Reappraisal of the Silfverskiöld test: Ultrasonographic study of the architectural properties of the triceps surae muscles

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<ABSTRACT>

Reappraisal of the Silfverskiöld test: Ultrasonographic study of the architectural properties of the triceps surae muscles

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The success of surgical correction of equinus contracture in children with spastic hemiplegic cerebral palsy (SHCP) depends on accurate identification of the affected muscles in the triceps surae. The Silfverskiöld test has long been used to decide surgical treatment, with minor consideration of the structural–functional complexity of the triceps surae muscles. This study used ultrasonography to investigate the architecture of the triceps surae muscles during passive knee and ankle motion in children with SHCP.

Ten children with SHCP and 10 age-matched normal children were recruited. Static near-sagittal ultrasound images of the lateral (LG) and medial (MG) gastrocnemii and soleus (SOL) muscles were acquired at various knee and ankle joint angles. On the basis of these images, changes in fascicle length, pennation angle, and muscle width of the triceps surae muscles, as well as displacement of the fascicle–deep aponeurosis junction were measured and compared among the paretic and nonparetic legs of patients and both legs of normal children. Subsequently, real-time elastography was performed to evaluate the elasticity of gastrocnemius muscles and the Achilles tendon. The mean intensity of colors red, blue, green were measured using semi-quantitative method. Analysis of histograms for each color of the sonoelastography images was performed for quantifying the elasticity of the Achilles tendon and gastrocnemius muscles.

Compared with fascicle length in normal legs, fascicle length was similar for the MG, longer for the LG and shorter for the SOL in paretic legs. The pennation angles were smaller for MG and LG in paretic legs than in normal legs, but were similar for SOL. The muscle widths of all triceps surae muscles were smaller in paretic legs than in normal legs. In the paretic legs of children with SHCP, the effects of ankle and knee joint positions were different and showed a complex pattern, unlike that in normal conditions. The median blue colors intensity were significantly higher in SHCP group suggesting that both Achilles tendon and gastrocnemius muscle in SHCP are stiffer than those of normal child.

In the paretic legs of children with Silfverskiöld-negative SHCP, the architectures and the elasticity of the triceps surae muscles and Achilles tendon were changed, and the normal actions between these muscles were disrupted according to knee and ankle joint positions. These results support the reliability of the Silfverskiöld test.

Key words : triceps surae, cerebral palsy, ultrasonography

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I. INTRODUCTION

Equinus gait is one of the most common abnormalities in patients with cerebral palsy, especially spastic hemiplegia. Although conservative treatments are typically used first, most patients eventually require surgical correction, in which the calf muscles are lengthened based on the assumption that the primary ankle plantar flexors, i.e., the triceps surae muscle–tendon unit, are abnormally short. The triceps surae muscle–tendon unit is a structurally complex unit[1-3] consisting of the soleus and medial and lateral gastrocnemii muscles. From the clinical perspective, the Silfverskiöld test[4, 5] has been used as a conventional tool to determine the affected muscle(s) in equinus contracture. When bending of the knee joint facilitates ankle dorsiflexion (Silfverskiöld positive), surgeons typically lengthen only the gastrocnemii (a biarticular muscle); otherwise, they lengthen the heel cord

(Silfverskiöld negative).

However, the Silfverskiöld test does not consider alteration of the muscles in patients with cerebral palsy. For example, some Silfverskiöld-positive patients demonstrate simultaneous activation of the soleus and gastrocnemii, and the limitation that surgeons should consider is that spasticity is primarily neural or contractural, as was suggested in a previous electromyography study[6]. Several studies using musculoskeletal modeling in conjunction with gait analysis have found short calf muscle–tendon lengths before surgery and increased calf muscle–tendon lengths after surgery according to the Silfverskiöld test in patients with cerebral palsy[7,8]; however, these studies estimated the muscle and tendon as a single unit and did not consider alterations in the muscle and tendon architectures.

For better treatment of equinus contracture, surgeons require more comprehensive understanding of the spasticity-induced structural–functional alterations along with the neural aspects[9]. The architectural properties of the skeletal muscles in the human body have been investigated in vivo using ultrasonography (US)[2,3,10,11]; the results of these studies have been applied to research on the differences in muscle architecture in various conditions[12, 13] as well as the changes in muscle architecture during passive and active joint motion[14-16]. Recently, ultrasound was introduced to investigate muscle architecture between normally developing children and those with cerebral palsy[17-22]. Although conventional US provided information about fiber length and cross-sectional area, it is not useful for the assessment of muscle stiffness, which is closely related to spasticity. Furthermore, the findings of these studies are not comparable because of lack of systematic control of knee–ankle joint position, skeletal deformity in patients with cerebral palsy, and insufficient consideration of disease entities such as diplegia and hemiplegia.

Sonoelastography is a newly introduced US technique that aims to assess tissue elasticity. While initial clinical applications of this technology have been largely in tumor detection, its usefulness has recently increased in the musculoskeletal field. The principle of elastography is that tissue compression produces a strain (displacement) within the tissue, and this strain is less in hard tissue than in soft tissue, thus allowing an objective determination of tissue stiffness. Quantitative measurement of strain distribution in spastic muscles allows an assessment of muscle stiffness and is useful for estimating the degree of spasticity.

Therefore, we used conventional ultrasonography as well as real time sonoelastography to investigate how fascicle length, pennation angle, and muscle thickness of the 3 muscles in the triceps surae muscle–tendon unit change with various ankle and knee joint positions in normal children and those with spastic hemiplegic cerebral palsy (SHCP). In this study, we hoped to obtain more comprehensive information on the functional implications of the architectural properties of the triceps surae muscles in knee and ankle motion. In addition, we sought to provide evidence on the reliability of the Silfverskiöld test[4,5]. Finally, the ultimate purpose of this study was to determine an appropriate surgical plan for the correction of abnormal gait caused by equinus contracture.

II. MATERIALS AND METHODS

1. Subjects

This study was approved by the Institutional Review Board of the hospital, and written consent was obtained in all cases from the parent/guardian. Ten children (6 boys, 4 girls; average age, 7 years 1 month; age range, 5 years to 10 years 1 month) with SHCP were recruited through the outpatient orthopedic clinic. All children could walk independently without any assistance or orthoses, and none had undergone any other treatment for the ankle equinus, such as selective posterior rhizotomy, surgical intervention, or botulinum toxin injection. Furthermore, a physician confirmed that none of the children had any ankle or foot deformity, such as equinovarus or planovalgus, or knee deformity, such as patella alta/baja or flexion contracture. Functional mobility, as measured by the Gross Motor Function Classification System[23], was above level I in all patients. All patients were Silfverskiöld negative and clinically considered to require lengthening surgery.

