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In vivo Biomechanical Evaluations of the Medial Gastrocnemius: Changes in Muscle Properties in Stroke Survivors

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Abstract— **Patients post stroke showed substantial changes in biomechanical properties of the ankle and knee joints. However, it is not clear what the underlying mechanisms are in the hypertonic calf muscles in stroke survivors. Biomechanical properties of the medial gastrocnemius muscle in both stroke survivors and healthy subjects were investigated *in vivo* and noninvasively. A programmable electrical stimulator was used to activate the medial gastrocnemius selectively and a GE LOGIQ-9 ultrasound machine was used to register the muscle images across the fiber lengths to examine its biomechanical properties *in vivo*. It was found that 1) stroke survivors showed shorter muscle fiber length; 2) stroke survivors' muscles had smaller pennation angles both anteriorly and posteriorly; 3) stroke survivors demonstrated an active torque-angle curve shifted towards dorsi-flexion, compared with healthy control subjects.**

I. Introduction

Considerable spasticity and/or contracture were usually observed in the stroke survivors around the ankle joint and this can be partially attributed to the variances of mechanical properties of muscles, especially the plantar flexor muscles, the gastrocnemius and soleus [1-7]. Clinically, the phenomenon of foot-drop is associated with an increase in muscle tone. Muscle tone may result from both reflex and intrinsic changes, and was usually accompanied with increase of passive joint/muscle stiffness [4]. A better understanding of the changes of muscle properties, such as geometric architecture and stiffness, could help us gain insight into the mechanisms underlying spasticity/contracture and provide us guidance to the rehabilitation of stroke patients.

Ultrasonography, as a state-of-the-art technology and a powerful *in vivo* tool, has been widely applied to the study of muscle function [8-10]. However, few ultrasonic studies have been conducted to examine hypertonic muscles in patients post stroke or other neurological disorders. In addition, most of the published studies only examined muscles as a functional group and rarely distinguished individual muscles and their specific contributions. Also, due to the limited width of ultrasound probe, in most of the studies, the measurements of muscle architecture, especially, the muscle fiber/fascicle length, is derived from geometrical extrapolation (such as line intersection), instead of direct measurement of the whole fiber length. Recent studies have suggested that the increase in muscle tone, especially the muscle stiffness could be attributed to a permanent shortening of the muscle tissue. [2]. However, currently there are no relevant convincing experimental results available to validate.

In this study, a programmable electrical stimulator was used to activate medial gastrocnemius (MG) selectively to examine its biomechanical properties *in vivo* and noninvasively. To overcome the limited field of view, a novel technique, LOGIQview, implemented in the GE LOGIQ-9 ultrasound machine was used to register the muscle images covering the full fiber lengths.

The purpose of the current study was to quantify *in vivo* and noninvasively biomechanical properties of the MG in both stroke survivors and normal subjects. In order to do so, muscle architectures including the pennation angle, fascicle length and muscle thickness in the MG were measured quantitatively. Torque signals at the ankle and knee joints induced by the selective MG contraction were also measured together with the dynamic ultrasonic images.

II. Methods

Ten healthy male subjects without neuromuscular injury and ten male stroke survivors participated in the study. The study was approved by an IRB panel and all subjects informed consent.

Subjects were seated upright on a custom chair with thigh secured using Velcro™ straps. An adjustable leg-foot linkage with JR3 force/torque sensors (JR3, Inc., Woodland, CA, USA) mounted at both the knee and ankle joints was used to constrain the shank and the foot. The anatomical rotation centers of knee and ankle were carefully aligned with the Z axis of the corresponding JR3 sensors. Four knee configurations, starting from fully extended position with increment of 30 degrees in flexion, were tested. At each knee configuration, ankle flexion was systematically varied with an increment of 10 (dorsi-flexion) /15(plantar flexion) degrees in the range from 20 dorsi-flexion to 45 plantar-flexion (Fig. 1). However, since stroke patients have limited range of motion, the tested ankle positions for stroke patients may be smaller than what described above and they were adjusted for the individuals.

