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On the design of a robot-assisted rehabilitation system for ankle joint with contracture and/or spasticity based on proprioceptive neuromuscular facilitation

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Abstract— **Ankle joint with contracture and/or spasticity can severely disable the mobility and the independence of stroke survivors. Robot-assisted rehabilitation has been proposed to support physicians in providing effective therapies. In this paper, we propose a robot-assisted ankle rehabilitation system integrated with human-computer interaction interface and acquisition of Electromyography signals, joint torque and joint angle. Furthermore, we investigate the effects of proprioceptive neuromuscular facilitation (PNF) rehabilitation method applied in our robotic system. The proposed robot-assisted system has been used in real experiments and provides PNF rehabilitation to five stroke patients for six weeks. Preliminary experimental results suggest that PNF is effective in increasing ankle range of motion(ROM), decreasing ankle resistance torque, and alleviating joint stiffness.**

I. Introduction

Human ankle joint, as a flexible and complex skeletal structure in human body, plays an important role in providing forward propulsion force during terminal stance phase and maintaining body balance during the whole gait cycle [1]–[3]. Cerebrovascular accident, or stroke, is one of the leading causes of ankle disability [4], [5]. One of the greatest challenges in stroke survivors' rehabilitation is to cure the lower limb with contracture and/or spasticity [6]–[10]. Spasticity is resulted from the hypertonus and reflex hyperactivity of flexor muscles. It reduces the joint range of motion and may cause severe physical pain. Lack of mobilization and prolonged spasticity may further change the structure of muscle fibers and connective tissues and finally lead to permanent contracture as a result. About 34% of stroke survivors have developed ankle contracture [10]–[12]. Therefore, ankle contracture and/or spasticity can seriously influence its normal functional activities.

Previous studies have presented that ankle joint with contracture and/or spasticity is generally rehabilitated via physiotherapy [13]–[15]. During the treatment, patient's ankle is manually moved within its range of motion (ROM) by physical therapists. Physical rehabilitation is a long-term continuous operation. Short-term treatment is usually insufficient to make patients fully recuperation [16]. Even if the patients have temporarily recovered from short-term treatment, they tend to relapse and have future problems [13], [17]. In addition, manual stretching is very laborious and strenuous to physical therapists. The effects of manual rehabilitation may not last long , partly due to the limitation of stretching frequency and duration time. For some severe patients, their ankle joints have a very high stiffness and can hardly be stretched by therapists, even with strong arms.

Robot-assisted rehabilitation has been proposed to support physicians in providing high-intensity therapy for the impaired limb [18]. Robotic technology can transform rehabilitation from labor-intensive operations to technology-assisted operations which can implement kinds of rehabilitation methods [19]. The robot-assisted system can offer an adequate stretching force and sustaining long-term training, which can cover the limitation of manual stretching. It can also record rich information, such as velocity, ROM, resistance torque, and electromyography (EMG) signal, which can facilitate patient diagnosis, functional assessment, therapy customization and rehabilitation history recording. Robot-assisted rehabilitation is gradually being thought to be as good as or even better than manual therapy [20].

Thus, several research groups have developed some robot-assisted rehabilitation systems [21]. Continuous passive motion (CPM) is mainly applied in those systems [22]–[25]. It has been confirmed in their studies that passive stretching is effective in treating the ankle joint with spasticity and/or contracture. CPM devices can provide regular and consistent passive stretching. The ankle joint is moved between two prescribe positions which usually not cover the whole ankle ROM. Therefore, calf muscle may not be fully stretched into the extreme position of dorsiflexion where the contracture and/or spasticity is significant. Meanwhile, with the concern of safety, the range of passive stretching could not be set too aggressively since the joint position is controlled without incorporating the joint resisting torque. Then an intelligent ankle stretching device was developed and successfully used in physical experiments [22], [25]. The stretching velocity is inversely proportional to the joint resistance torque. However, since lower limb is totally relaxed during passive stretching, the improvement of muscle strength and coordination are limited.