Ten age-matched normally developing children (6 boys, 4 girls; average age, 6 years 7 months; age range, 5 years 2 months to 8 years) were recruited for comparison. These children were examined by a physician and confirmed to be free from any neuromusculoskeletal disorders (Table 1).

Table I. Details on patient

	No.	Sex	Age (months)	Affected side	Femoral anteversion (degree)		Tibial torsion (degree)	
					Rt	Lt	Rt	Lt
SHCP*	1	M	87	Lt	18.0	10.2	22.4	17.8
	2	M	60	Rt	10.7	15.8	5.1	13.9
	3	M	60	Rt	23.6	21.9	28.7	18.6
	4	M	66	Rt	16.3	27.7	14.9	14.3
	5	M	60	Lt	14.4	22.0	15.5	22.8
	6	F	92	Rt	5.8	15.6	22.0	16.1
	7	F	109	Lt	12.3	23.8	19.7	22.4
	8	F	121	Lt	17.8	10.4	13.6	18.2
	9	F	71	Rt	20.5	11.2	17.4	26.4
	10	M	70	Rt	5.3	10.8	13.4	10.7
Normal	11	M	83		8.3	9.1	17.2	19.5
	12	M	62		20.4	22.3	21.1	19.8
	13	M	85		17.5	19.7	20.1	23.2
	14	M	85		9.8	11.5	14.6	18.2
	15	M	84		13.0	11.2	15.6	18.1
	16	F	96		19.3	22.1	18.7	21.5
	17	F	88		16.5	15.8	21.1	23.5
	18	F	73		20.2	19.3	16.9	20.4
	19	F	76		15.8	13.5	23.1	21.8
	20	M	92		7.6	8.3	15.2	16.9

The physical characteristics were similar between the children with SHCP and the normally developing children. Subjects were categorized into 3 groups: Group I consisted of patients' paretic legs (n = 10), group II consisted of patients' nonparetic contralateral legs (n = 10), and group III comprised both legs of the 10 normally developing children (n = 20). The degree of involvement in all patients with SHCP was type II hemiplegia, characterized by tibialis anterior weakness and spasticity in the triceps [24].

2. Procedure

Ultrasound examinations were performed for all participants using a linear phased array transducer with a frequency of 5–13 MHz (HIvision Avius, Hitachi Medical, Japan). The same conditions of brightness, contrast, intensity, and gain of the ultrasound system were used in all examinations. However, because the numeric elastography information is displayed using a rainbow color-coded scale, with values from 0 to 255, changes in the system settings did not affect the subsequent post-processing analysis. For each joint configuration, longitudinal ultrasound images of the medial and lateral gastrocnemii (MG and LG, respectively) and soleus (SOL) muscles were acquired from the midbelly of the muscles. Each measurement level was located at the maximal anatomic cross-sectional area of the respective muscle: at the proximal 30% (for MG and LG) and 50% (for SOL) of the distance between the popliteal crease and the center of the lateral malleolus [2].

The subject lay prone on the examining table and was instructed to refrain from any voluntary joint movement. The number of joint configurations involved in the study was 12: 3 knee joint angles (0°, 45°, and 90° of flexion) and 4 ankle joint angles (10° of dorsiflexion, and 0°, 15°, and 30° of plantarflexion). Subsequently, real-time elastography was performed. The Achilles tendons and gastrocneminus muscles were examined longitudinally while the patient was lying in the prone position with the foot hanging over the edge of the examination table in a relaxed position. Free hand compression force was applied while the transducer was placed perpendicular to the tendon in order to avoid anisotropy. Applied pressure was adjusted appropriately according to the visual strain graph seen on the video screen. The condition of compressing is shown as a graph in real time (Fig. 1). Real-time sonoelastographic scans were repeated by compression and relaxation of the scan area for at least four cycles so that findings could be verified as reproducible. Real-time sonoelastographic images of the tendons and muscles were obtained in the longitudinal plane in the same position. In the procedure, the calculation of tissue elasticity distribution was performed in real-time, and the examination results were represented on a color map superimposed on the B-mode image. The color represented the relative stiffness of the tissues within the region of interest and ranged from blue (stiff) to red (soft) in the spectrum. Green and yellow indicated medium stiffness. All of these images were recorded on a hard disk and used for statistical evaluation (Figure 1).

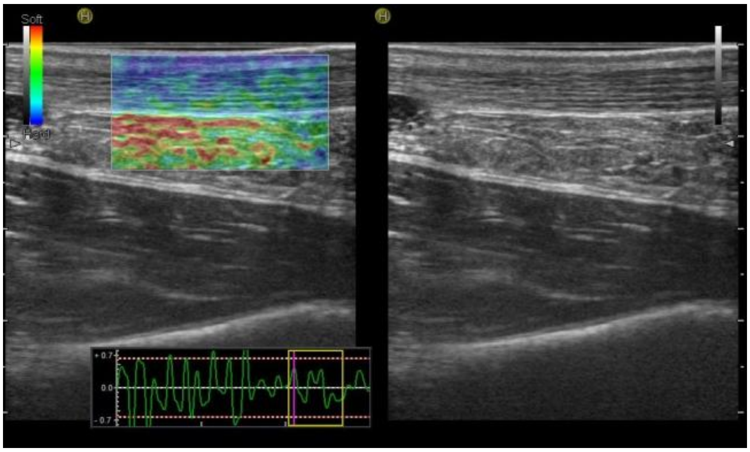

Figure 1. Longitudinal real-time sonoelastography view of the Achilles tendon. The condition of compression is shown as a graph in real time on the video screen.

3. Measurement of Muscle Architecture Variables

From the acquired ultrasound images, fascicle length, pennation angle, and thickness of the MG, LG, and SOL were measured using public domain image processing software (Image J, version 1.37, National Institutes of Health, Bethesda, MD). By visualizing the fascicles along their lengths from the superficial to deep aponeurosis, one can be convinced that the plane of the ultrasonogram is parallel to the fascicles[10]. Based on a simple planimetric muscle model[11], we defined and measured the pennation angle (the angle formed between the fascicular path and deep aponeurosis of the muscle), muscle thickness (T; the shortest distance between the superficial and deep aponeurosis), and fascicle length (Lf; the distance between the origin [the point where the fascicle and superficial aponeurosis met] and insertion [the point where the fascicle and deep aponeurosis met]) (Fig. 2). Movement of the fascicle–aponeurosis junction was defined as displacement of the fascicle–deep aponeurosis junction during passive ankle joint motion over full and constant (from 30^o-15^o plantar flexion) range of motion of the ankle joint at each knee joint position (Fig. 3).

