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Changes of Calf Muscle-Tendon Properties Due to Stretching and Active Movement of Children with Cerebral Palsy – A Pilot Study

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Abstract—**A portable ankle rehabilitation robot with intelligent stretching and game-based active movement training was used to treat the spastic impaired ankle of children with cerebral palsy over six weeks. The subject's calf muscles and Achilles tendon properties were evaluated before and after treatment using ultrasonography and biomechanical measures. It was found that there were decreased Achilles tendon resting length (2.5%), increased cross-sectional area (5.5%), increased stiffness (22.9%), increased Young's modulus (13.8%), decreased soleus muscle fascicular stiffness (53.7%), and decreased medial gastrocnemius fascicular stiffness (46.1%).**

I. Introduction

Cerebral palsy (CP) is a non-progressive neuromotor disorder caused by damage to the brain before, during or shortly after birth. The neurological disorder can cause secondary changes in the musculoskeletal system such as muscle weakness, spasticity or contractures around joints which severely reduce the mobility of the patients.

Passive stretching is a common strategy to treat the soft tissue tightness [1]. Clinically, a physical therapist (PT) manually moves the joint throughout the range of motion (ROM) to reduce spasticity/contracture. However, due to limited and infrequent therapy, the effects of passive stretching may not persist. In addition, manual stretching by PTs is laborious and the outcome depends on subjective assessments such as the therapist's measurement of the limits of the ROM or "end feel". Splints, casts, tilt-table, and some other external devices also are used to assist treating the patients, among which continuous passive motion (CPM) devices are widely used in clinics and in patients' homes to prevent postoperative adhesion and reduce joint stiffness [2]. However, CPM machines can only move the limb at a constant speed between two prescribed joint positions. The passive movement does not usually stretch into the extreme positions where contracture/spasticity is significant. Furthermore, aggressive setting of a CPM machine may result in joint injury. Besides passive stretching, strength training is used to treat muscle weakness. Some studies indicate strength training may enhance motor development in younger children, counteract deterioration in youth, and no increased spasticity or other serious side-effects were found [3].

Intelligent ankle stretching technique has been developed for treatment of ankle contracture/spasticity [4]. The intelligent stretching device is driven by a servomotor controlled by a digital signal processor (DSP) controller. The stretching velocity is controlled to be inversely proportional to the joint resistance torque. Near the ROM limits, increasing joint resistance gradually slows the motor and the muscles/tendons involved are stretched slowly and safely. Once the specific peak resistance torque is reached, the motor holds the joint at the extreme position for a prescribed period of time that can be conveniently adjusted. The intelligent ankle stretching device can be operated under several different modes. Besides the passive stretching driven by motor, the device can also be driven by ankle active movement with motor applying assistant, resistant or zero torque. Motivated by interactive games, the patient can actively move the ankle across the ROM and the exercise intensity can be adjusted progressively by changing the game difficult level and the assistant/resistant torque level. Also the intelligent ankle stretching device is portable which provides a convenient and low-cost treatment for CP patients.

The functional outcomes of using intelligent stretching technique to treat ankle joints with contracture/spasticity in stroke survivors have been investigated [5]. However, the outcomes were mainly focused on the biomechanical measures of the ankle joint, including stiffness, viscosity, and ROM. A detailed understanding of *in vivo* calf muscle and tendon adaptations may be used to assess the efficacy of such treatment. *In vivo* gastrocnemius muscle architecture in CP has been studied using ultrasonography and shortened muscle fascicles were found [6, 7]. Several studies have also been carried out to investigate the calf muscle or tendon mechanical properties change due to repeated stretching and resistant exercise in able body subjects [8, 9]. The objective of

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this study was to use ultrasound to evaluate the calf muscle and tendon properties of children with CP before and after intelligent stretching and active movement treatment.

TABLE I
SUBJECT'S CHARACTERISTIC

Age	11
Sex	Male
Weight	68 kg
Height	165 cm
CP type	Diplegia
Orthotics	Solid ankle-foot orthotics
Modified Ashworth scale	3

II. METHOD

A. Subject

With the study still in progress, only one subject finished all the training and evaluations and was included in this paper with the subject's relevant information listed in Table I.

Informed consent (parental consent and minor assent) approved by the Institute Review Board were obtained before the experiment.

B. Experimental Setup

The patient was treated using intelligent ankle stretching device shown in Fig. 1. The device was 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 was secured to a footplate with the center of rotation of the ankle aligned with the motor rotation axis. The motor was controlled by a digital controller. A personal computer (PC) was used to read the ankle joint torque, position, send out commands through the serial port and display the game.

Fig. 1. Intelligent ankle stretching device. The device can be configured to treat either left or right ankle. The size of the footplate and the position of the leg support can also be adjusted.

