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Development of a Real-time Upper Limb's Motion Tracking Exoskeleton Device for Active Rehabilitation Using an inertia Sensor

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***Abstract* - In this paper, a real-time upper limb's motion tracking exoskeleton device is proposed and developed, which can be used in active rehabilitation of upper limb for stroke. This device is portable and wearable and is potential to be used in the passive and active training for stroke patients. Passive training has been finished in previous work and in this paper, the preliminary work for active rehabilitation is presented, which is realization of the real-time upper limb's motion tracking. We use an adaptive weighted average filtering and double close-loop control to realize real-time and stable tracking performance. Experiments have been conducted to prove that it is suitable for active rehabilitation.**

Index Terms – Exoskeleton device, Motion tracking, Inertia sensor, Upper limb.

I. INTRODUCTION

As we known, stroke is a leading cause of disability in Europe Union countries and U.S. Approximately 700,000 people experience a stroke each year in the United States[1]. The financial burden of stroke is heavy for social and family. It is estimated to cost 62.7 billion dollars in medical expense and lost wages in United States [2]. Passive training and active training of rehabilitation influence plasticity and recovery of the brain following a stroke [3], [4], but there is still an argument that which is more effective in rehabilitation of stroke.

With the development of robotics and mechanotronics, both of rehabilitation strategies can be realized by using rehabilitation device. One of the first robotic rehabilitation systems for upper limb recovery of stroke is developed by Krebs et al, which is called MIT-MANUS [5], [6]. It allows two degrees of freedom for movement of upper limbs including wrist, elbow and shoulder movements by performing task-oriented training. It can provide passive and active rehabilitation to stroke patients and it has improved motor function in the hemiparetic upper limb of acute and chronic stroke patients in clinical trials [7]. In 1997, with the cooperation of Stanford University and Rehabilitation Research and Development Centre, another rehabilitation system named MIME (Mirror-image motion enabler) has been developed [8], [9]. This robot can work in preprogrammed position and orientation trajectories. It can also provide mirror movement that affected upper limb can perform as the movement of intact upper limb. Different from it, Guo and Song in Kagawa University have developed a coordination rehabilitation of bilateral upper limb using a haptic device and an inertia sensor [10]. The ARM Guide is a singly-actuated, four-DOF robotic device that consists of a hand piece attached to an orientable linear track and actuated by a DC servo motor. [11]. Gentle/s was a three year project funded by the European Commission to develop machine mediated therapies for neurorehabilitation of people with stroke. Gentle/s had the aim to improve quality of treatment and reduce costs [12]. These robots have succeeded to provide patients enough assistance of force and training range. However, they can not perform rehabilitation in joints respectively, so that there are also some limits in rehabilitation training, especially in each patients training. The exoskeleton robots developed recently for rehabilitation solve this problem. One of typical device MEDARM, developed by the Canadian Institutes of Health Research (CIHR), is based on a cable driven curved track mechanism that provides independent control of all five major degrees of freedom (DOF) at the shoulder complex [13]. ARMin[14] is an exoskeleton device with six independently actuated degrees of freedom and one coupled DoF. It can provide passive and active rehabilitation to stroke patients. It can significantly improve motor function of the paretic arm in some stroke patients, even those in a chronic state [15]. These systems have advantages in upper limb rehabilitation including providing passive and active rehabilitation, enough range of movement, but they are still of some disadvantages. For example they are heavy and not suitable for home-rehabilitation. In this paper, we designed a novel upper limb rehabilitation system, which is compact and portable and it is suitable for home-rehabilitation.

In previous work [16], we have realized the passive training by using this system. It is necessary for severe stroke patients. But some researcher indicated that active training can induce better rehabilitation outcome, because it can improve brain neuron recovery. In order to enlarge the rehabilitation function, in this paper, some important preliminary work is presented, which is realizing real-time upper limb's motion tracking. Difference from other research [17], [18], we use an inertia sensor (MTx) [19] to track the motion of upper limb. Certainly, electromyography (EMG) is good to predict upper limb's motion, but it is not easy to be used in real-time because of the difficulty in using the EMG signals as the controller input signals, and in the other hands, it is expensive and not compact. This paper is organized as follows. It first introduces the relative research. In Section 2, the previous work and the proposed rehabilitation system are presented. The proposed assessment system for rehabilitation is shown in Section 3. Experiments and results are presented in Section 4. The assessment of training results is presented in Section5. The last section presents paper conclusion. should observe the following instructions.