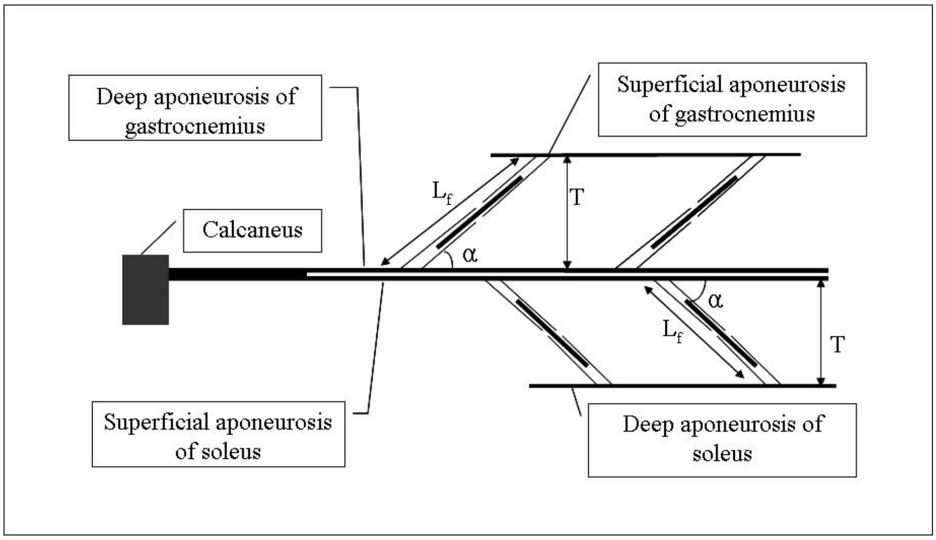

Figure 2. Measured muscle architecture variables: fascicle length (Lf), pennation angle (α), and muscle thickness (T) in a schematic model of the triceps surae.

Since elastograms reveals only the relative stiffness of tissues examined in the B-mode US image, secondary analysis of real-time elastograms was required to obtain semi-quantitative information. The acquired images in the phase of compression in the longitudinal planes were reviewed to quantify the elasticity of the Achilles tendon and gastrconemius muscle. The color pattern of the images was quantitatively analyzed by using Image J software. Each pixel of the image was automatically separated by the image J program into the red, green and blue components (0-255). The program then computed the mean intensity of each component. The histogram provided a mean value and a standard deviation for the respective color.

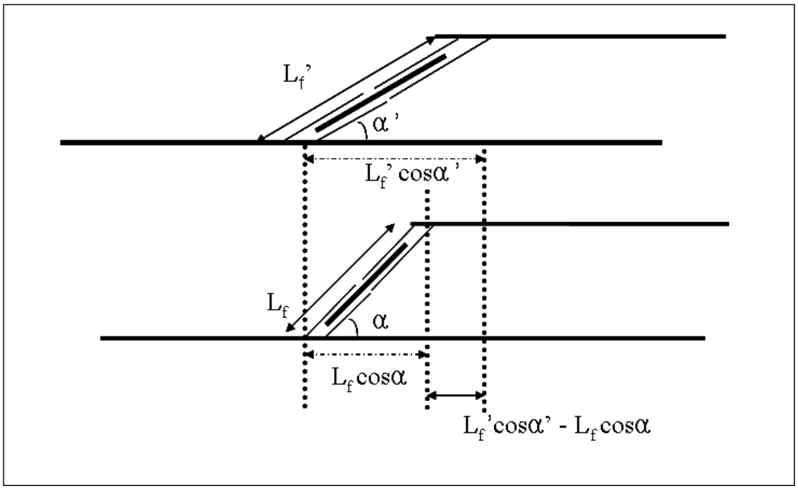

Figure 3. Displacement of the fascicle–deep aponeurosis junction = Lf'Cosα' – Lf Cosα.

4. Statistical Analysis

Each architectural variable of the triceps surae muscles were measured twice, without information on joint position from the ultrasonography images. The intraclass coefficient (ICC) values of the ultasonographic measurements (fascicle length, pennation angle and muscle width) were between 0.5307 and 0.9915 (Table 2). The ICC of elasticity of gastrocnemius muscles and Achilles tendons were between 0.728 and 0.960.

Statistical analyses were performed using SAS version 9.1 software (SAS

Institute, Cary, NC). The obtained architectural variables were compared among groups (groups I, II, and III) and joint positions (ankle–knee configurations). A mixed model was used to allow for repeated measurements in individual patients, and to test the effect of the joint configurations on the muscle architecture independently among groups and muscles. In addition, to adjust for the effects of age, sex, and fibula length, we performed multivariate analysis. Displacement of the fascicle–deep aponeurosis junction was compared under the conditions of full range and same range of ankle motion in each group. The level of significance was set at $P < .05$.

III. RESULTS

1. Fascicle Length

For the MG and LG, the knee joint position significantly influenced the fascicle length in all groups ($P = .0018$ for the MG in group II; $P < .0001$ for the others). The lengths of the MG and LG fascicles increased with increase in knee extension angle. However, for the SOL, the effect of the knee position was only significant in group III ($P = .0004$), showing an increase in the fascicle length with increase in knee flexion angle.

The ankle joint position significantly influenced the fascicle length only for the SOL ($P = .0017$), and not for the MG ($P = .7995$) or LG ($P = .4320$) in group I. The lengths of the MG, LG, and SOL fascicles, except for the MG and LG in group I, increased with increase in ankle dorsiflexion angle ($P = .0017$ for the SOL in group I; $P < .0001$ for the others).

The LG fascicle in group I ($P < .0001$) and SOL fascicle in group III ($P < .0001$) were longer than those in the other groups. There was no significant difference in the length of the MG fascicle among the groups ($P = .5638$). Data are summarized in Table 3.

2. Pennation Angle

Table 2. Intraclass correlation coefficient (ICC) of ultrasonographic measurements

	Group	Muscle	ICC	95% Confidence Interval		
		MG[*]	0.9503	0.9151	~	0.9736
	Group I	LG[†]	0.9375	0.8836	~	0.9639
		SOL[‡]	0.8572	0.6927	~	0.9276
		MG	0.9352	0.9050	~	0.9603
Length	Group II	LG	0.9285	0.8956	~	0.9570
		SOL	0.8616	0.7225	~	0.9213
		MG	0.7230	0.6832	~	0.9192
	Group III	LG	0.7477	0.6847	~	0.8177
		SOL	0.5307	0.4912	~	0.7053
		MG	0.6234	0.4056	~	0.7658
	Group I	LG	0.6833	0.5775	~	0.8747
		SOL	0.7961	0.6455	~	0.9260
		MG	0.8964	0.8452	~	0.9340
Angle	Group II	LG	0.8372	0.7512	~	0.8914
		SOL	0.9377	0.8648	~	0.9677
		MG	0.8811	0.8299	~	0.9052
	Group III	LG	0.6247	0.4932	~	0.6925
		SOL	0.7585	0.6775	~	0.8221
		MG	0.9762	0.9552	~	0.9859
	Group I	LG	0.9546	0.9137	~	0.9724
		SOL	0.9699	0.9359	~	0.9833
		MG	0.9893	0.9858	~	0.9943
Width	GroupII	LG	0.9915	0.9861	~	0.9943
		SOL	0.9297	0.8752	~	0.9562
		MG	0.9772	0.9661	~	0.9817
	Group III	LG	0.8385	0.8418	~	0.9134
		SOL	0.9233	0.8985	~	0.9741