In order to achieve a better control of the experimental conditions and easier access of the ultrasound probe to the leg, another knee-ankle joint driving device was used specifically for ultrasound evaluation. Along with the knee-ankle device, GE LOGIQ-9 imaging system (GE Healthcare, Waukesha, WI), Bagnoli electromyography (EMG) system (Delsys Inc., Boston, MA), and a PC were also used for the evaluation. Fig. 2 illustrates how the four devices worked together. Briefly the ankle joint torque signal from the knee-ankle device, the EMG signal from the EMG system and the ultrasound data from the imaging system were sent to the PC. The PC also sent out a trigger signal to synchronize the ultrasound data and the torque signal acquisition. The torque signal was displayed on the PC monitor in real-time as a visual feedback. Each of the devices were described in detail in [10].

C. Experimental Design

The study was comprised of 18 training sessions and 2 evaluation sessions. The training was carried out 3 times a week and lasted for 6 weeks. In the beginning of each training session, the subject's passive ROM was measured. Then the range limit was set 5^o larger than the subject's ROM and the ankle joint torque targets were set according to subject's tolerant levels which were 10~15 Nm at dorsi-flexion and 5 Nm at plantar flexion. The ankle joint was held at extreme positions for 5 seconds before it was moved back towards the other direction. The ankle was repeatedly stretched using intelligent stretching technique following the torque target and within the range limit for 30 minutes. The intelligent stretching device was then switched to active mode and the subject's active ROM was measured. The game was configured according to the subject's active ROM and the assistant/resistant torque level was set so that the subject could play the game with certain effort and without causing frustration.

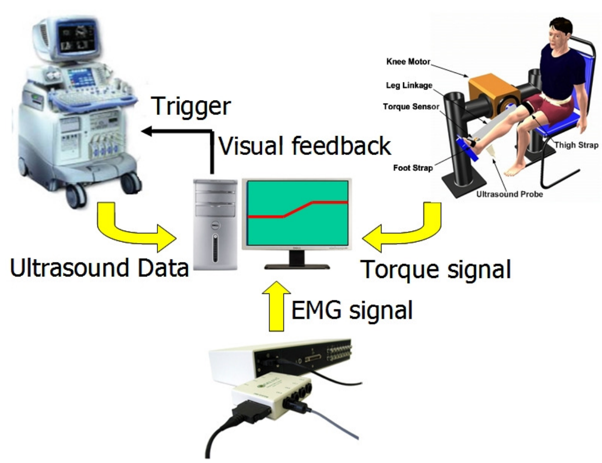

Fig. 2. Setup for ultrasound evaluation of muscle and tendon biomechanical properties.

The calf muscle and tendon biomechanical properties were evaluated before and after the 18 treatment sessions following the same protocol.

To evaluate medial gastrocnemius (MG) muscle and soleus (SOL) muscle biomechanical properties, the subject was seated upright with the thigh and trunk secured using Velcro straps. The leg and foot were securely attached to the leg linkage and footplate, with the knee fixed at 0^o and 90^o flexion and the ankle joint fixed at 10^o, 0^o dorsi-flexion, and

10°, 20°, 30° plantar flexion, respectively. The ultrasound images of MG and SOL fascicles using an extended-field-of-view technology [11] called LOGIQView (Fig. 3 and 4) and the passive ankle joint torque at each combination of the knee-ankle positions were recorded. The protocol to evaluate the Achilles tendon properties was the same as in [10].

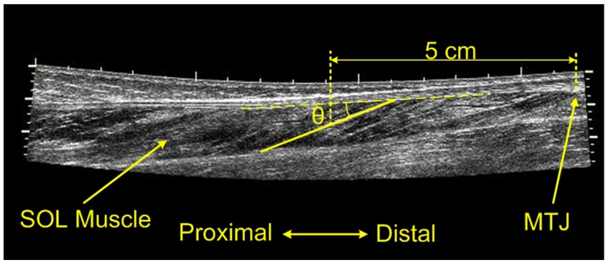

Fig. 3. SOL muscle LOGIQView image.

D. Achilles Tendon Biomechanical Properties

The subject's Achilles tendon length, cross-sectional area (CSA), moment arm, stiffness, and Young's modulus before and after treatment were measured using the methods described previously [10].

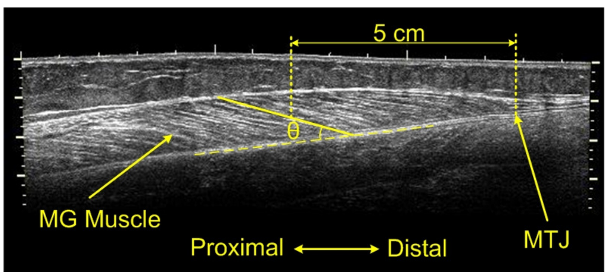

Fig. 4. MG muscle LOGIQView image.