Proprioceptive Neuromuscular Facilitation (PNF), as a

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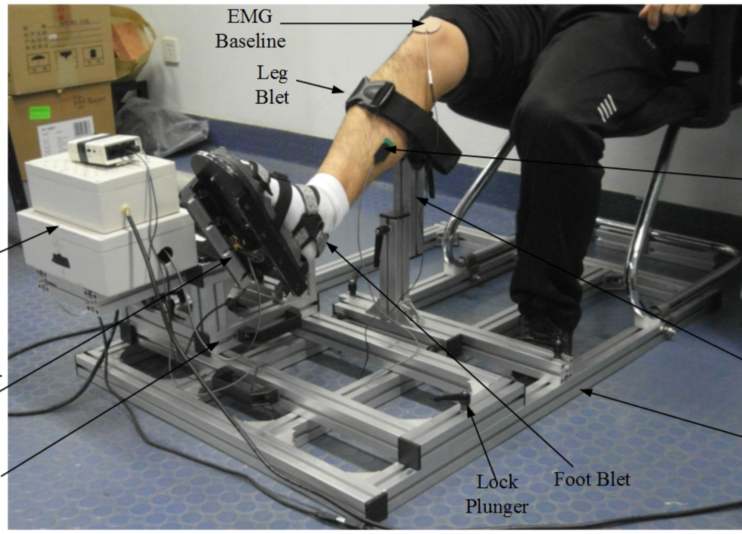


Fig. 1. The proposed robot-assisted ankle rehabilitation system. It consists of immobile base, leg support, sliding platform, control cabinet and surface EMG acquisition system.

novel treatment technique, is first proposed by Kabat and Knott for the rehabilitation of polio patients with paralysis [26]. Klein *et al.* finds that PNF treatment in elderly will significantly improve flexibility, ROM, strength and ADL function [27]. The PNF is even found effective to increase muscle volume and alter muscle fiber types [28]. Compared to passive stretching, PNF technique is more effective [29]. Therefore, it could be an effective treatment in alleviating ankle joint contracture and/or spasticity. More importantly, this technique may improve stroke survivors' functional performance, such as walking or balance control.

In this paper, we developed a robot-assisted ankle rehabilitation system for the ankle joint with contracture and/or spasticity. Furthermore, we applied PNF to the ankle rehabilitation system for investigating its effects. The effectiveness of the rehabilitation system is evaluated by treatment of joint spasticity and/or contracture for five stroke patients. Treatment outcome is quantitatively evaluated in multiple aspect of ankle joint biomechanics.

This paper is organized as follows. In Section II, we describe the design of the robot-assisted ankle rehabilitation system. PNF and experiment protocol are illustrated in Section III. Performance of the proposed robot-assisted ankle rehabilitation system and effectiveness of PNF stretching are shown by experimental results in Section IV. We conclude in Section V.

II. Robot-Assisted Ankle Rehabilitation System

A. Mechanical Design

The proposed robot-assisted ankle rehabilitation system consists of an immobile base that contains a seat, a motor suite and its controller, an adjustable sliding platform in two degrees of freedom which is used to move the motor bracket to an appropriate position, an adjustable leg support (see Fig. 1). The motor is fixed on the sliding platform. The leg support can be adjusted in four degrees of freedom and the leg is strapped to the leg support by the leg belt. The adjustable sliding platform and leg support together ensure that ankle axis is aligned with the motor shaft with knee flexed at a fixed angle position. They are all locked by the lock plungers after being adjusted to the desired position. For safety, rotation limits of the footplate are set in the motor drive and control module. The system will stop running if the obliquity of the footplate is out of the prescribed range. In addition, a mechanical limit stop is set to constrain the range of motion. The motor bracket with location holes on the perimeter is used to place the mechanical limit stop. Besides, the operator and the subject all have their own emergency switches and either of them could shut down the motor by pressing their switches.

