record the flexion angle. In this case, the biceps muscle needed to contract and conquer the weight of both the device (totally 1.3kg) and the forearm. Fig.4 and Fig.5 show the experimental results in the first case which are the relationship between the flexion angle and the reconstructed sEMG or interaction force respectively. The peak value of the RMS value of sEMG is 0.08V and the peak value of the interaction force is 0.36N. In the second situation, the grooved pulley connected with the shaft sleeve using the friction facing. In this case, the device became non-backdrivable caused from the high friction in the gear reductor. By implementing the proposed control method, the device became soft and the desired force was set zero in this case. The experimental results are shown in the Fig.6 and Fig.7 which are also the relationship between the flexion angle and the reconstructed sEMG signal or the interaction force respectively. The peak value of the RMS value is 0.07V and the peak value of the interaction force is 0.62N. Compared with the two cases, the sEMG recorded from the biceps muscle was almost the same, and the interaction force was a little increased by 0.26N. The reason was caused by the delay of the angle detection relative to the motion. In the other word, the device must detect the motion and then the device can follow the motion. The result reveals that the proposed control method can minimize the interaction force with a low value. And the device can provide a variable assisting force during the active training with some additional power to the patient.

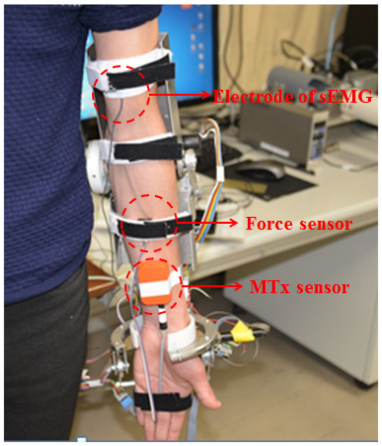

Fig.3 Performance evaluation of the proposed control method

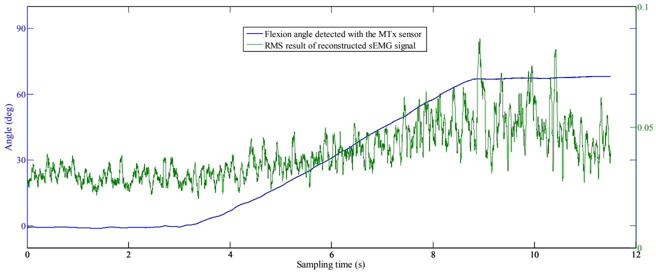

Fig.4 Flexion angle and the reconstructed sEMG (The shaft sleeve is apart from the grooved pulley)

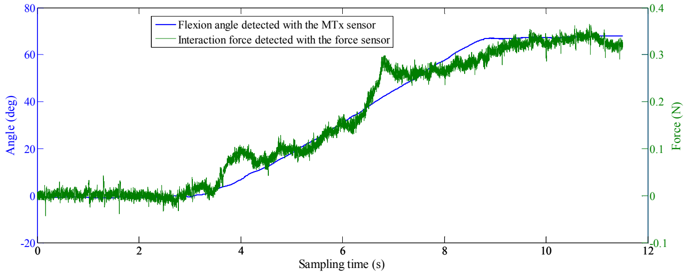

Fig.5 Flexion angle and the interaction force (The shaft sleeve is apart from the grooved pulley)

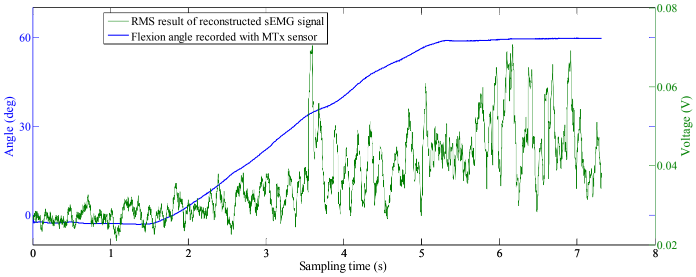

Fig.6 Flexion angle and the reconstructed sEMG (The shaft sleeve connects with the grooved pulley using friction facing)

