Changes of Achilles tendon properties via 12-week PNF based robotic rehabilitation of ankle joints with spasticity and/or contracture

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Abstract— **Ankle joint with spasticity and/or contracture can severely affect mobility and independence of stroke survivors. Due to that, the Achilles tendon(AT) is affected. In this paper, we aim to study changes of AT properties via proprioceptive neuromuscular facilitation (PNF) treatment. A robotic ankle-foot rehabilitation system has been proposed, which consists of a robotic ankle-foot platform and a graphic user interface. In this pilot study, two post-stroke patients participated and carried out a 12-week PNF treatment with the robotic system. The treatment is evaluated quantitatively in AT properties. The evaluation shows that after the PNF treatment, the average decrease of AT length is 4.1 mm (6.5%) and the recovery ratio is 30.4%, while the thickness has no change. The results indicate that the PNF based robotic rehabilitation for ankle joints with spasticity and/or contracture is effective to improve the ankle spasticity/contracture.**

I. INTRODUCTION

Human ankle joint plays an important role in providing forward propulsion force during terminal stance phase and maintaining body balance and gait smooth during the whole gait cycle [1]. Considerable spasticity and/or contracture are usually observed in the cerebrovascular accident or stroke survivors around the ankle joint, especially the plantar flexor muscles(the gastrocnemius and soleus) [2]. Ankle joints with spasticity and/or contracture can severely disable their mobility and independence [3]. Spasticity is resulted from the hypertonus and reflex hyperactivity of flexor muscles. It reduces the range of motion (ROM) of the ankle joint and may cause severe physical pain. Moreover, lack of mobilization and prolonged spasticity can further change the structure of muscle fibers and connective tissues and finally lead to permanent contracture.

In clinic, the ankle joint with spasticity and/or contracture is typically rehabilitated via physiotherapy [4]. During the treatment, patient's ankle is manually moved within its ROM by a physical therapist (PT). Physical rehabilitation is in need of a long-term continuous operation as short-term treatment is less effective and usually insufficient to make patients fully recuperation [5]. Thus robotic rehabilitation is gradually being thought to be as good as or even better than manual therapy [6], [7]. Continuous passive motion (CPM) is mainly applied in those devices [8]–[10]. It has been proven that the 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 predefined 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 spasticity and/or contracture is significant.

To address these problems, we try to apply proprioceptive neuromuscular facilitation (PNF) technique to robotic rehabilitation. The PNF was firstly proposed by Kabat and Knott for the rehabilitation of polio patients with paralysis [11]. Generally PNF stretching involves a shortening contraction of the opposing muscle to place the target muscle on stretch. Klein *et al.* reported that the PNF treatment in elderly can significantly improve flexibility, ROM, muscle strength and ADL function [12]. The PNF is even found effective to increase muscle volume and alter muscle fiber types [13]. Above all, the PNF technique can cover the problems in the previous treatment and is more effective than passive stretching [14]. Moreover, the active participation of patients in the PNF treatment can greatly improve their compliance and initiative.

The functional outcomes of using PNF based robotic ankle-foot system in stroke survivors have been studied in our recent study [15]. The outcomes were mainly focused on the biomechanical measurements of the ankle joint, including joint stiffness, viscosity, and ROM. On the other hand, the Calf muscle architecture in stroke via passive stretching has been studied using ultrasonography [16], [17]. However, due to spasticity and/or contracture, the calf muscle is contracting and shortening, while the Achilles tendon(AT) is forcefully elongated [16] and it may show increase in length and decrease in thickness. In this paper, we investigate AT properties to evaluate the effectiveness of PNF rehabilitation in ankle joints with spasticity and/or contracture. Two post-stroke patients participated in our pilot experiments and finished a course of a 12-week PNF treatment using the robotic ankle-foot system. Clinical results show the improvement of joint spasticity and/or contracture.