[*]MG: medial gastrocnemius
[†]LG: lateral gastrocnemius
[‡]SOL: soleus
[§]Ac: Achilles tendon

Table 3. Fascicle length (mm)

Knee angle		0°				45°				90°			
Ankle angle		10° DF||	0° PF¶	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF
MG*	Gr§ I		42.0 ± 12.6	43.4 ± 11.3	42.6 ± 12.4		39.9 ± 10.0	36.4 ± 8.4	37.3 ± 8.0		32.9 ± 9.8	33.6 ± 6.5	31.9 ± 9.3
	Gr II	44.8 ± 8.2	41.0 ± 9.6	41.5 ± 9.3	38.3 ± 8.2	44.9 ± 9.4	41.7 ± 11.0	37.7 ± 7.2	34.8 ± 9.9	39.5 ± 7.3	38.5 ± 8.7	36.8 ± 8.9	34.4 ± 7.4
	Gr III	46.0 ± 8.1	45.4 ± 8.4	42.9 ± 9.4	38.5 ± 7.5	40.0 ± 4.5	38.4 ± 4.4	35.4 ± 3.9	33.8 ± 3.6	36.7 ± 4.5	36.5 ± 5.4	36.1 ± 5.7	35.3 ± 6.2
LG†	Gr I		48.2 ± 12.0	46.2 ± 9.8	44.6 ± 9.3		43.2 ± 9.2	40.3 ± 8.2	36.8 ± 8.3		34.5 ± 8.2	34.7 ± 7.2	33.7 ± 7.5
	Gr II	46.7 ± 10.3	43.1 ± 6.4	41.6 ± 9.8	38.8 ± 9.6	42.8 ± 7.1	38.4 ± 7.3	35.9 ± 5.3	34.8 ± 7.2	36.6 ± 7.0	35.6 ± 7.2	34.0 ± 9.1	32.5 ± 8.4
	Gr III	44.7 ± 5.4	41.1 ± 4.7	37.9 ± 4.2	33.9 ± 3.5	37.9 ± 6.4	35.1 ± 6.4	32.2 ± 5.9	30.3 ± 6.2	34.8 ± 5.0	33.6 ± 5.2	33.0 ± 5.4	31.1 ± 4.5
SOL‡	Gr I		29.3 ± 4.8	27.9 ± 7.0	23.6 ± 7.0		31.2 ± 3.3	28.3 ± 3.7	23.6 ± 3.0		32.6 ± 3.1	30.6 ± 7.2	27.2 ± 5.6
	Gr II	32.6 ± 7.0	30.2 ± 9.0	29.1 ± 8.1	24.7 ± 13.4	35.3 ± 4.5	31.2 ± 5.3	30.0 ± 4.3	25.8 ± 2.7	36.8 ± 3.2	34.3 ± 5.0	31.4 ± 5.3	29.5 ± 2.9
	Gr III	34.5 ± 6.6	30.6 ± 5.9	29.2 ± 5.7	27.8 ± 5.4	35.9 ± 4.0	32.3 ± 3.7	29.2 ± 4.2	27.5 ± 3.8	37.0 ± 7.4	35.3 ± 8.2	32.7 ± 7.9	29.3 ± 6.7

Values are mean ± standard deviation.
*MG: medial gastrocnemius
†LG: lateral gastrocnemius
‡SOL: soleus
§Gr: group
|| DF: dorsiflexion / ¶PF: plantar flexion

For the MG, the pennation angle increased with increase in knee flexion angle in all groups (P = .0025 for group I; P < .0001 for groups II and III). For the LG, the pennation angle increased with increase in knee flexion angle only in group III (P < .0001). For the SOL, the pennation angle significantly increased with increase in knee extension angle in groups I (P = .0240) and II (P = .0353).

As the ankle joint went into plantar flexion, the pennation angle increased for the MG (P = .0384, P < .0001, and P < .0001 in groups I, II, and III, respectively), LG (P < .0021, P = .0004, and P < .0001 in groups I, II, and III, respectively), and SOL (P = .0005 and P < .0001 in groups I and III, respectively), except for the SOL in group II (P = .0717).

The pennation angles of the MG (P < .0001) and LG (P < .0001) were the greatest in group III. For the SOL, there was no significant difference in the pennation angle among the groups (P = .3963). Data are summarized in Table 4.

3. Muscle Width

The width of the MG increased with increase in knee flexion angle in group II (P = .0013). For the LG, the effects of the knee joint position were significant in groups I (P < .0087) and II (P < .0012), with the widths increasing with increase in knee extension angle. For the SOL, the effect of the knee position was not significant in any group.

Changes in the ankle joint position did not significantly influence the muscle width of any muscle in any group, except for the MG in group III (P = .0029), which increased with increase in ankle plantar flexion angle.

The muscle widths of the MG (P < .0013), LG (P = .0002), and SOL (P = .0003) were the greatest in group III. Data are summarized in Table 5.

4. Displacement of the Fascicle–Deep Aponeurosis Junction

During full range of ankle motion, the effects of the knee position were significant only for the MG (P = .0014) and LG (P < .0001) in group III, with

Table 4. Pennation angle (degrees)

