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Morphological Classification of the Sagittal Tendon Plate in the Soleus Muscle in Japanese Cadavers

Clasificación Morfológica de la Lámina Tendinosa Sagital del Músculo Sóleo en Cadáveres Japoneses

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SUMMARY: The human soleus muscle has attracted attention in the fields of sport science, rehabilitation medicine, etc. for improving exercise performance in training, preventing injuries, and rehabilitation. The sagittal tendon plate of the soleus muscle is particularly important in rehabilitation. Few studies, however, have evaluated the shape of the sagittal tendon plate in the human soleus muscle in detail and attempted to classify its variations based on its morphology. In this study, we conducted a detailed analysis of the morphology of the sagittal tendon plates in soleus muscle specimens from Japanese cadavers and constructed a morphology-based classification system and evaluated their frequencies of occurrence. First, the specimens were divided into those with a sagittal tendon plate that was visible on the anterior surface (pennate muscle group) and those without (non-pennate muscle group). Next, based on the “number” and “breadth” of the sagittal tendon plates, the pennate muscle group specimens were further classified into four classes: Class I (one tendon, thin), Class II (one tendon, slightly broad), Class III (one tendon, very broad), and Class IV (two tendons, thin). Subsequently, the specimens were further divided into three types based on the position where the sagittal tendon plate joined the Achilles tendon: median tendon type, lateral tendon type, and medial tendon type (a total 13 divisions). When 458 Japanese soleus muscle specimens were classified into these divisions, the occurrence frequencies of Class I–IV were 80.57 %, 4.59 %, 5.46 %, and 1.09 %, respectively. In Class I, the median tendon type was more frequent than the lateral and medial tendon types, accounting for 48.47 % overall. The classification types of the sagittal tendon plate and their respective occurrence frequencies shown in this study are expected to serve as fundamental data in implementing rehabilitation of soleus muscle.

KEY WORDS: Soleus muscle; Sagittal tendon plate; Morphological classification; Rehabilitation; Cadaver.

INTRODUCTION

The human soleus muscle, one of the triceps surae, is situated in the anterior side (i.e., in the depth) of the gastrocnemius muscle. It originates from the posterior side of the head, the neck, and the upper third of the fibula, the soleal line, and the proximal medial margin of the tibia, and the tendinous arch of the soleus muscle between the fibula and the tibia. It constitutes the calcaneal tendon (Achilles' tendon) along with the tendinous insertion of the gastrocnemius muscle and inserts at the calcaneal tuberosity (Henle, 1858; Testut, 1893; Poirier & Richer, 1896). Humans have a more developed soleus muscle than other animals because the entire body weight is supported solely with the lower limb. As such, the soleus muscle is the largest and heaviest muscle in the human lower leg (Ito *et al*., 2003; Hanna & Schmitt, 2011). The proximal part of the soleus muscle has only developed in humans, which forms a bulge on the calf (Frey, 1913; Morimoto, 1969). Since the distal part of the soleus is broader than the gastrocnemius muscle, the bulging medial and lateral margins of the soleus muscle can be observed on the medial and lateral sides of the calcaneal tendon posteriorly (Frey, 1913). Both the origin and the insertion of the soleus muscle have a broad sheet-shaped aponeurosis structure. The origin aponeurosis is situated in the anterior side (bone side), and the aponeurosis

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of insertion is on the posterior side (gastrocnemius side). The short bundles of muscle fibers originating from the origin aponeurosis run parallelly to each other toward the lower posterior side and end at the aponeurosis of insertion. In this case, the muscle fibers insert at a point slightly diagonally lower than the origin. Based on the morphology formed by the muscle fibers, sagittal tendon plate (also referred to as median septum or central tendon), and aponeurosis, the soleus muscle is classified as a pennate muscle. Nevertheless, in humans, the inner structure in the central part of soleus muscle varies considerably, which is a complex pennate configuration combining unipennate, pennate, and multipennate muscle components (Finni *et al*., 2003; Bolsterlee *et al*., 2018). Moreover, in addition to the inner structure of the central part of the muscle belly, the anterior part of the soleus muscle also has considerable morphological variations. Specifically, the origin aponeurosis is divided into two parts at the center, and the sagittal tendon plate, which is a part of the dorsal aponeurosis (aponeurosis of insertion), runs toward the sagittal direction at the center of that fissure (Frey, 1913; Sekiya, 1991). The sagittal tendon plate then penetrates the muscle belly and appears on the anterior surface. Toward this sagittal tendon plate, muscle fibers from the origin aponeuroses on both sides run toward each other and then converge to form a pennate shape. This creates a pennate-shaped configuration with the sagittal tendon plate functioning as a tendon of insertion on the anterior surface of the soleus muscle.

The pennate-shaped soleus muscle is involved in the plantar flexion and elevation of the heels. Accordingly, the soleus muscle is considered an important muscle in maintaining stable posture while standing (Trzenschik & Loetzke, 1969; Okada, 1973) and in supporting the lower leg during the initial movement of actions that require large instantaneous forces (Trzenschik & Loetzke, 1969). A study using human cadavers reported that the soleus muscle has the largest physiological cross-section area, an index of muscle strength exertion, among all limb muscles (Ward *et al*., 2009). Accordingly, the soleus muscle has been attracting attention in the fields of sport science, rehabilitation medicine, etc. Some studies have shown that the strain injuries detected on magnetic resonance imaging (MRI), others have performed the three-dimensional structural and functional evaluation of the pennate muscle (Chow *et al*., 2000; Agur *et al*., 2003; Balius *et al*., 2013; Lieber *et al*., 2017).