II. Proposed System

A. MTx sensor

MTx sensor is an inertia sensor with small size (Fig.1). Its unit combines a tri-axial accelerometer, a tri-axial magnetometer and a tri-axial gyroscope. With sensor fusion algorithm, the sensor is able to distribute the raw sensor data and a drift free orientation. It can be used in detection of “pitch”, “yaw” and “roll” directly after calibration.

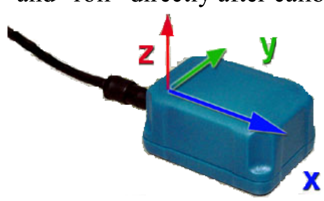


Fig. 1 MTx sensor

B. Mechanism of exoskeleton device designed

Allowing for realizing passive and active rehabilitation and precise control, we choose brushless DC motor instead of other actuator. The exoskeleton device for upper limb rehabilitation has 3 DoF, including elbow extension/flexion, forearm pronation/supination and wrist extension/flexion. In this paper, elbow extension/flexion is mainly to be presented. The transmission component utilizes a steel cable and a helically grooved capstan shaft, because it is backlashless. We fixed the middle of cable onto a helically grooved capstan shaft, which can realize back driven in passive rehabilitation.

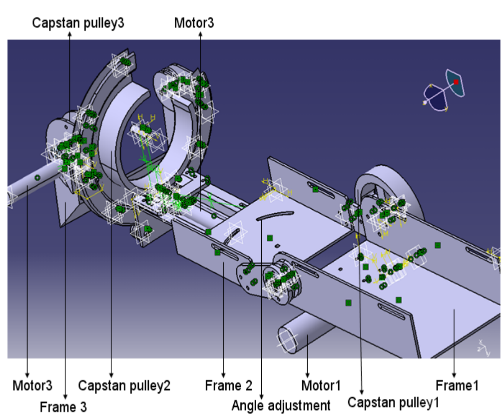


Fig. 2 Exoskeleton device concept

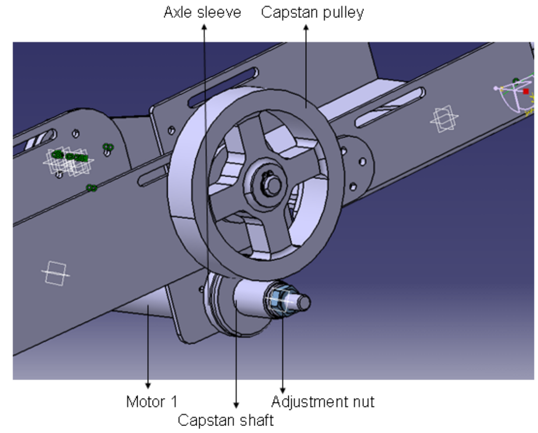


Fig. 3 Transmission mechanism

Allowing for safety, there is also mechanical design to keep the patients safe during rehabilitation. The helically capstan shaft can be apart from motor shaft when overload in terms of each patients. Specifically speaking, axle sleeve of motor connect with the helically capstan shaft depending on the friction which can be adjust by an outer thumb nut. The safety precaution should be done before rehabilitation.

C. Actuator

It is important to choose the actuator in the process of designing a portable and wearable exoskeleton device for upper limb rehabilitation. We choose Maxon BLDC motor because of light weight, compact size, higher power density and torque density than conventional motors (Table I). Because in passive or active rehabilitation mode, patients’ upper limbs rotate slowly, the gear ratio should be high. In general haptic device used in rehabilitation, gear ratio is low [20]-[23]. We should implement real-time motion tracking before active rehabilitation so that patients perform active rehabilitation with less resistance. In this paper, we focus on realizing elbow joint’s motion tracking in real-time with an inertia sensor.

Table I: character of actuator combination

weight	85 g
voltage	24 V
Max. continuous torque	14.2mNm
Max. continuous speed	50000rpm
Encoder precision	512
Gear mechanism	231:1

III. Control Methodology

We created visual graph by utilizing OpenGL, and it can monitor the status of device, including angler and velocity of rotation. In order to realize the real-time motion tracking, the thread of reading and setting angle or velocity is of higher priority than rending OpenGL graph (Fig. 4). The real-time motion tracking system is implemented in the environment of Visual Studio 2003, where the computer is a HP workstation with Pentium 4 (3.4GHz) CPU. The wearable exoskeleton device will be back-drivable so that patients can move their