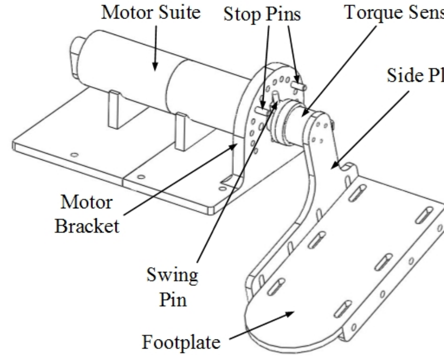


Fig. 2. Schematics diagram of the motor suite and the footplate.

As shown in Fig.2, the motor is fixed on the motor bracket and the footplate is fixed on the motor shaft through the side plate. The motor suite consists of a DC motor and an inline gearbox with a 250:1 gear ratio which increases the loading capacity of the motor up to 100 Nm. It also has a inline

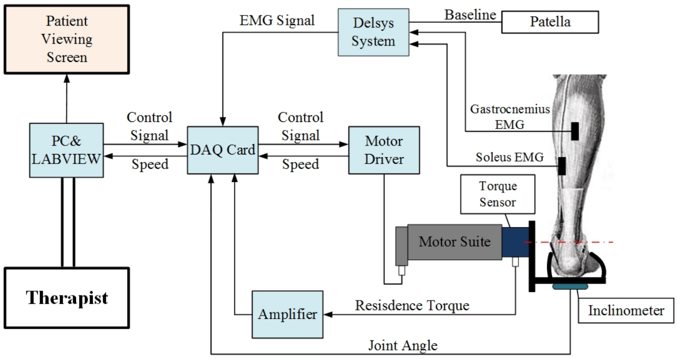


Fig. 3. The signal flow diagram of the proposed rehabilitation system.

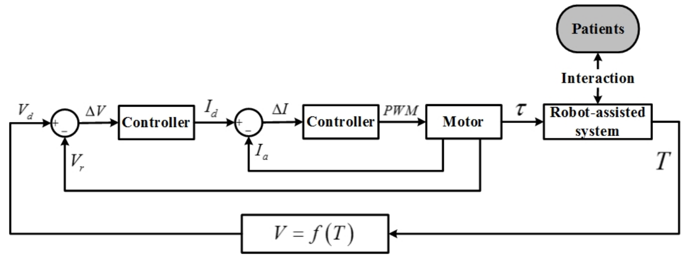


Fig. 4. Control flow diagram of the ankle rehabilitation system.

rotation encoder for speed control. The motor is controlled by a motor drive which is self-designed. Two stop pins on the motor bracket are used for limiting the rotation range of the swing pin, which is fixed on the motor shaft. The separation angle of two adjacent location holes is 10 degree. Additionally, the footplate can move along the side plate. First, we measure the length of the lower leg and height of foot (distance from the bottom of foot to the lateral malleous) which is represented by D_0. Before the ankle is placed on the footplate, we adjust the footplate position depending on D_0 to ensure footplate rotating axis is aligned with the ankle flexion axis. The foot is secured on the footplate by Velcro at the dorsal foot and the heel.

One uni-axial torque sensor is mounted on the shaft to measure the torque signal. The underneath of footplate is attached with an inclinometer which can record the joint angle with the reference to the ground (see Fig. 3). Torque, obliquity signal, encoder signal and EMG signal are fed into the Labview program through a USB Data Acquisition(DAQ) Card with the sampling rate at 1000Hz. Thereinto, the resistance torque and the joint angle are simply processed through a second order butterworth low-pass filter with a cut-off frequency of 20 Hz. The raw EMG signals are firstly bandpass filtered through a fourth order butterworth filter with a cutoff frequency of 20 Hz and 450 Hz, then full-wave rectified, and low-pass filtered through another fourth order butterworth filter with a cutoff frequency of 5 Hz. Then it is filtered by moving average with a window length of two hundred sample points. The processed EMG also need to subtracts the measured offset when the muscle is relaxed. Therapists control the motor through a customized Labview program. Torque and normalized EMG signal are presented on another screen. Patient can adjusted the activation of his/her soleus according the graphical feedback.