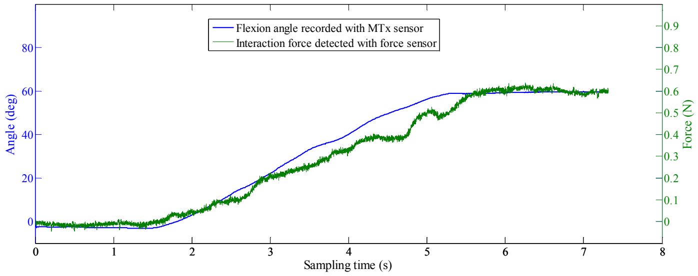

Fig.7 Flexion angle and the interaction force (The shaft sleeve connects with the grooved pulley using friction facing)

III. COORDINATED TRAINING ON THE VERTICAL PLANE

The hardware of the training system (Fig.1) is consist of two inertia sensors (MTx, Xsens Technologies B.V), a haptic device (Phantom Premium) and a PC combined with a graphic interface. The training interface is developed with Microsoft Visual Studio 2010 combined with OpenGL environement. Both of the two limbs should move from the initial position where two limbs relax vertically. And the affected limb operates the handle of the Phantom and synchronously move together with the unaffected arm to the target position. The position of the target can randomly change. The training model is illustrated in Fig.8. H_1 and H_2 represent the height showed in screen, and the height are relative to the flexion or extension angle (Euler angle) recorded with the inertia sensor (Fig.8). The condition that the target changes its position happens when $|H_1 - H_2| < 5\,\text{deg}$ and overlaps the target, where the 5deg is the actual angle difference detected with the inertia sensor. The threshold degree can be changed according to the training difficulty. The Phantom Premium can generate the needed force with an open-loop impedance controller which is shown in Fig.9. In this controller, the linearized device dynamics are represented by ${}^{j}Z_h^{-1}$ which is the relationship between the torque input and the differential angular output. The desired position deflection is

$$\Delta x_d = x_d - x_0 \tag{1}$$

And the actual deflection is shown in (2).

$$\Delta x = x - x_0 \tag{2}$$

Therefore, the force command F_d can be obtained with (3).

$$F_d = Z_d(\Delta x_d - \Delta x) = Z_d H \tag{3}$$

In the proposed training, the desired environmental impedance Z_d is set as a spring condition, and the elastic coefficient is selected considering about the force sensing ability of human and the tolerated toque of the Phantom. The environmental impedance can also be changed easily with task demand. Obviously, the affected arm can obtain the force feedback with two directions. If the affected limb is located above the unaffected limb, the Phantom will provide a force downward. On the contrary, an upward force is provided. Therefore, the patient can judge their motion and correct it according to the force magnitude and direction. The proposed feedback can provide information on errors in movement and how to correct them. The angle information also transmits from the unaffected limb to the affected limb.

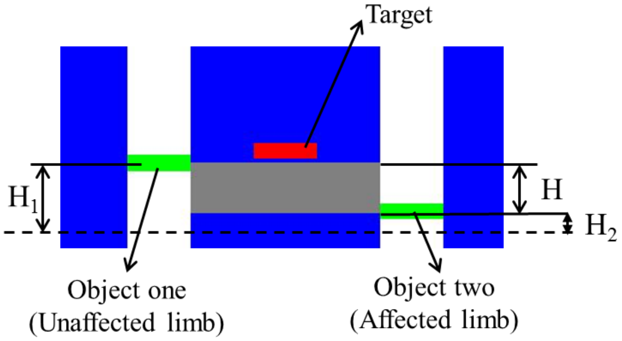

Fig.8 The proposeed training model

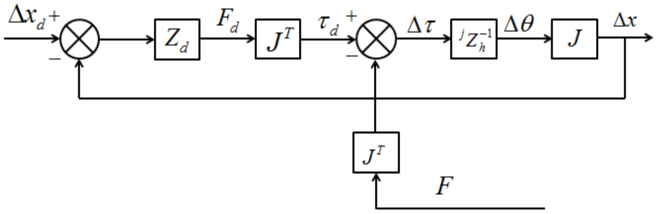

Fig.9 Open-loop impedance controller for Phantom Premium [15]