II. METHODS

A. Proprioceptive Neuromuscular Facilitation (PNF)

Proprioception means 'sense of self'. In human limbs, the proprioceptor provides information about joint angles,

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TABLE I

DETAILED INFORMATION FOR TWO POST-STROKE SUBJECTS

No.	Age (yeah)	Gender (M/F)	Height (cm)	Weight (kg)	Impaired side	Injury duration (Months)
1	50	M	170	85	Left	64
2	75	F	160	64	Right	16

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.

B. *Subjects*

Since the study is still in progress, only two post-stroke patients finished all the training and evaluations and were included in this paper with the subject's relevant information listed in Table I. The Ashworth scale (in the range of 0 to 4) of the stroke patients is all 3. They are all from the Department of Rehabilitation Medicine, First Hospital, Peking University. The inclusion criteria for the patients have hemiparesis following a stroke at least six months earlier, have ankle joint with spasticity and/or contracture, are able to walk with a cane or without any mechanical aid, and generate plantar flexion torque using the calf muscles. Exclusion criteria are having other severe disease, leg musculoskeletal injuries, and/or orthopedic surgeries on the leg. All procedures are approved by the institutional review board of the First Hospital, Peking University. Participants provided informed consent before the experiment. The training was carried out 3 times a week and lasted for 12 weeks.

C. *Experimental Setup*

The patient is treated using a robot-assisted ankle rehabilitation system shown in Fig. 1 (the details of the system can be found in our recent study [15]). The device is conveniently linked to a chair where patient could be comfortably seated with leg supported by a brace and fixed at a prescribed position. The foot of the patient is secured to a footplate with the center of rotation of the ankle aligned with the motor rotation axis. The motor is controlled by a digital controller. One uni-axial torque sensor is mounted on the shaft to measure the torque signal. The underneath of footplate is attached with an inclinometer to measure the joint angle. Two-channels EMG system (Delsys Inc.) is used to measure EMG signals of gastrocnemius muscle and soleus muscle. They are fed into the Labview program through a USB Data Acquisition (DAQ) Card with the sampling rate at 1000Hz. A customized graphical user interface (GUI) is developed in Labview environment (see Fig. 2).

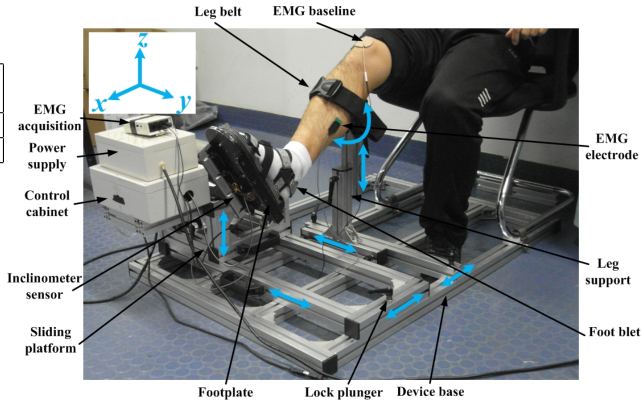


Fig. 1. The robotic ankle-foot rehabilitation system. It consists of the immobile base, the sliding platform, the leg support, the control and power supply cabinet and the sensory system. The footplate is driven by a motor which is fixed on the sliding platform. It can be configured to treat either left or right ankle. Multi-DOFs(blue markers) can ensure human and machine being a desired position.

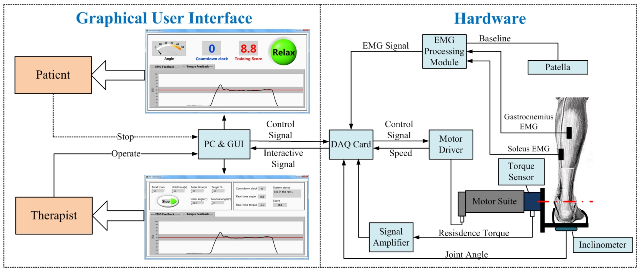


Fig. 2. The overall structure of the proposed robotic ankle-foot rehabilitation system. The top layer is GUI and the bottom layer is hardware. Two displays are configured for patient and therapist, respectively. The therapist can operate the software interface and monitor current state of the whole system.

For safety during rehabilitation treatment, 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.

D. *Experiment Protocol*

At first, the subject seats comfortably with knee flexed at 30° which is 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.