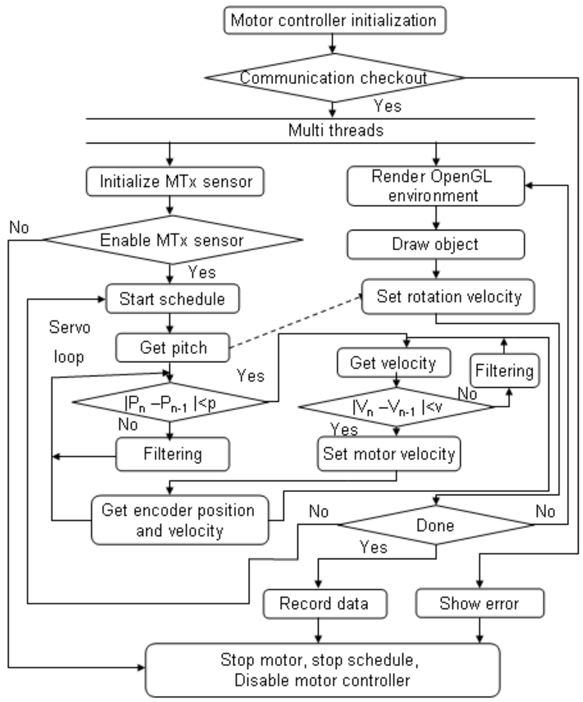


Fig.4 Software flow chart

elbow joints with less resistance from the motor–driven device when it works in active model. But the high gear ratio involved makes it not back- drivable owing to large friction torque. Therefore we used MTx sensor to detect motion of upper limb and realize the device can be back-drivable.

A. *Adaptive weighted filtering*

The values derived from sampling of angle and rotation velocity of MTx sensor could include additive noise, rotation velocity in special. Therefore, it is necessary to process these raw values. Some predefined values derived from many times experiments are set as threshold value to make data effective. If value derived from sampling is over the threshold value, it will be modified through filtering. But it is not enough to obtain desired values. There are some kinds of filtering that can be realized in program [24]-[26], but few of them can be satisfied in real-time control. Some splendid filtering methods require lots of calculation. In this paper, we used a simple adaptive weighted averaging filtering which is be calculated with only 4 values within one time (1).

$$\bar{y} = 1/N\sum_{n=1}^{N} A \cdot y_n \tag{1}$$

Where y_n is the raw value derived from sampling; $N = 4$ in this paper; A is the weighted coefficient which is calculated according to y_n . Fig.5 and Fig.6 show one example of rotation velocity derived before filtering and after filtering. It is obvious that the value after filtering become smooth.

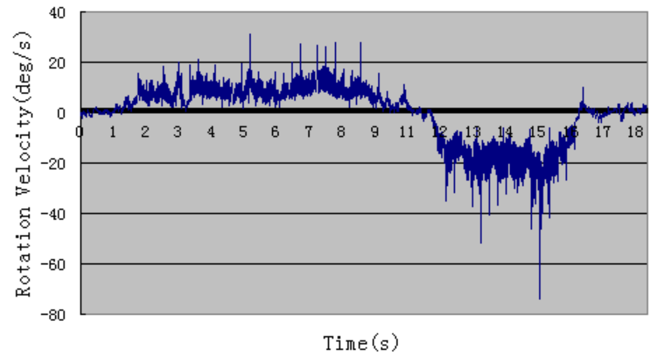


Fig.5. Rotation velocity before filtering

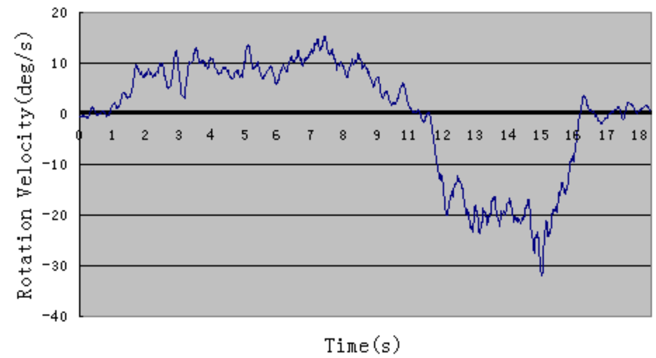


Fig.6. Rotation velocity after filtering

B. *Double closed-loop control*

In order to obtain precision motion tracking, a double closed loop control is proposed. The block diagram of control is shown as Fig. 7. k_p , k_i and k_d are the coefficients of PID in motor controller and they can be set through RS232. a is the pitch angle of MTx sensor. ω_1 is pitch angle velocity processed. ω is output velocity of motor. k_1, k_2 and k_3 are proportional coefficients in every element. The coefficients of PID in motor controller can be obtained through many times experiment under variable velocity circumstance before motion tracking experiment. Therefore system transfer function can be calculated with (2). Though the current loop is not mentioned in this paper, it is also detected to make sure that torque exerted by motor is under safe level.