`		0°				45°				90°			
Ankle angle		10° DF[‖]	0° PF[¶]	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF
MG[*]	Gr[§] I		11.5 ± 2.1	13.1 ± 2.7	13.8 ± 2.7		10.7 ± 2.1	11.2 ± 2.7	12.8 ± 2.5		13.9 ± 5.2	14.4 ± 4.1	14.2 ± 4.5
	Gr II	12.9 ± 3.7	14.5 ± 3.3	14.4 ± 2.9	15.6 ± 2.9	12.4 ± 4.0	12.4 ± 3.6	12.3 ± 4.2	14.0 ± 4.2	14.1 ± 4.7	15.4 ± 4.1	16.0 ± 3.7	18.1 ± 4.6
	Gr III	12.4 ± 2.5	12.9 ± 2.8	14.1 ± 2.7	16.1 ± 3.6	12.4 ± 3.5	13.4 ± 3.1	15.3 ± 3.7	16.3 ± 3.1	14.3 ± 2.8	14.9 ± 3.0	16.4 ± 3.4	18.0 ± 4.0
LG[†]	Gr I		12.4 ± 2.4	13.9 ± 2.5	15.4 ± 3.3		11.3 ± 4.1	13.9 ± 4.8	16.4 ± 4.6		14.8 ± 5.4	15.9 ± 3.6	16.1 ± 4.8
	Gr II	13.7 ± 3.2	14.5 ± 3.2	16.3 ± 3.3	17.8 ± 4.0	15.3 ± 3.9	15.4 ± 4.5	16.2 ± 5.8	17.7 ± 5.6	15.9 ± 4.8	15.8 ± 5.4	16.9 ± 6.1	19.7 ± 8.3
	Gr III	16.7 ± 2.2	17.9 ± 2.4	19.9 ± 2.6	22.0 ± 3.0	19.2 ± 2.7	20.9 ± 3.6	22.7 ± 3.4	25.3 ± 4.1	20.8 ± 4.0	20.8 ± 4.0	22.3 ± 3.6	24.3 ± 4.4
SOL[‡]	Gr I		18.7 ± 4.6	21.7 ± 6.2	23.8 ± 5.6		19.7 ± 4.5	21.0 ± 3.9	24.5 ± 6.4		18.1 ± 4.1	19.2 ± 5.9	20.0 ± 5.1
	Gr II	16.8 ± 5.4	17.3 ± 5.1	18.0 ± 7.0	17.9 ± 7.2	19.3 ± 6.3	20.3 ± 7.5	20.3 ± 6.6	23.1 ± 9.0	16.1 ± 4.6	18.4 ± 6.2	17.5 ± 5.7	19.8 ± 5.2
	Gr III	18.6 ± 3.3	19.3 ± 4.0	21.3 ± 4.6	22.5 ± 5.9	17.5 ± 3.6	19.0 ± 4.9	21.5 ± 4.5	24.3 ± 6.4	17.5 ± 2.7	18.6 ± 3.6	20.3 ± 5.8	21.6 ± 6.7

Values are mean ± standard deviation.
[*]MG: medial gastrocnemius
[†]LG: lateral gastrocnemius
[‡]SOL: soleus
[§]Gr: group
[‖]DF: dorsiflexion / [¶]PF: plantar flexion

Table 5. Muscle width (mm)

Knee angle		0°				45°				90°			
Ankle angle		10° DF[‖]	0° PF[¶]	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF	10° DF	0° PF	15° PF	30° PF
MG[*]	Gr[§] I		10.3 ± 3.9	10.9 ± 3.0	11.5 ± 3.1		8.8 ± 3.3	8.6 ± 3.4	9.4 ± 3.3		8.5 ± 4.4	9.6 ± 3.0	9.6 ± 3.4
	Gr II	11.1 ± 3.0	11.0 ± 3.4	11.0 ± 3.6	11.0 ± 3.5	11.1 ± 3.2	10.2 ± 3.8	10.1 ± 3.8	10.1 ± 3.8	11.4 ± 3.7	11.2 ± 3.9	11.6 ± 4.0	11.9 ± 4.1
	Gr III	10.7 ± 1.8	10.7 ± 1.9	10.7 ± 1.8	10.8 ± 1.7	9.7 ± 1.2	9.9 ± 1.3	10.0 ± 1.4	9.9 ± 1.4	9.8 ± 1.3	10.2 ± 2.1	10.8 ± 2.0	11.7 ± 1.9
LG[†]	Gr I		12.5 ± 4.7	12.9 ± 3.3	12.1 ± 2.8		10.9 ± 4.7	10.3 ± 3.7	11.3 ± 2.7		10.0 ± 4.2	10.7 ± 3.1	10.7 ± 3.5
	Gr II	12.9 ± 4.3	12.9 ± 4.5	12.6 ± 4.2	12.5 ± 4.3	12.5 ± 3.9	11.4 ± 3.9	11.6 ± 4.0	11.3 ± 3.5	10.9 ± 3.7	10.8 ± 3.6	10.8 ± 4.4	11.3 ± 4.9
	Gr III	13.1 ± 1.6	12.9 ± 1.5	12.8 ± 1.3	12.9 ± 1.6	12.9 ± 1.5	12.7 ± 1.5	12.9 ± 1.8	13.2 ± 1.7	12.8 ± 2.0	12.8 ± 2.0	13.0 ± 1.9	13.4 ± 2.0
SOL[‡]	Gr I		11.5 ± 2.6	12.0 ± 2.8	11.4 ± 2.9		11.1 ± 2.0	11.3 ± 2.4	10.8 ± 2.9		11.4 ± 2.1	11.3 ± 1.9	10.9 ± 1.9
	Gr II	13.1 ± 3.3	11.7 ± 2.3	11.4 ± 2.4	11.3 ± 2.3	12.2 ± 2.9	11.9 ± 2.6	11.7 ± 2.6	11.2 ± 3.3	11.4 ± 1.9	11.1 ± 2.1	10.9 ± 2.4	10.8 ± 2.8
	Gr III	11.8 ± 2.1	11.8 ± 2.4	12.0 ± 2.7	11.9 ± 3.1	11.6 ± 2.0	11.4 ± 2.1	11.3 ± 2.1	11.5 ± 2.2	11.9 ± 2.2	12.1 ± 2.1	11.7 ± 3.0	11.4 ± 2.7

Values are mean ± standard deviation.
[*]MG: medial gastrocnemius
[†]LG: lateral gastrocnemius
[‡]SOL: soleus
[§]Gr: group
[‖]DF: dorsiflexion / [¶]PF: plantar flexion

Table 6. Displacement of the fascicle-deep aponeurosis junction according to knee angle during full range of ankle motion (mm)

	Paretic (Group I)			Non-paretic (Group II)			Normal (Group III)			*P value*		
	Knee 0°	Knee 45°	Knee 90°	Knee 0°	Knee 45°	Knee 90°	Knee 0°	Knee 45°	Knee 90°	Group I *vs* Group II	Group I *vs* Group III	Group II *vs* Group III
MG*	0.8 ± 4.8	0.9 ± 3.2	1.5 ± 5.0	5.2 ± 7.7	6.4 ± 5.1	5.1 ± 4.5	*8.0 ± 6.7*	*6.6 ± 4.6*	*2.3 ± 6.1*	0.0075	0.0029	0.6353
LG†	1.5 ± 3.1	3.2 ± 4.5	1.1 ± 4.8	7.9 ± 5.5	7.3 ± 7.4	5.4 ± 3.0	*11.4 ± 4.9*	*8.6 ± 3.6*	*3.9 ± 3.7*	0.0008	0.0004	0.7661
SOL‡	3.7 ± 2.0	7.1 ± 3.2	2.8 ± 2.7	8.0 ± 7.5	9.3 ± 4.4	9.3 ± 3.4	5.6 ± 8.6	7.9 ± 3.9	6.6 ± 5.5	0.0312	0.0948	0.3784

Values are mean ± standard deviation.
*MG: medial gastrocnemius
†LG: lateral gastrocnemius
‡SOL: soleus
Data in *italic format* in Group III indicate significant differences among different knee positions (p=0.0014 for the MG and p<0.0001 for the LG)

displacement of the fascicle–deep aponeurosis junction being smaller in the flexed knee position. There was no significant difference in the SOL in any group (P = .1566, .5861, and .1380 for groups I, II, and III, respectively). In comparison among the groups, displacement of the fascicle–deep aponeurosis junction in the MG and LG was smaller in group I than in groups II and III (Table 6).