For verifying the effectiveness of the proposed training method, three subjects with physical fitness were involved, including a female with the age of 26, two males with the age of 25 and 27. Fig.10 shows one of the three subjects (27, male) who is performing the training. During the training, each subject achieved 5 groups contrastive experiment, and each group contained two experiments including one without force feedback and one with force feedback. The concrete information that the force provided by the Phantom was not told to the subject. In the other word, the subject did not understand what kind of force that the Phantom will provide. After introducing the function of the developed graphic interface and some basic requirements, the subject was requested to start the experiment from the condition that two limbs relax vertically and two limbs synchronously move together to the target position. Each subject was requested to achieve 20 times tasks in each group, and the speed and time was not limited. Fig.11 to Fig.13 show the experimetal result of the third group of subject one (female, 26). In Fig.13, it can be seen that the magnitude and direction changes along with the relative position between the two limbs. The performance was appraised with squared error as (4). In the (4), $x^{'}(i)$ represents the trajectory of the affected limb and the $x(i)$ is the trajectory of the unaffected limb. N is the sampling numbers which is relative to the time. The feedback can help to speed up the learning process proved by the statistical data which is shown in Table I to Table III. And there are some feedbacks from the subject. These feedbacks can reflect the state when performing the training. And the feedback can next be considered when the proposed training system applied on the stroke patient.

(1) May be caused by the instinct of human, sometimes the limb will resist the force come from the Phantom.
(2) Sometimes, the subject was inclined to use the unaffected limb to assist the affected limb. For example, in the case of upward motion, the subject would consciously let the unaffected limb higher than the affected arm, and the Phantom will provide an upward force.
(3) In order to achieve the training task well, sometimes the subject paid more attention on the error of the two limbs other than which one is higher than the other one.

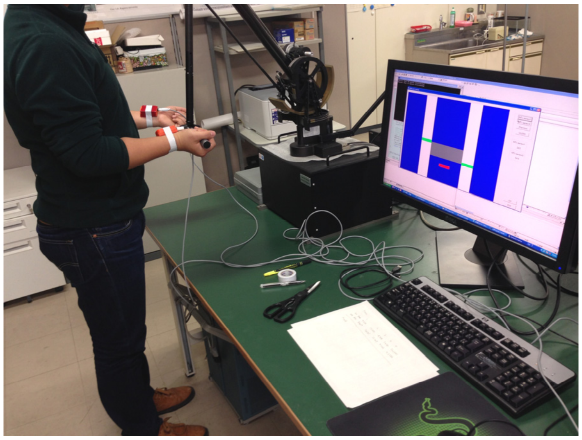

Fig.10 Performing the training (One of the three subjects, 27, male)

$$\delta = \sum_{i=1}^{N} (x'(i) - x(i))^2 / N \qquad (4)$$

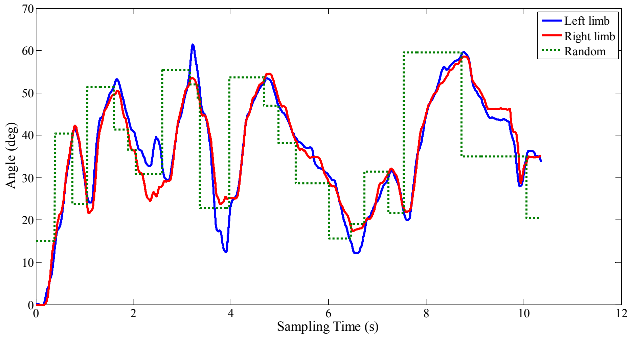

Fig.11 No force feedback (The third group, Subject one)