A Compex™ electrical stimulator was used to produce trains of biphasic, monopolar pulses with pulse width of 300

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µs and frequency of 40 Hz. The duration of each electrical pulse was 2 seconds and the interval between electrical pulses trains was 3 seconds (Fig.2). The targeted muscle, the MG, was activated selectively at a steady level during the 2 seconds stimulation. Paired circular self-adhesive electrode pads, connected to the stimulator were used to apply the electrical stimulation. The skin was cleaned and conditioned by warm water before attaching the pads. The motor point of the MG muscle was searched carefully and

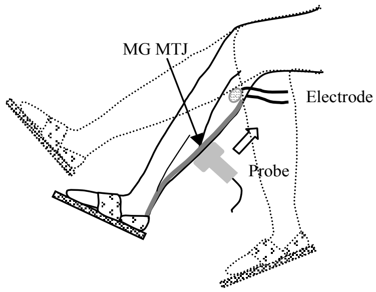

Fig. 1: Illustration of experimental setup. Hollow arrow represents the moving direction of the ultrasound probe. The legs drawn in dashed line stand for different knee configurations. The ankle angle was also systematically adjusted at each of the knee configurations.

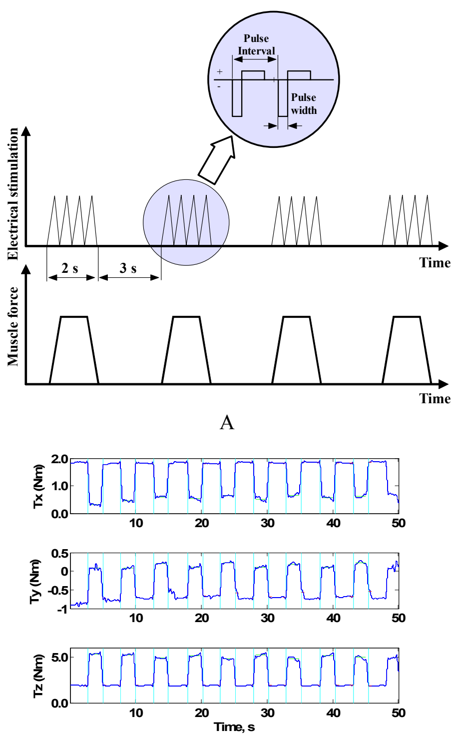

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Fig. 2: Panel A: Schematic illustration of electrical stimulation. Top panel, electrical pulses trains. Bottom panel, Force produced by the selectively activated muscle. Panel B: Example of torques at the ankle joint in 3D space (knee is flexed 30^o and ankle is at neutral position), T_z represents the torque about the flexion axis. Square-wave like torque signals were identified as illustrated in the figure and the torque during each stimulation is calculated as the average torque within the window highlighted by the vertical lines. The resultant torque signals were used for further analysis.

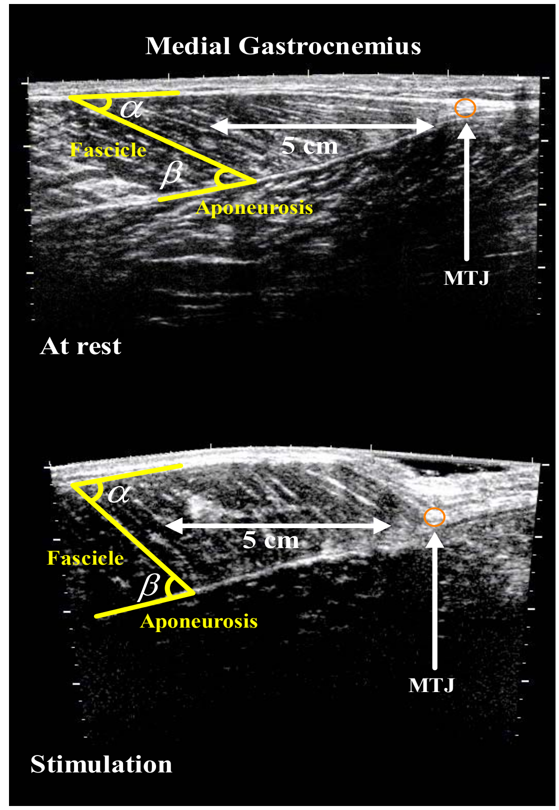

Fig. 3: Longitudinal ultrasound images of the medial gastrocnemius muscle at rest and under contraction induced by electrical stimulation. MTJ represents musculo-tendon (muscle aponeurosis) junction. α and β represent the posterior and anterior pennation angle respectively. MTJ of MG was identified and treated as a distal reference point. Muscle thickness was then measured 2 cm away and the fascicle lengths were measured around 5 cm from the reference point. Pennation angle measurements were taken at the fascicular insertion in both deep and superficial aponeurosis, namely, the anterior pennation angle and the posterior pennation angle.

determined as the most sensitive point through palpation of the tendon/muscle [11]. The amplitude of stimulation was adjusted for individual subjects due to subject-dependent thresholds to gain a measurable level of torques around the ankle joint. Each stimulation trial lasted 50 seconds and there were about 10 stimulations per trial.