During constant range of ankle motion (from 30^{o}-15^{o} plantar flexion), the effects of the knee joint position were significant only for the MG (P = .0040) and LG (P = .0360) in group III, with displacement of the fascicle–deep aponeurosis junction being smaller in the flexed knee position. There was no significant difference in the SOL in any group (P = .1566, .5246, and .1317 for groups I, II, and III, respectively). In comparison among the groups, there was no significant difference in displacement of the fascicle–deep aponeurosis junction in any muscle (Table 7).

5. Elasticity of Achilles tendon and gastrocnemius muscle

The mean value for the intensity of red, green, and blue colors from the elastography images of the Achilles tendon were 88.0, 132.9, and 81.9 in normal group and 76.2, 131.0 and 118.0 in CP group. There were significant differences in red and blue colors between two groups (p=0.018 for red, p<0.001 for blue). The mean values for the intensity of red, green and blue colors of the MG were 85.1, 140.2, and 95.2 in normal group and 94.2, 155.9, and 139.3 in CP group. The mean green and blue colors intensity were significantly higher in CP group (p=0.004 for green, p<0.001 for blue). The median values for the intensity of red, green and blue colors of the LG were 105.6, 150.9, and 110.1 in normal group and 100.7, 150.7, and 133.0 in CP group. The median blue colors intensity were significantly higher in CP group (p<0.001, Figure 4.

Table 7. Displacement of the fascicle-deep aponeurosis junction according to knee angle during ankle plantarflexion 15° to ankle plantarflexion 30° (mm)

	Paretic (Group I)			Non-paretic (Group II)			Normal (Group III)			*P value*		
	Knee 0°	Knee 45°	Knee 90°	Knee 0°	Knee 45°	Knee 90°	Knee 0°	Knee 45°	Knee 90°	Group I *vs* Group II	Group I *vs* Group III	Group II *vs* Group III
MG*	0.8 ± 4.8	0.9 ± 3.2	1.5 ± 5.0	3.3 ± 3.0	3.2 ± 4.5	2.7 ± 3.0	*4.7 ± 4.8*	*1.7 ± 3.4*	*1.0 ± 5.1*	0.0556	0.1010	0.6693
LG†	1.5 ± 3.1	3.2 ± 4.5	1.1 ± 4.8	3.0 ± 2.7	1.3 ± 2.8	2.1 ± 3.7	*4.2 ± 3.8*	*2.5 ± 2.5*	*2.4 ± 3.3*	0.6977	0.3805	0.6140
SOL‡	3.7 ± 2.0	7.1 ± 3.2	2.8 ± 2.7	1.6 ± 5.4	4.1 ± 3.1	3.5 ± 2.6	1.5 ± 2.1	2.2 ± 3.5	3.0 ± 3.6	0.4189	0.2348	0.6989

Values are mean ± standard deviation.
*MG: medial gastrocnemius
†LG: lateral gastrocnemius
‡SOL: soleus
Data in *italic format* in Group III indicate significant differences among different knee positions (p=0.0040 for the MG and p=0.0360 for the LG)

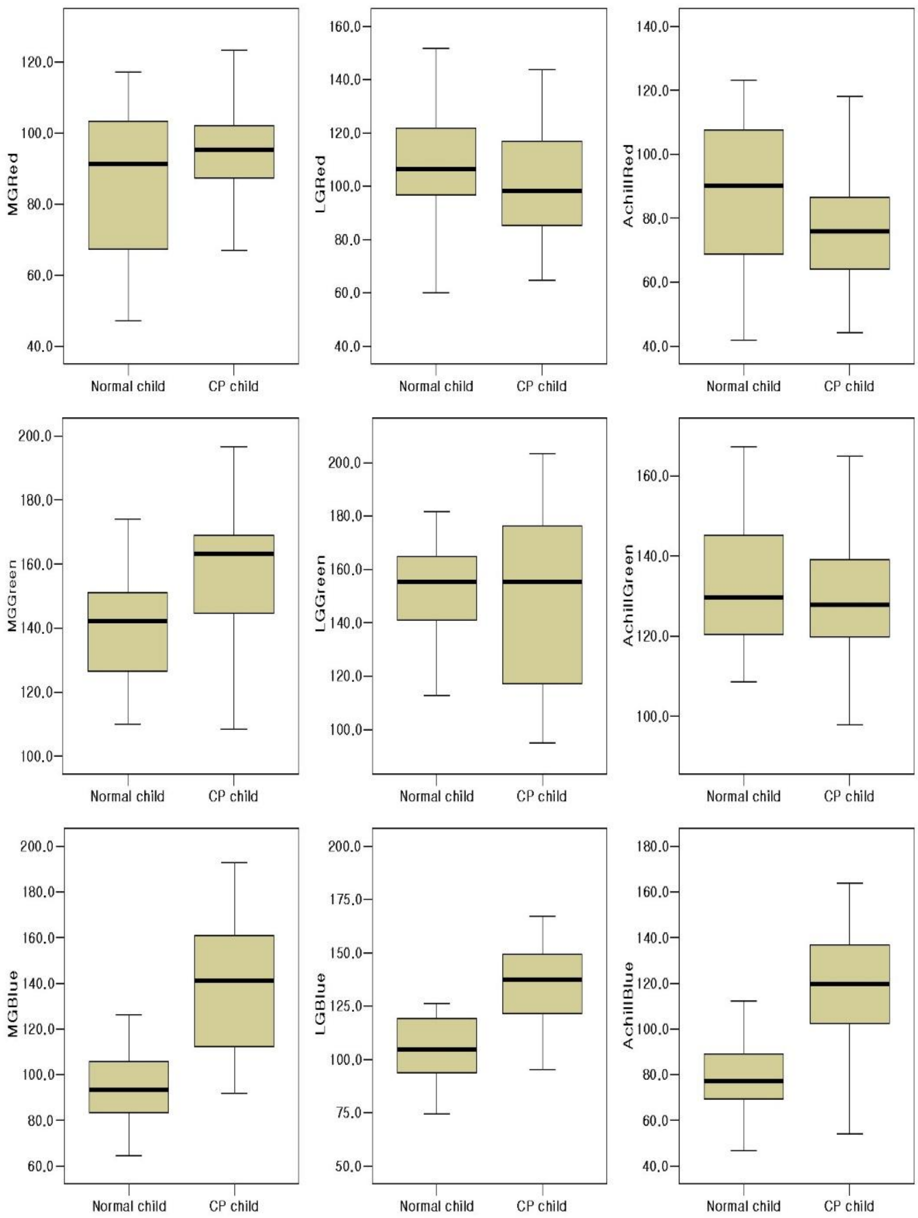

Figure 4. Box plots of real-time elastography results for red, green and red intensity colors in each group.