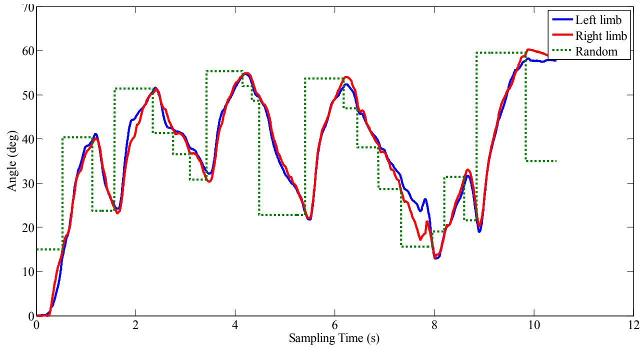

Fig.12 With force feedback (The third group, Subject one)

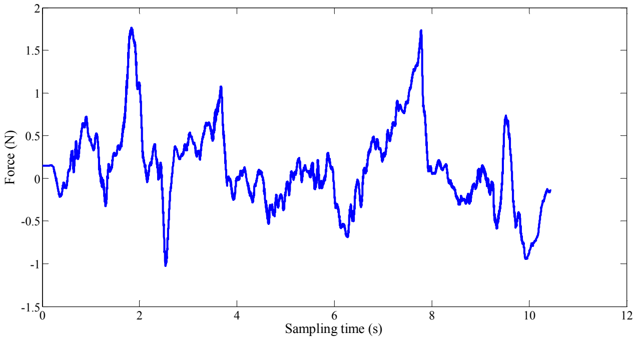

Fig.13 Force feedback from the Phantom (The third group, Subject one)

TABLE I
THE MEAN SQUARED ERROR OF THE SUBJECT ONE

	No.1	No.2	No. 3	No. 4	No. 5
Without force feedback	6.4816	8.8010	10.5493	4.7729	4.7385
With force feedback	3.4094	3.6119	2.9431	3.2552	3.4413

TABLE II
THE MEAN SQUARED ERROR OF THE SUBJECT TWO

	No.1	No.2	No. 3	No. 4	No. 5
Without force feedback	4.6174	4.5014	5.0388	3.3374	6.1847
With force feedback	3.8656	2.8593	2.0375	2.3277	2.5208

TABLE III
THE MEAN SQUARED ERROR OF THE SUBJECT THREE

	No.1	No.2	No. 3	No. 4	No. 5
Without force feedback	15.2873	4.7814	4.6092	6.9055	13.3800
With force feedback	13.7250	2.4285	4.4684	3.2595	8.5418

IV. CONCLUSIONS AND FUTURE WORKS

For recovering the motor function of stoke patients with hemiparesis and help them adapt to the activities of daily living (ADL) as soon as possible, a novel bilateral training system is introduced. The advantages of this system are summarized as follows.

(1) By using the OpenGL environment, a visual feedback is provided. With the stimulation of the visual feedback, the patient can know well the state of their limbs, and the error to the target.

(2) The motion of the two limbs is detected by an inertia sensor. This sensor is easy to wear and can obtain an accurate result.

(3) The combination of a haptic device and an exoskeleton device on the affected limb is a novel attempt. The haptic device provides the information on movement errors and the patient can correct their motion with the feedback. However, the stroke patient is not easy to operate the haptic device caused by their muscle twitch and other reasons. The exoskeleton device can provide a partial assisting force to help them achieve the task.

The effectiveness of force feedback is verified with several experiments and involved three subjects with physical fitness. The mean squared error is calculated with the trajectory of affected and unaffected limb. And the experimental result reveals that the coordinative motion can be performed well with the force feedback.

In the future, more experiments should be carried out to find the relationship between the external feedback and the training effect. Some other intelligent sensors are considered to add in this system, consequently a more effective training system.

ACKNOWLEDGMENT

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