E. MG and SOL Fascicle Length and Stiffness

For both MG and SOL, the length of the fascicles 5 cm proximal to each muscle-tendon junction (MTJ) was defined as its fascicle length. The pennation angles of SOL and MG were defined as the angle between SOL fascicle and the upper fascia, and the angle between MG fascicle and the lower fascia, respectively. Since the SOL muscle does not cross knee joint while MG does, the passive ankle joint torque contributed by SOL muscle does not change with knee position. Based on this assumption, the fascicle lengths of SOL muscle at various ankle positions with 90° knee flexion should be the same as the corresponding ankle positions with 0° knee flexion. The ankle joint torque contributed by MG and lateral gastrocnemius (LG) was the torque at 0° knee flexion subtracted by the torque at 90° knee flexion. Assuming the ratio of the torque contribution from MG and LG was 3:1 [12], the passive MG muscle force was calculated which was further divided by cosine of the pennation angle to calculate the fascicular force. The fascicular stiffness was estimated by dividing the fascicular force with the fascicle length difference between the two knee positions. Subtracting the force contributed by MG and LG muscles from the total force, the SOL fascicular force and stiffness were also calculated.

TABLE II
ACHILLES TENDON BIOMECHANICAL PROPERTIES CHANGE

	Before treatment	After treatment
Resting length (mm)	68.6	66.9
CSA (mm^2)	45.5	48.0
Stiffness (N/mm)	113.3	139.2
Young's modulus (MPa)	170.7	194.3

III. RESULTS

Comparison of the Achilles tendon biomechanical properties between before and after the stretching and active movement treatment is shown in Table II. The Achilles tendon resting length decreased 1.7 mm (2.5%). The CSA increased 2.5 mm^2 (5.5%). The stiffness increased 25.9 N/mm (22.9%). And the Young's modulus increased 23.6 MPa (13.8%).

The SOL and MG muscle fascicle lengths at various ankle joint positions with 0° and 90° knee flexions are shown in Fig. 5.

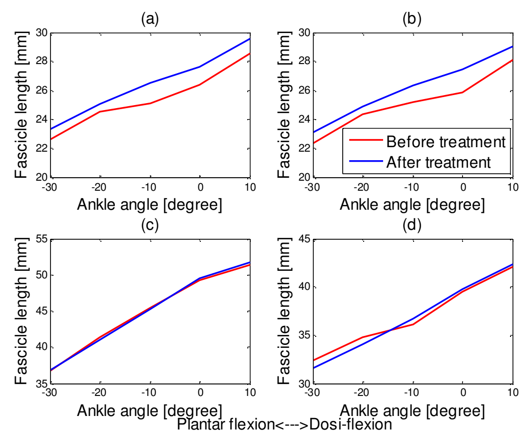

Fig. 5. SOL and MG Muscle fascicle length before and after treatment. (a) SOL fascicle length at 0° knee flexion; (b) SOL fascicle length at 90° knee flexion; (c) MG fascicle length at 0° knee flexion; (d) MG fascicle length at 90° knee flexion

As shown in the figure, the length of the SOL and MG muscle fascicles in general increased slightly after treatment, but the increase was not significant. Also comparing the fascicle length at different knee positions, SOL muscle fascicle length decreased around 0.5 mm when the knee flexion angle changed from 0° to 90°, while MG muscle fascicle length decreased more than 5 mm. By using the method introduced in Section II.E, the MG fascicular stiffness at 0° ankle dorsi-flexion was 14.7 N/mm before treatment and 6.8 N/mm after treatment. And the SOL fascicular stiffness at 0° ankle dorsi-flexion was 41.4 N/mm before treatment and 22.3 N/mm after treatment.

IV. Discussions

Considerable muscle fascicular stiffness decrease (about 50%) and variation (SOL fascicular stiffness was almost 4 times of MG) might be affected by the simplified method of calculating fascicular stiffness. The model did not take into account the ankle joint torque contribution from other muscles and soft tissues, the intramuscular force, the complicated relation between muscle force and fascicular force. The passive force ratio between MG and LG might not be accurate either.

Although no statistical conclusions could be drawn from this single case, some information might still be of great importance for future study. According to the results, for both muscles and tendon, mechanical property change was greater than the physical size change, which indicated the treatment induced change was more associated with the activities at sarcomere and extracellular matrix level. The results also showed increased tendon stiffness and decreased fascicular stiffness. According to [9], resistant strength training had more impact on tendon stiffness than stretching treatment. We speculate the tendon stiffness increase was due to the active movement while muscle fascicular stiffness decrease came from intelligent ankle stretching.

More patients have been recruited for this study and other mechanical measurements and clinical evaluations will be applied to corroborate with ultrasound evaluation in the future.

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