IV. DISCUSSION

In this study, ultrasonography findings showed that changes in the architectural properties of the triceps surae muscles caused by systematic variation in passive ankle–knee joint positions were different between children with Silfverskiöld-negative SHCP and normally developing children. Since structural and functional abnormalities can occur in the gastrocnemii (a 2-joint muscle crossing both the knee and ankle joints) or in both the gastrocnemii and soleus (a 1-joint muscle), it is necessary to evaluate the architecture of these 3 muscles as well as the interactions between these muscles, tendons, and aponeurosis. Although many studies using electromyography[6] and gait analysis[7,8] have reported on the Silfverskiöld test, they did not consider the complex structure of the triceps surae muscle–tendon unit and aponeurosis[1]; consequently, it is difficult to confirm which component in the muscle is most affected or where the lengthening surgery should be performed.

The architectural features of the triceps surae muscles have been studied in vivo using ultrasonography in children with spastic cerebral palsy and equinus contracture, but those studies have reached inconsistent conclusions[17-22]. For the gastrocnemii, Shortland et al.[21] showed a similar fascicle length between children with spastic diplegic cerebral palsy (SDCP) and normally developing children, whereas Mohagheghi et al.[20] revealed a shorter fascicle length in children with SDCP. Children with SDCP can have many different skeletal deformities, such as planovalgus, equinovarus, tibial/femoral rotational deformity, and knee flexion deformity. Considering that it is difficult to control skeletal deformity in patients with SDCP, the studies on children with SDCP did not seem to control skeletal deformity sufficiently to test the aforementioned hypothesis. In the present study, homogeneity of the SHCP group was considered the most important factor in the selection of patients; thus, it was ensured that all patients were ambulatory without any assistance, free from severe skeletal deformity, and had type II hemiplegia.

Compared with fascicle lengths in normally developing children, the fascicle lengths in children with SHCP were the same for the MG, longer for the LG, and smaller for the SOL. Mohagheghi et al.[9] suggested that reduced fascicle length and muscle thickness in the gastrocnemii are possible causes of equinus contracture in SHCP. However, their study did not consider that in children with equinus contracture, the resting ankle dorsiflexion angle is smaller than that in any other condition, which suggests that the fascicle would be longer if it was measured only at the resting ankle joint angle. In normal persons, the fascicle length of the LG is the longest among the triceps surae muscles, indicating that the number of sarcomeres is the largest in this muscle [2]. Therefore, the effect of cerebral palsy in terms of the fascicle length was noted only in the LG; however, we believe that the effect of cerebral palsy on alteration of the absolute fascicle length of the MG and SOL cannot be confirmed because of the relatively short fascicle length and small number of subjects.

The overall muscle widths in our study were smaller in patients' paretic legs compared with the other groups. Malaiya et al.[18] suggested that equinus contracture in children with SHCP is not due to a decrease in fascicle length of the gastrocnemii, but rather to a lack of cross-sectional growth and decreased muscle volume of the MG [25]. Although muscle thickness was only an estimation of muscle volume in our study, differences between the groups indicates the presence of substantial muscle atrophy in paretic legs, consistent with previous reports[9,17,19]. Muscle width was considered to be most affected by muscle weakness caused by cerebral palsy. In this aspect, the effect on all the muscles of the triceps surae in patients with Silfverskiöld-negative SHCP can be explained. In addition, the pennation angles of the MG and LG showed a significant decrease in children with SHCP compared with normally developing children. Considering the finding that the pennation angle is increased in hypertrophied muscles[13] and that the pennation angle increases after gastrocnemius lengthening in children with spastic diplegia[22], the results of this study indicate that the MG and LG in children with SHCP are weakened, and, after proper surgery, the pennation angle would be increased.

The present study showed that the pennation angles of both gastrocnemii in patients' paretic legs (group I) were smaller than those in patients' nonparetic legs (group II) and normally developing children (group III) under the same joint conditions with knee extension. In addition, the LG fascicle length was longer in children with SHCP compared with normally developing children. From these results, the limited ankle dorsiflexion due to the LG in children with SHCP can be explained. Our muscle model suggests that smaller pennation angle and longer fascicle length of the LG in patients' paretic legs (group I) at ankle plantar flexion are already similar to those in normally developing children (group III) at a neutral ankle angle. Thus, further dorsiflexion could not be achieved in patients' paretic legs (group I). In addition, this model demonstrated that there was no difference in displacement of the fascicle–deep aponeurosis junction between the groups during the same range of ankle motion; however, displacements in the SOL and both gastrocnemii were most decreased in patients' paretic legs (group I) during full range of ankle motion. Under this model, lengthening of the deep aponeurosis in the gastrocnemius or Achilles tendon is considered to be appropriate.

We should consider that Silfverskiöld-negative patients show limited ankle dorsiflexion when knee joint flexion is increased. Many studies [2, 3, 17] on the changes in fascicle length and pennation angle of the triceps surae during isometric plantar flexion at various knee and ankle joint positions have demonstrated that the fascicle behavior of the SOL is affected by ankle joint angle but not by knee joint angle. We measured the fascicle length and pennation angle with various knee and ankle joint positions. The effect of the knee position was not significant in displacement of the fascicle–deep aponeurosis junction in the SOL in any group. However, the fascicle length of the SOL in normally developing children (group III) increased with increasing knee flexion angle, contrary to the changes in fascicle length in both gastrocnemii. The changes in pennation angle also were different between both gastrocnemii and the SOL. The differential displacements of the SOL and gastrocnemius aponeuroses during isometric plantar flexion [14] depending on the knee position, and the different fascicle behavior between the MG and SOL during walking[15] also have been noted in previous studies. The important finding is not the effect of the knee joint position, but the complex dynamic movement between both gastrocnemii and the SOL during knee flexion and extension.