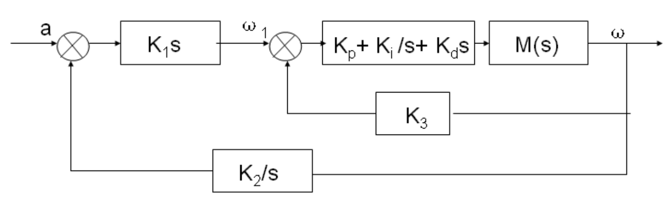
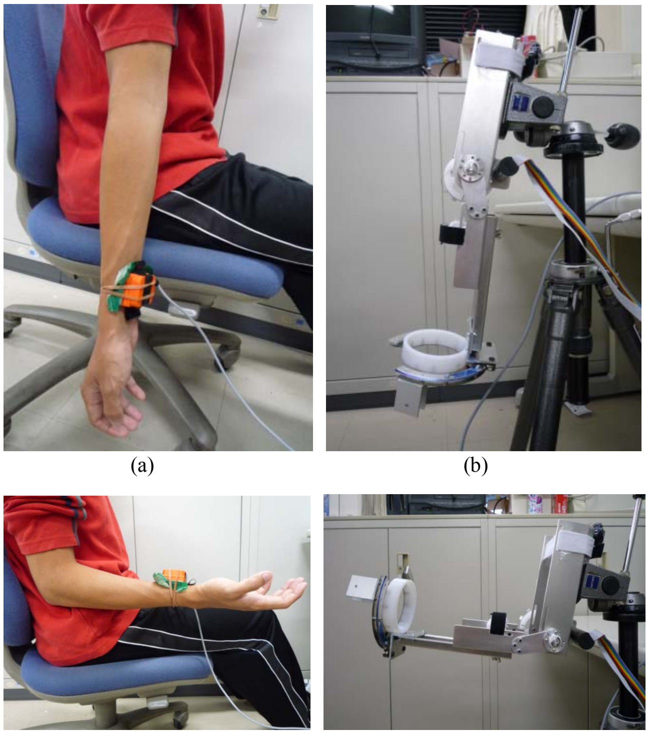


Fig.7 Double closed-loop control block chart

$$G(s) = \frac{K_1 K s}{1 + K_3 K + K_1 K_2 K} \tag{2}$$

$$K = (K_p + K_i / s + K_d s) M(s) \tag{3}$$



(a) (b)

(c) (d)

Fig.8. (a) shows elbow joint and exoskeleton device extension. (b) shows elbow joint and exoskeleton device flexion

IV. Experiments and Results

A. *Motion detection and coefficients calculation of system*

Before performing real-time motion tracking experiment, we should detect the motion of upper limb and obtain the coefficients of system and calibrate the inertia sensor and exoskeleton device. Firstly, the inertia sensor is fixed onto a healthy subject's upper arm near to his wrist. The subject is required to perform elbow extension/flexion at a slower speed than normally with upper arm fixed (Fig. 8 (a) and (c)).

Because the purpose of experiment is to realize the function that exoskeleton device rotates at the same step with subject's lower arm. According to this condition, we can estimate the proportional coefficients or set lower value to system. Then we conduct the experiment that subject rotates his lower arm around elbow joint with inertia sensor fixed near to his wrist joint. On the other hand, exoskeleton device is fixed on a tripod with component of upper arm fixed (Fig. 8 (b) and (d)). The optimized proportional coefficients can be calculated by input and output of system in many times according to (2) and (3).

Generally speaking, human elbow can perform flexion and extension from 0° to 135°. In order to facilitate more patients, range of rehabilitation is set to 0° to 90°. If the capstan pulley rotates over this range, the motor will be stopped at once. Besides, if the capstan pulley rotates at or over the safety velocity, the motor will be also stopped at once, which can be set according to the therapist's experience and patients' physical condition.