B. Control System

The robot-assisted ankle rehabilitation system is driven by a DC motor which is controlled by a self-designed driver. It implements a double closed-loop system with the current as the inner-loop and the speed as the outer-loop (see Fig. 4). In the outer-loop, V_d and V_r are the desired speed and the real-time speed from encoder, respectively. Input of speed controller is $\triangle$V and output is I_d which serves as the input of current closed-loop. In the inner-loop, I_a represents the motor armature current. Input of current controller is $\triangle$I and output is PWM. Then PWM is used to control the motor.

The velocity is controlled in such a way that the speed is inversely proportional to the resistance torque. Thus, when the position of the ankle joint gets closed to the extreme position of ROM, the increasing resistance slows down the motor gradually and at the same time the muscle-tendons involved are stretched slowly and safely. In the middle of ROM where the resistance is usually low, the motor stretches the slack muscles at higher speed. Certainly, if the resistance is high in the middle, the movement will also be slowed down accordingly. Specifically, the following rules are implemented in the driver to control the motor where $\theta(t)$ and $T(t)$ are the position of the ankle flexion and the resistance torque at time t, respectively. θ_d and θ_p are the extreme position of the joint ROM in ankle dorsiflexion and plantarflexion, respectively(both are positive numbers). T_p is a specified peak resistance torque when the motor reaches the mechanical stops. If $T(t)$ is beyond the T_p, the system will shut down immediately as a kind of self-protection. It can serve as a safe value to protect the patient and the system. V_{min} and V_{max} (two positive numbers) are the minimum and maximum speeds (for stretching in the middle of ROM) which are predetermined, respectively. C_1 and C_2 are two constants. C_2 scales the $1/T(t)$ to the appropriate stretching velocity.

When the position θ_t is in the middle of ROM, the motor velocity V_t is calculated by

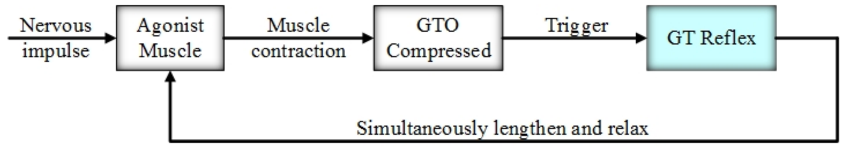
$$V(t) = \begin{cases} V_{min} & V_t \leqslant V_{min} \\ C_1 + \dfrac{C_2}{|T(t)|} & V_{min} < V_t < V_{max} \\ V_{max} & V_t \geqslant V_{max} \end{cases} \tag{1}$$

$T(t)$ is resistance torque. It is calculated by

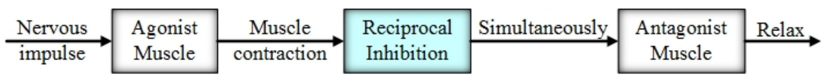
$$T(t) = T_m(t) - T_s(t) - T_f(t) \tag{2}$$

where T_m is the value of the torque sensor, T_s is the system inertia and T_f is relate to weight of the foot.

When the position θ_t reaches the end of ROM, namely θ_d or θ_p, the motor velocity V_t is 0. The motor driver implements a position close-loop by PI controller and current loop also serves as the inner-loop.



(a) Direct hold-relax PNF



(b) Indirect hold-relax PNF

Fig. 5. Principles of two kind of PNF methods. Direct hold-relax PNF and indirect hold-relax PNF are shown in subfigure (a) and (b), respectively.