At the beginning of each training, the extreme position in ankle dorsiflexion which the patient is able to reach is measured. Subject's foot is moved passively to its dorsiflexion. When the extreme position is reached, the motor will shut down. With the ankle at the extreme dorsiflexion position, the 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.

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 maintain the soleus EMG in the range of 50% ± 10% MVC for 15 seconds. The target range and the duration time are adjusted based on actual condition of different subjects and the rehabilitation phase. Processed EMG feedback and target range are provided through a customized GUI in the patient monitor. After the 15 seconds muscle activation, ankle joint is moved back to its neutral position to relax the muscle. The break between each PNF stretching is 10s. Each training session is about 30 minutes including about 15 trails.

E. Evaluation

Before the treatment session, we firstly measured the length and thickness of the AT for the impaired side and the intact side respectively. The data from the intact side was taken as the control group. Repetitive measurements (at least 3 times) were conducted to minimize the measurement error. And we also did the same after the whole 12-week treatment. During the process of the ultrasound measurement, the subjects were asked to relax their legs pronely. The ankle to be measured by Ultrasound was held at the natural position (90° between the leg and the foot) using a fixed apparatus.

1) Measurement of AT length: The length of the AT (see the top figure of Fig. 3) was measured from the muscle-tendon junction (MTJ) (Point A), where AT (or called "free tendon") divides into soleus aponeurosis and gastrocnemius tendon, to its insertion into the calcaneus notch (Point C). A tissue string was placed on the skin surface as a marker(Point B), around the level of the tip of the medial malleolus. The marker divided the length of the AT into two short segments, which were measurable by the 5 cm-probe of Philips IU22. During the measurement, the probe applied with ultrasound transmission gel was placed perpendicular to the skin with moderate pressure and moved smoothly along the crest of the AT, to avoid compressing the muscle-tendon considerably. The two segments of the tendon were shot in two parallel windows, using Dual mode function (Fig. 3, top). The length of both segments were measured and summed as the total length of the AT.

2) Measurement of AT thickness: To measure the thickness of the AT, the probe was applied to the AT from posterior-to-anterior direction. On the sagittal plane of the AT, a line vertical to the fiber of the AT was drawn at the level of the tip of the medial malleolus (Fig. 3, bottom). This line intersected the AT aponeurosis at two points (Point D and Point E), the distance between which was measured as the thickness of the AT.

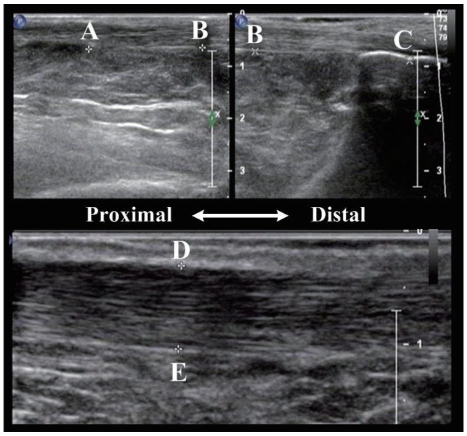


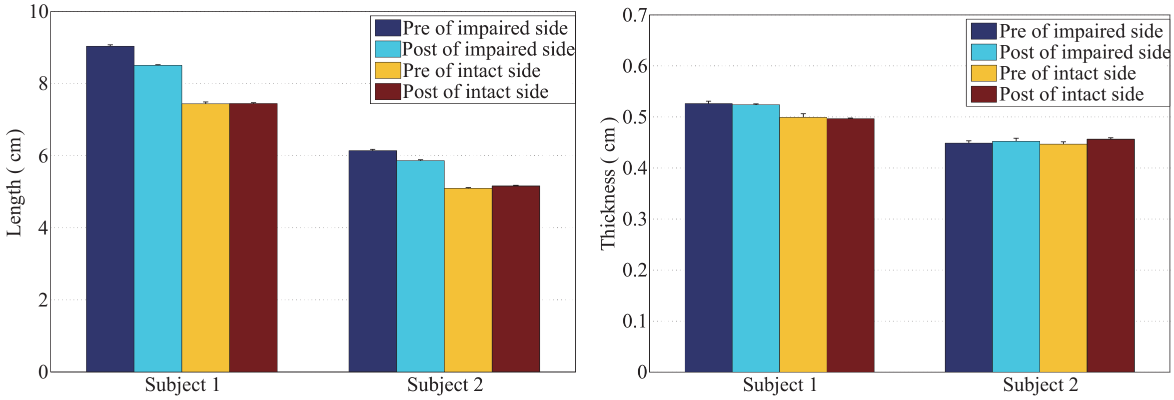
Fig. 3. The Ultrasound image of AT. The length is the distance from the muscle-tendon junction (MTJ) (Point A) to the calcaneus notch (Point C). The thickness is the distance between the point D and the point E.