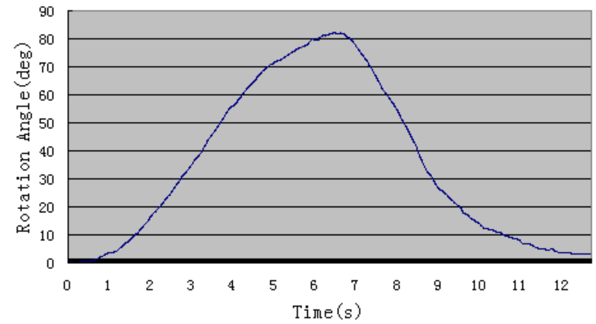


Fig.9. Rotation angle of upper arm with MTx sensor

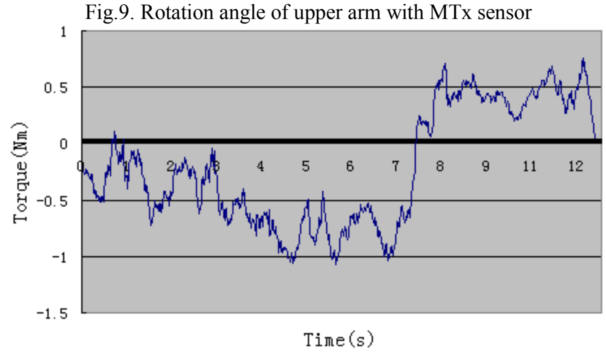


Fig.10. Motor current

Fig. 9 shows the angle value derived from inertia sensor when subject rotates his upper arm around elbow joint from 0° to 90° and from 90° to 0° without wearing exoskeleton device. The frame2 (Fig.2) of exoskeleton device also rotates around elbow joint at the same step of inertia sensor. In this system, force sensor is not adopted, and we have considered an alternative to estimate the resistance during experiments and it will also be used to make performance safe. That is the motor current because of the relationship between the torque and motor current. Therefore, the filtered current I_m is used to assess the resistance of elbow joint. The torque exerted on motor can be obtained in terms of current.

$$T = nlI_m$$

(4)

where T is the torque exerted on motor. l is the coefficient of motor (here, $l = 23.5mNm/A$), n is gearhead ratio. Fig. 10 shows one example of filtered torque when elbow joint of exoskeleton device rotates.

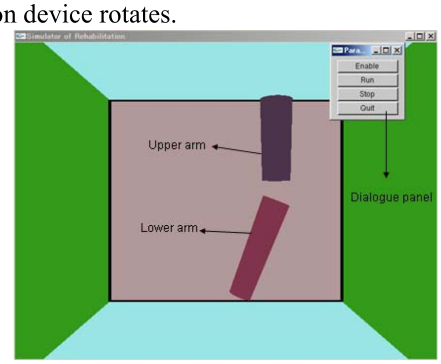


Fig.11. Experimental virtual environment

Fig.12. Subject wears the exoskeleton device with MTx sensor fixed on his upper arm.

B. *Experiments of motion tracking of upper limb*

We create visual interface using OpenGL, in which two linkages stand for upper arm and lower arm. There are also some manipulation buttons on the monitor, including “enable”, “quit” and so on (Fig.11). After confirming the proportional coefficients, motion tracking of upper limb will be performed. Subject sits on a chair facing the monitor of computer. The exoskeleton device is fixed onto his right arm with flexible cable. The MTx sensor is fixed on the upper arm near to wrist joint (Fig.12). The purpose of this experiment is to realize the synchronization motion of upper arm and exoskeleton so that the subject should feel less resistance during performing experiment. If it can be realized, programmed resistance could be added to patients and active rehabilitation can be provided in that kind of condition.

At the beginning of experiments, subject is required to stretch his lower arm and relax so that his arm is put vertically like Fig.12. Then he puts up his lower arm and keeps his upper arm immovable until his lower arm is in horizontal plane and then put his lower arm down to original place. During this process, subject is looking at monitor. Allowing for in active rehabilitation, stroke patients move their upper limbs slowly, so that in this experiment, subject is required to perform task in more slowly than normally.