All ultrasound images were collected by an experienced operator using a B-mode ultrasonography scanner with 12 MHz, 45mm high-resolution matrix probe (GE LOGIQ-9 with M12L probe, Waukesha, WI). Working in the LogiqView mode, the probe was placed perpendicular to the skin and moved smoothly along the middle line of the MG starting proximal to the distal part of the muscle (Fig. 3).

At each knee configuration, subjects were asked to relax with the ankle resting at a relaxed position. The corresponding ankle position and torque, namely, the resting angle and torque were recorded. In addition, the resistance torque at 0 degree dorsi-flexion was also measured. At each task condition, longitudinal scan of MG using LogiqView was conducted without electrical stimulation to evaluate the muscle properties under passive conditions. Then longitudinal scan was conducted as the stimulation was applied. The scan was repeated three times and averaged values were used for further analysis.

Data acquisition was implemented through a custom LabView program (National Instruments, Austin, TX, USA) and torque signals were sampled at 100 Hz. Data analysis including ultrasound images measurement was conducted by custom MATLAB programs (The MathWorks Inc., MA, USA). The torque signals were first transformed from the sensor coordinate system to the joint coordinate system, followed by digital low-pass filtering with a 4^{th}-order low pass Butterworth filter at 5 Hz. A two-way ANOVA was used to analyze response variables including the fascicle lengths (assumed to be equivalent to muscle fiber length), pennation angles and muscle thickness with the subject population and joint position as the factors involved. Significant level was set at 0.05.

III. RESULTS

The resting ankle angles are significantly more into plantar flexion in the stroke patients than in the normal subjects (Table I, P<0.001). The knee position also significantly affects the resting ankle positions (P<0.05). The resting angles shifted towards plantar flexion for both groups as knee was extended and this could be attributed to the increased tension of MG, as it spans both the knee and ankle joints.

TABLE I
RESTING ANGLES OF ANKLE UNDER DIFFERENT KNEE CONFIGURATIONS (MEAN±STD)

	Fully extended	*Flexed 30°*	*Flexed 60°*	*Flexed 90°*
Stroke	-22.0±7.1	-16.6±6.24	-17.7±3.56	*-15±4.69*
Normal	-13.4±2.68	-12.9±2.77	-12.5±2.76	*-12.5±2.01*

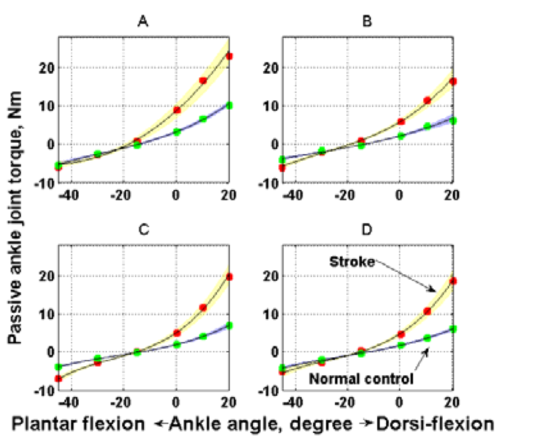

Fig. 4: Passive torque at ankle joint for both normal subject and stroke patient under different knee configurations: A) Full knee extension B) 30° knee flexion C) 60° knee flexion D) 90° knee flexion.

Stroke patients showed reduced range of motion, especially smaller dorsi-flexion angles, ranging from 2 to 10 degree compared to 19.5±1.6 degree in the normal control group (P<0.05). However, the knee configuration showed little effect on the range of motion (P>0.2). Due to spasticity and/or contracture stroke patients have significantly higher resistant torque at the neutral ankle position (0 degree plantar flexion) (P<0.05, Fig. 4).