III. EXPERIMENTAL RESULTS

Due to spasticity and/or contracture of calf muscle induced by cerebral vascular accident, calf muscle is contracting and shortening. Meanwhile, the AT is forcefully elongated [16] and it may show increase in length and decrease in thickness. It is also verified in our result and we can obviously find that the length of the impaired side is markedly longer than that of the intact side before treatment. The elongation is averagely 1.3 cm (20.7%) compared with intact side(Fig 4). But for the thickness, we can find that the injured side and the intact side has no large difference and it is about 0.01mm (2.5%). For their impaired side, we want to find that the change of AT properties due to our rehabilitation treatment which can explain the improvement of spasticity and/or contracture [16], [17]. The changes include decrease in length and increase in thickness. The properties should be recovered to nearly the intact side.

As illustrated in Fig. 4, for intact side, the length is nearly identical pre- and post-treatment due to no special training on it. But for the impaired side, large changes happen. For a representative case, such as subject 1, the length decreases form 9.04 cm to 8.50 cm after treatment and the decrease is 0.54 cm (7.3%) of his intact side (7.44 cm). More importantly, the recovery ratio is 33.5%. For all subjects, the decrease is averagely 4.1mm (6.5%) and the recovery ratio is 30.4%. For thickness, no significant changes and tendency after treatment mainly due to no difference between the two insides before treatment.

Above all, we measure the properties of AT of the sound side as control group to study the effectiveness level. The clinical experimental results show that the length of the AT largely decreases. The recovery ratio shows a very



(a) The length of the AT

(b) The thickness of the AT

Fig. 4. AT properties.(a) and (b) are the length and the thickness of the AT(mean ± SE) when pre- and post- treatment for the injured side and the intact side, respectively. Repetitive measurements (at least 3 times) were conducted to minimize the measurement error.

good tendency which can indicate the improvement of the spasticity and/or contracture.

IV. DISCUSSION

This study is the first to evaluate the Achilles tendon properties of post-stroke patients via PNF treatment based robotic rehabilitation. It is measured by ultrasound images. Ultrasound evaluation is described in previously published papers [16]. AT properties due to PNF treatment are compared with the passive stretching.

The main findings of this study include: 1) stroke survivors with ankle spasticity and/or contracture have longer AT length and shorter muscle fiber length obviously, compared with their own intact side; 2) PNF treatment can alter the properties of the muscle-tendon, with shortening of the AT associated with relaxation and possibly lengthening of muscle fascicles; 3) PNF treatment can reduce the tightness of the ankle joint and decrease ankle joint stiffness in result of alleviate ankle spasticity and/or contracture.

Although no detail statistical conclusions can be drawn from the small sample, some information may still be of great importance for future study. In previous study [9], there was no significant change in the AT length after the repeated passive stretching for ankle spasticity. However, after the PNF treatment, the average decrease of AT length is 4.1 mm (6.5%) and the recovery ratio is 30.4%. The thickness has no change, mainly because there is almost no difference between the intact side and impaired side. We will recruit more subjects whose thickness is different between two sides to study the PNF impact.

In this pilot study, only two patients finish all the training to evaluate the effectiveness of PNF rehabilitation via AT properties. In the future, more patients will be recruited and further clinical evaluations will be carried out with ultrasound evaluations.

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