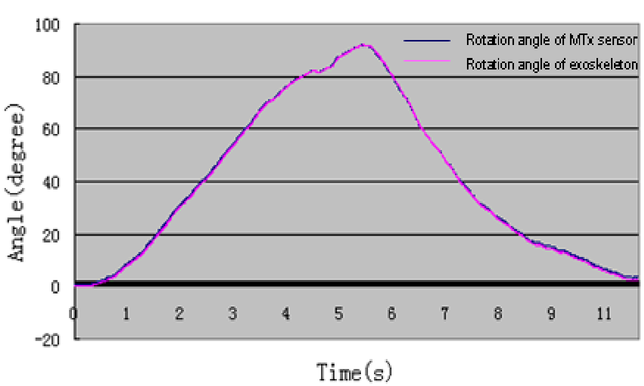


Fig.13. Rotation angle of MTx sensor and exoskeleton device

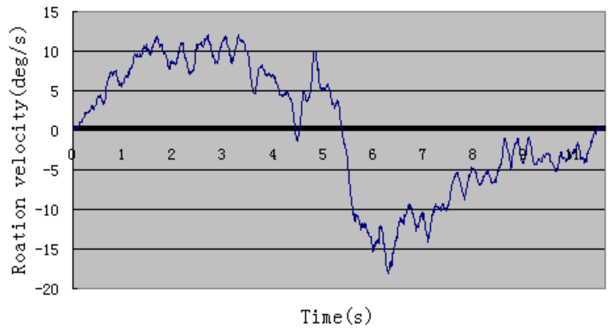


Fig.14. Rotation velocity of MTx sensor

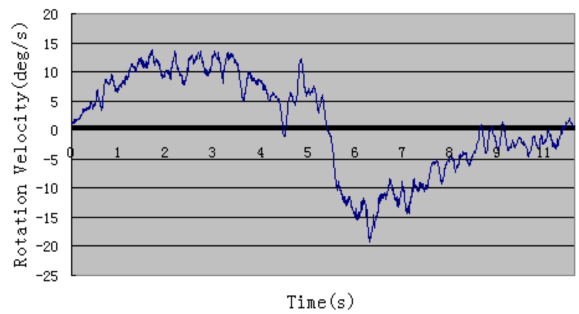


Fig.15. Rotation velocity of exoskeleton device

From Fig.13 and Fig.9, we can know that subject’s performance of the rotation motion of lower arm with wearing the exoskeleton device and MTx sensor is almost the same with that without wearing the exoskeleton device. Therefore, this prototype of exoskeleton device is suitable to be used in active rehabilitation. In Fig.13, blue curve stands for the rotation angle of MTx sensor and pink curve stands for the rotation angle of exoskeleton device. It is also observed that both of curves are almost the same. At the beginning of experiment, the rotation angle of MTx sensor is a little higher than that of exoskeleton, because the filtering mentioned above adopted 4 values. At the end of experiment, the same problem appears which is because the softness of skin makes lower arm moves a little relative to exoskeleton device. But it influences the performance weakly. When subject puts up his lower arm to horizontal plane, the velocity becomes lower.

From Fig. 14 and Fig.15, the rotation velocity of MTx and exoskeleton device is also almost the same, expect at the end of experiment.

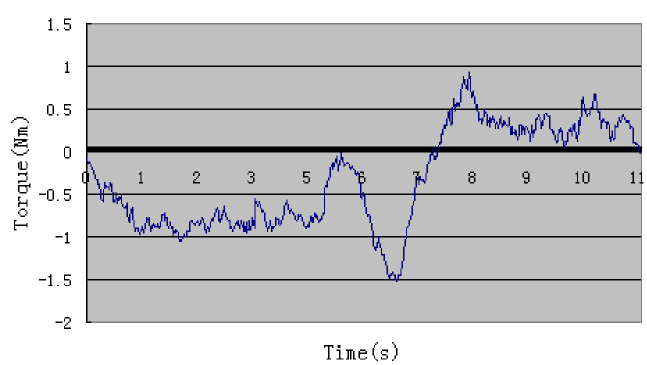


Fig.16. Output torque of motor

Fig.16 shows the output torque of motor during the experiment. According to Fig.10, we can learn the output torque is higher than before at fifth second, which is because the elastic cable prevent skin stretching. Resistance of structure influences subject's performance only in small range. Above all, this exoskeleton device can realize the motion tracking of upper arm in real-time in large range.

V. CONCLUSION AND FUTURE WORK

In this paper, a real-time upper limb's motion tracking exoskeleton device is proposed and developed, which can be used in active rehabilitation of upper limb for stroke. MTx sensor is used to detect the rotation motion of upper limb. We use an adaptive weighted average filtering and double close-loop control to realize real-time and stable tracking performance. Values of rotation angle of MTx sensor and exoskeleton are almost the same and output torque of motor in experiment of subject's wearing exoskeleton is almost the same with before, expect for in horizontal plane. Subject can move his upper arm with less resistance in a large range. Therefore, it verifies that this system can realize the real-time motion tracking in large range and is potential to be used in active rehabilitation. This system is portable and wearable and is suitable for home-rehabilitation. In the future, we will solve the resistance in horizontal plane and program some force model by using this system.

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