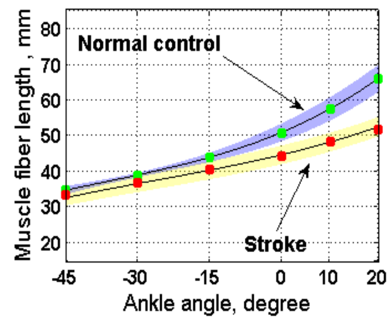

Fig. 5: Muscle fiber length at resting with 30° knee flexion configurations and subjects (mean±SE) (negative angle represents plantar flexion and positive angle stands for dorsi-flexion).

Muscle fiber length increased as the ankle position changed from plantar to dorsi-flexion for normal subjects. Compared to normal subjects, stroke patients exhibit significantly shorter muscle fibers as illustrated in Fig. 5 (P<0.05, except at plantar flexion of 15 and 45 degrees). Stroke survivors also demonstrated smaller posterior and anterior pennation angles at most of the tested positions. For instance, the anterior pennation angle are 21.9±6.5 degrees and 15.5±5.2 degrees for the control and stroke survivors respectively (Fig. 6, P<0.05) with 30 degree knee flexion and neutral ankle position. As the ankle was flexed in the direction of plantar flexion the MG became more relaxed and resulted in an increase in the muscle thickness. However, there was no significant difference for the muscle thickness and the mean values are 6.09±2.59 mm and 5.77±1.54 mm for stroke survivors and control respectively (P>0.05).

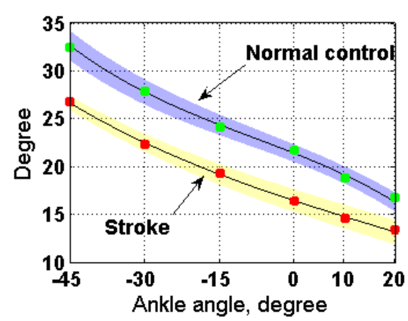

Fig. 6: Anterior pennation angle at resting with 30° knee flexion configurations and subjects (mean±SE) (negative angle represents plantar flexion and positive angle stands for dorsi-flexion).

As illustrated in Fig. 7, for normal subject, the torque peaks around neutral ankle position across all four knee configurations, however, stroke patient showed a considerably shifted pattern and the peak values were further away from the neutral positions towards dorsi-flexion.

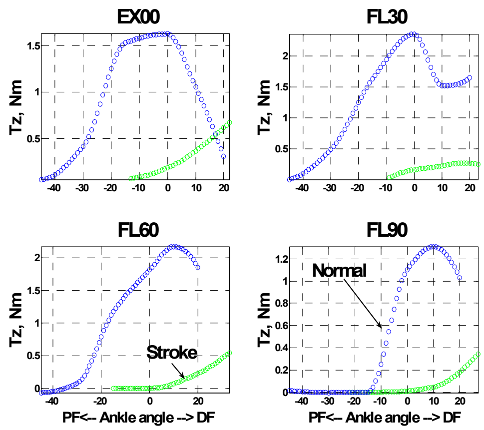

Fig. 7: Typical active torque-angle relation. Four panels correspond to four different knee configurations.

IV. DISCUSSION

To the best of our knowledge, this study was the first to examine biarticular muscle architecture/functions both passively and actively in stroke survivors as well as healthy subjects. The muscle architecture in healthy subjects in this study agrees with previously published data [8-10, 12-13]. The MG is a bi-articular muscle and spans both the ankle and knee joints. Systematic changes of both knee and ankle angles resulted in larger range of muscle fiber length changes compared to previous studies in which only one joint position was altered. One novelty of this study is that an extended-view-of-field technique, implemented in the state-of-the-art GE ultrasound device was used to measure the full length of muscle fibers.

The main findings of this study include: 1) stroke survivors with spastic calf muscles had shorter muscle fiber length; 2) stroke survivors showed smaller pennation angles both anteriorly and posteriorly; 3) stroke survivors showed shifted active torque-angle relation, compared to the normal control.

It has been shown that the number of sarcomeres is highly adaptable to changes in muscle length [14-16]. The shortening in muscle fibers observed in the current study might be related to a reduction of the number of sarcomere in series.

This study has direct clinical relevance. Information on force-length relation of in vivo muscles is critical in surgical procedures, such as tendon transfer [17] or guidance to rehabilitation treatment. Further studies on the muscle fiber level are carried out to examine relationship between the muscle architectural and biomechanical changes at both the joint and fiber levels.

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