In patients' paretic legs (group I), the changes in fascicle length and pennation angle were different compared with those in normally developing children (group III). For the LG and MG in patients' paretic legs (group I), the fascicle length did not change according to the changes in ankle joint angle, whereas the length decreased with increasing ankle plantar flexion in patients' nonparetic legs and in legs of normally developing children. For the SOL, the fascicle length remained constant at the various knee joint positions in children with SHCP. This abnormal fascicle characteristic in children with SHCP, compared with normally developing children, was also seen in the pennation angles of the LG and SOL as well as displacement of the fascicle–deep aponeurosis junction in both gastrocnemii. Based on this observation, one possible explanation is a disruption in the normal differential displacement of the SOL and gastrocnemius aponeuroses in children with Silfverskiöld-negative SHCP. Therefore, lengthening of the Achilles tendon would be more appropriate because of the disruption in the normal movement between the 3 muscles and aponeuroses.

Several studies have shown that increased stiffness of the muscles in CP child and increased in elasticity after injection with Botulinum toxin. In the present study, the intensity of red color was lower and blue color was higher in SHCP group. Similarly, the intensity of blue color of MG and LG was higher in SHCP group indicating that both Achilles tendon and gastrocnemius muscle in SHCP are stiffer than those of normal child. This finding also explain the need of lengthening of Achilles tendon rather than aponeurosis lengthening of the gastrocnemius in SHCP patients and the high recurrence rate after surgery for equinus deformity in these patients.

There are several limitations to our study. Generalization of our data would be more accurate with a larger number of subjects and the inclusion of multiple blinded examiners. Furthermore, we did not use a normalization technique for the fibula length in the comparison of fascicle lengths. However, the absence of a significant correlation between muscle fascicle and leg lengths in healthy adults has been reported [12]. In our study, we used a mixed-model procedure that included fibula length, age, and sex. The Achilles tendon length and length of the muscle belly were not compared in this study, but relatively increased length of the Achilles tendon in patients with cerebral palsy has been reported in previous studies [26,27]. To compare the muscle architecture, the lengths of the Achilles tendon and muscle belly should be compared in future studies. Second, we used real-time elastography for the evaluation of elasticity of the gastrocnemius muscle and Achilles tendon. This is the most common available in commercial units. In this mode, manual compression force is applied to the ultrasound probe to measure the relative stiffness of the tissue. And since the real-time elastography reveals only the relative stiffness of the tissues and need quantification to compare between subjects. We used the pixel distribution histogram in an acquired image to compare the elasticity which is a “semi-quantification” method [28,29]. Therefore, it is operator dependent compared to other modalities such as acoustic radiation force imaging that generate short-duration acoustic radiation forces instead of using external compression. We evaluate the architectural properties of the triceps suare under passive joint condition to assess the reliability of Silfverskiöld test. Further investigation of dynamic change of the tricep surae complex during gait or active motion would be necessary.

V. CONCLUSION

To the best of our knowledge, this is the first study to use ultrasonography in children with cerebral palsy to characterize the muscle architecture including elasticity of the triceps surae muscles by systematically varying knee and ankle joint configurations, and to assess the reliability of the Silfverskiöld test. The present study demonstrates that the muscle architectures of the gastrocnemii and SOL in the paretic legs of children with Silfverskiöld-negative SHCP respond abnormally to knee and ankle joint positions.

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Silfverskiöld 검사의 재평가: 초음파를 이용한 하퇴삼두근의 구조적 특성 평가

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주 선 영

뇌성마비 환아에서 첨족 보행의 교정을 위한 하퇴 삼두근의 연장은 고식적인 Siverskiold 검사에 의해 결정되었다. 그러나 Siverskiold 검사는 두 개의 근육이 분리된 가상의 모델에서는 적용이 가능하나, 하퇴 삼두근에서는 비복근의 경직이 심부 근막 혹은 아킬레스 건을 통해 가자미근의 운동에 영향을 줄 수 있으며, 각각의 근육 및 인대의 탄성에 대한 고려가 필요하다. 정상 환아와 첨족 보행을 보이는 경직성 편마비 환아를 대상으로 초음파 검사를 이용하여 슬관절과 족관절의 조건에 따른 근육의 미세구조의 차이를 정량적으로 분석하고자 한다.

환자군은 총 10 명의 편마비 환아였으며, 같은 연령대의 정상아 10 명을 대조군으로 하였다. 모든 환아는 Silverskiold 검사 상 음성으로 아킬레스 건에서의 연장이 필요하다고 판단되었다. 초음파를 이용하여 내외측 비복근(Gastrocnemius)과 가자미근(Soleus)의 근섬유 속 길이(fascicle length)와 근섬유속 각(fascicle angle)을 측정 하였다고, 측정된 결과를 이용하여 근 두께 및 심부 근막의 변화를 측정하였다. 측정값들에 대해 정상군과 편마비 환자군, 환자군의 건측 하지와 각각 비교 하였다. 음향 탄성 영상법을 이용하여 내외측 비복근과 아킬레스건의 탄성도를 측정하였고, 얻어진 이미지의 적, 녹, 청색의 평균 강도를 측정하는

반정량적 방법을 통하여 정상군과 편마비 환아의 아킬레스건과 비복근의 탄성도를 비교하였다.

정상아와 비교시 근섬유속의 길이는 편마비 환아의 내측 비복근은 유사하였고, 외측 비복근은 증가되어 있었던 반면, 가자미근의 근섬유속 길이는 단축되어 있었다. 내측 및 외측 비복근의 근섬유속각은 정상군에 비해 환자군에서 감소되어 있었던 반면 가자미근의 근섬유속각은 유사하였다. 근육 두께는 내외측 비복근 및 가자미근 모두 정상군에 비해 환자군에서 감소되어 있었다. 편마비 환아에서는 심부 근막의 이동이 같은 관절 조건하에서 정상아보다 감소되어 있으며, 전체 관절 운동범위내에서 심부 근막의 이동에는 차이가 없었다. 음향탄성 영상법을 이용한 탄성도 측정에서 환자군의 아킬레스건과 내외측 비복근에서 청색의 평균 강도가 증가되어 있어 탄성도가 정상아에 비해 감소되어 있음을 시사하였다.

Silverskiold 검사 상 음성인 경직성 편마비 환아에서는 하퇴삼두근의 탄성도가 감소되어 있었고, 근육의 미세구조가 변화되어 있었다. 또한, 슬관절과 족관절의 조건에 따른 이들 하퇴 삼두근 사이의 정상적인 움직임이 이루어지지 않았다. 이와 같은 결과는 Silverskiold 검사의 신뢰성을 뒷받침 해주는 것으로 Silverskiold 검사 음성인 환아에서는 아킬레스 건의 연장이 효과적일 것으로 생각된다.

핵심되는 말: 하퇴 삼두근, 뇌성마비, 초음파