III. METHOD

A. Proprioceptive Neuromuscular Facilitation (PNF)

Proprioception means 'sense of self'. In human limbs, the proprioceptor provides information about joint angles, muscle length, and muscle tension, which give information about the position of the limb in space. The Golgi tendon organs (GTO) serves as a kind of proprioceptive sensory receptor organs in our body. It can provide information about changes in muscle tension. One end of GTO is connected to the muscle fibers and the other end merges into the tendon bundles. When the central nervous system sends a message to the agonist muscle to contract(here the agonist muscles are gastrocnemius and soleus muscle),these target muscles develop active force. Due to the applied force, GTO gets compressed, and triggers Golgi tendon reflex (GT reflex), which can relax and lengthen the target muscle. Therefore the patient actively contracts his gastrocnemius and soleus muscle, meanwhile makes these muscles get further relaxed. The repetition of this process facilitates the patient to further contract and relax his ankle joint. Since the target muscle is also the agonist, this technique is usually called direct hold-relax PNF (see Fig. 5(a)).

On the other hand, there is an indirect hold-relax PNF technique (see Fig. 5(b)). In human body, there exists a neural phenomenon called Reciprocal inhibition. When the agonist muscle (muscle causing movement) starts to contract, the tension in the antagonist muscle (muscle opposing movement) is inhibited by impulses from motor neurons, and thus must simultaneously relax. With reciprocal inhibition as one muscle contracts, the opposing (antagonist) muscle will relax and allow more movement around the joint. In this case the target muscle is the opposing muscle (antagonist) and this technique is called indirect hold-reflex PNF.

B. Subjects and Experiment Protocol

Five male chronic stroke patients with ankle contracture and/or spasticity participated in the study. Detail information is shown in Table I. Subjects' age mean $\pm$ std is 65.6 $\pm$ 9.0 years, height is 170.4 $\pm$ 11.0 cm and weight is 71.0 $\pm$ 12.6 kg. Two of them are left impaired side and others are right. Their first stroke occurred 42.8 $\pm$ 13.3 years ago. All the stroke patients are able to walk in an abnormal gait without any mechanical aid, and able to generate plantar flexion using the calf muscles. They are totally from the Rehabilitation Medicine Department, Peking University First Hospital, and they gave written and informed consent before the experiment.

The experiment protocol mainly involves three steps, namely preparation, initialization and stretching.

1) Preparation: The length of the lower leg and height of foot (distance from the bottom of foot to the lateral malleous) are measured in order to properly adjust the position of the device. It can ensure that the ankle joint is able to aligned with the axis of the motor shaft. Subjects are seated comfortably with knee flexed at 30 degree which was determined after multiple comparison. The lower leg is strapped to the leg support and foot is attached to the footplate. The skin is cleaned and conditioned with warm water before attaching the electrode pads. Surface EMG electrode is placed according to the recommendation of the SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) to detect soleus muscle EMG.

2) Initialization: At the beginning of each training, the extreme position in ankle dorsiflexion was measured. Subject's foot was moved passively to its dorsiflexion. when the extreme position is reached, the motor is shut down. With the ankle is set at the extreme dorsiflexion position, subject is asked to perform maximum voluntary contraction(MVC) of EMG in plantar flexion direction by activating the soleus muscle. MVC generally needs to be measured up to three times. The peak value of MVC is used for normalization in the PNF stretching.

3) Stretching: During the PNF stretching, ankle is rotated from its neutral position to the extreme dorsiflexion position. Then, the subject is asked to perform isometric contraction with the soleus muscle activated and maintains the soleus EMG in the range of 45% - 65% MVC for 20 seconds. Processed EMG feedback and target range are provided through a customized Labview program in the patient monitor. After the 20 seconds muscle activation, ankle joint is moved back to its neutral position to relax the muscle. The break between each PNF stretching is about 10s. 30 trails are performed in each training session. Before and after each training, ankle joint is passively rotated between its neutral position and extreme dorsiflexion position for about 1 min to warm-up or relax the soleus and gastrocnemius muscle.

TABLE I

SUBJECT DATA

No.	Age(yeah)	Gender(M/F)	Height(cm)	Weight(kg)	Impaired side(L/R)	Injury duration(Month)
1	77	M	156	51	L	50
2	65	M	170	85	L	59
3	72	M	165	69	R	26
4	58	M	185	76	R	46
5	56	M	176	74	R	33
Mean±Std	65.6±9.0	/	170.4 ±11.0	71.0±12.6	/	42.8±13.3

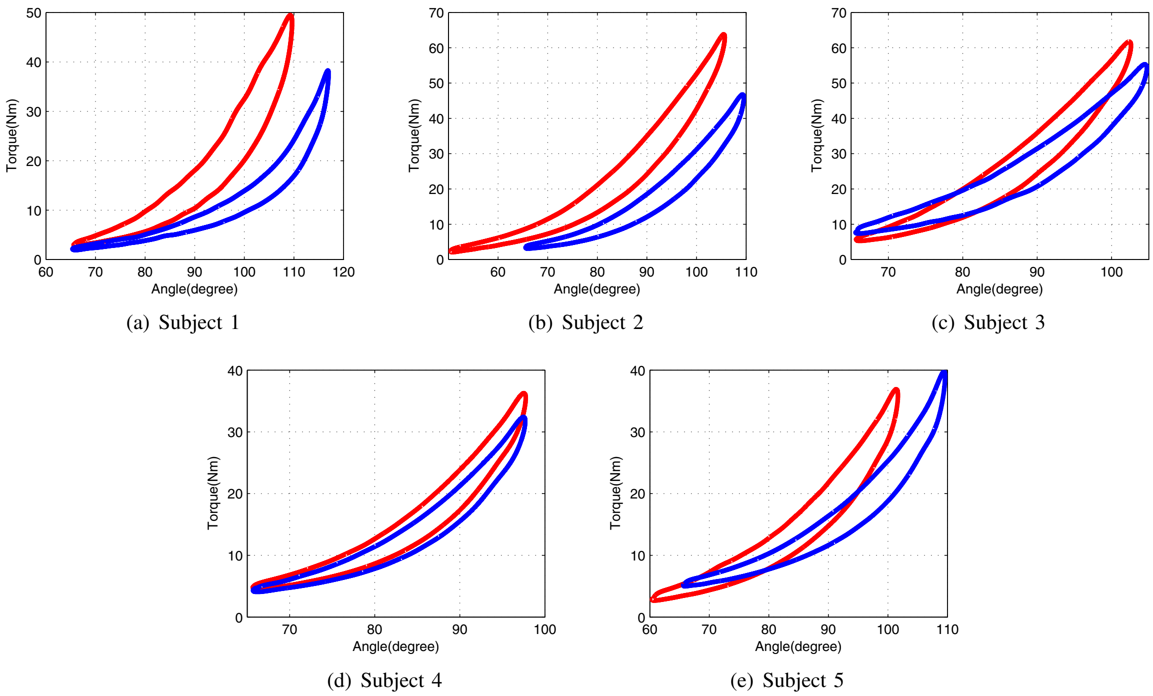


Fig. 6. Torque-angle relationship during passive movement before (red line) and after (blue line) about six weeks PNF training. The x-axis is the footplate angle in degree. 0 degree refers that the footplate is parallel with ground while 90 degrees is when the footplate is vertical to the ground. The Y -axis is the external dorsiflexion torque or plantar flexor resistance torque in Nm. The torque caused by the weight of foot and footplate was subtracted.

IV. Experimental Results

The contracture and/or spasticity in calf muscle can causes very large resistance torque during dorsiflexion. We have checked the torque-angle relationship(hysteresis loop) during one cycle of passive dorsiflexion and plantarflexion movement before and after PNF training of about six weeks. The results of five subjects are all shown in Fig. 6. Ankle joint is moved passively from its neutral position to the extreme dorsiflexion position with the subject seated in the same position during each training. For each angle-torque relation (hysteresis loop), the ascending curve represents the passive dorsiflexion phase and the descend curve represents the plantarfelxion phase. By comparison of before and after PNF training, We can tell from hysteresis loop that resistance torque in the extreme dorsiflexion position decreases or the extreme dorsiflexion angle increases, or two of them changes at the same time. For stroke survivors with ankle contracture or spasticity, we pay close attention to dorsiflexion range since their ankle is in plantarflexion position(drop foot) all the time. For a representative case, such as subject 1, the extreme position in dorsiflexion has increased from 109.4 degrees to 116.9 degrees. At the extreme position in dorsiflexion, the resistance torque decreased from 49.4 Nm to 38.1 Nm. We can also analyze data of other subjects like this. These results indicate that PNF stretching can effectively increase ankle joint range of motion and reduce joint stiffness after continuous training. However, it is remarkable that the effect in subject 4 after PNF training is very little. Since he suffers from another cerebrovascular disease, it may influence the effect of rehabilitation.

Passive stretching is characterized by rigidly moving the foot through a prescribed pattern, so that the stroke patients can hardly influence these motions. However, during the PNF training, ankle is rotated from its neutral position to the extreme dorsiflexion position and subject is asked to perform isometric contraction with the muscle activated and maintain the EMG in the range of percentage of MVC for a period of time. Thus, PNF regarding as a active training method can significantly increase muscle strength and improve out of control of the flexor muscle which is influence by stroke, but passive stretching can not. As shown in Fig. 7, we can see that MVC of every subject is showing a rising trend as

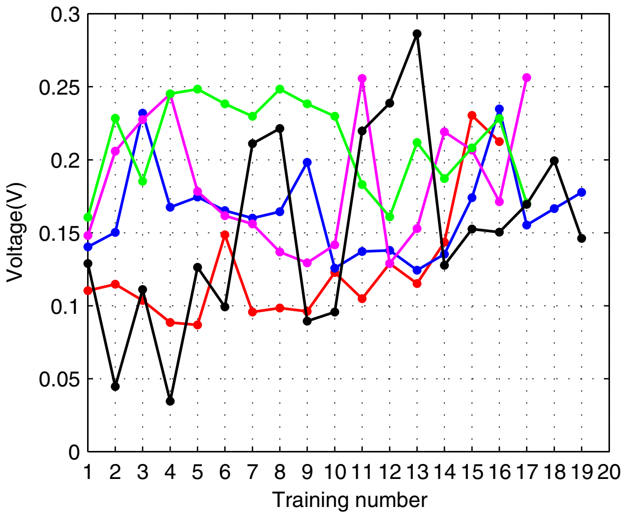


Fig. 7. MVC of subjects in each training, subject 1 in red line, subject 2 in blue line, subject 3 in mauve line, subject 4 in green line and subject 5 in black line. The x-axis is the training number. The training frequency is about three times each week and the total time is six weeks. The Y-axis is MVC of soleus muscle EMG. It has subtracted baseline of EMG in slack muscle.

time goes on. For a representative case, such as subject 1, his MVC of soleus has increased from 0.11 V to 0.21 V. Other subjects are similar. In addition, subject is becoming faster to track the target line in the experiment project.

V. Conclusion and Future Work

In this paper, we have developed a robot-assisted ankle rehabilitation system and verified a new rehabilitation method on it. In this pilot study, the subjects show increase of ROM and decrease of resistant torque during dorsiflexion after 6 weeks PNF training. The muscle strength is also improved. The preliminary experimental results indicate that PNF is an effective method used in robotic system to treat ankle joint with contracture and/or spasticity. Future work is to verify more subjects to achieve more comprehensive and reliable evaluation of both the system and the rehabilitation therapy comparing with different training methods. In addition, we will continue the long-term treatment for those patients and further experiments on the effectiveness of their treatment.

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