The sagittal tendon plate is deeply associated with the pennate structure of the soleus muscle. Given its function as the terminal point of the muscle, it is structurally and functionally important. Recent studies have reported that athletes who suffered from the sagittal tendon plate injuries required more time before returning to competition than the other injured athletes (Pedret *et al*., 2015), and that patients with the sagittal tendon plate injuries had a poorer prognosis than these with injuries in other sites (Pedret *et al*., 2015). These studies indicate the clinical importance of the sagittal tendon plates.

The sagittal tendon plate can be observed and evaluated by MRI and ultrasonography (Balius *et al*., 2013; De-la-Cruz-Torres & Romero-Morales, 2021). However, only a few reports on the morphology of the sagittal tendon plate that could serve as a standard definition and classification for clinical evaluation have been published (Loetzke & Trzenschik, 1969; Olewnik *et al*., 2020). Therefore, data on the sagittal tendon plate needs to be properly accumulated for clinical applications in sport science and rehabilitation medicine. In this study, we conducted a detailed analysis of the morphology of the sagittal tendon plate in Japanese specimens of the soleus muscle and constructed a morphology-based classification system.

MATERIAL AND METHOD

Subjects. The specimens were collected from the deceased members of the "Toju-Kai", a body donation organization affiliated with the Tokyo Medical University, who had given their pre-mortem informed consent for medical education and research. The age of death ranged from 58 to 105 years, with a mean age of 84.00 ± 10.39 years (male: 80.10 ± 9.93; female: 86.99 ± 9.69). This study was approved by the Ethics Committee of Tokyo Medical University (Approval No.: T2020-0050).

Specimen measurements. The specimens were collected from embalmed bodies treated with 10–15 L of 3.8 % formalin fixative solution which was injected into the femoral artery. The shape of the sagittal tendon plate was studied in a total of 234 soleus muscle specimens (224 bilateral specimens; 10 unilateral specimens). Based on the findings, the sagittal tendon plate in each soleus muscle was classified as per our new classification system and the occurrence frequency of each type was analyzed. Of these specimens, the 46 unilateral muscles from the 23 specimens were digitally photographed along with a scale (PENTAX, DIGITAL CAMERA K-5II, Tokyo), and their morphology was evaluated and various parts were measured from the anterior surface of the specimens using an image-processing software ImageJ (public domain). The measured items were as follows: A) the maximum length of the soleus muscle: the distance between the apex of the soleus muscle origin and the distal free end of the calcaneal tendon; B) the maximum length of the soleus muscle belly: the distance between the tip of the upper end (proximal) and the muscular lower end (distal); C) the medial lobe length of origin aponeurosis: the distance between the uppermost end and the distal end of the origin aponeurosis on medial (tibial) side; D) the lateral lobe length of origin aponeurosis: the distance between the upper end and the lower end of the origin aponeurosis on lateral (fibular) side; E) the length of the sagittal tendon plate: the length of the sagittal tendon plate on anterior surface; F) the lowermost end height of the medial lobe of pennate muscle: the distance between the distal free endof the calcaneal tendon and the lowermost end of the medial lobe; and G) the lowermost end height of

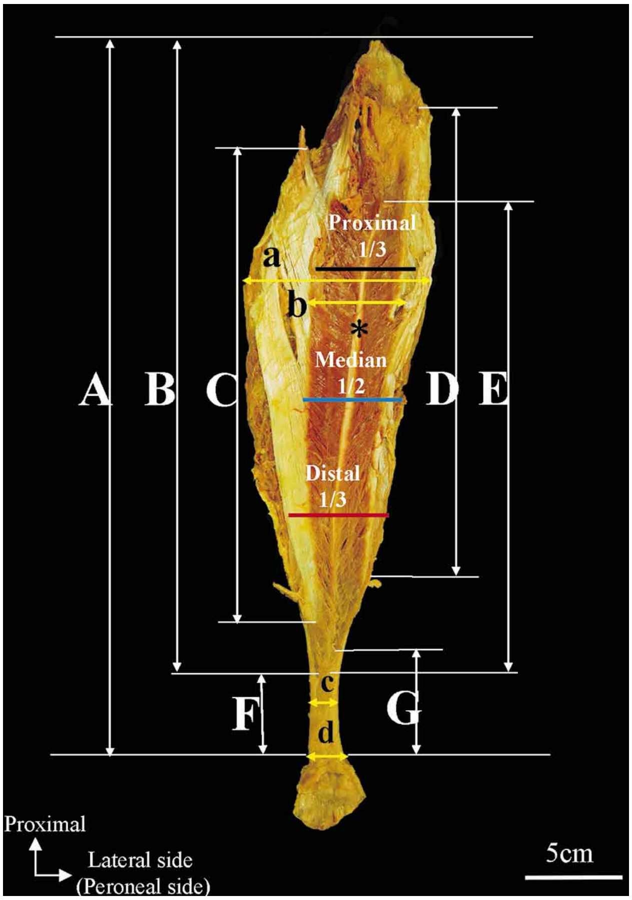


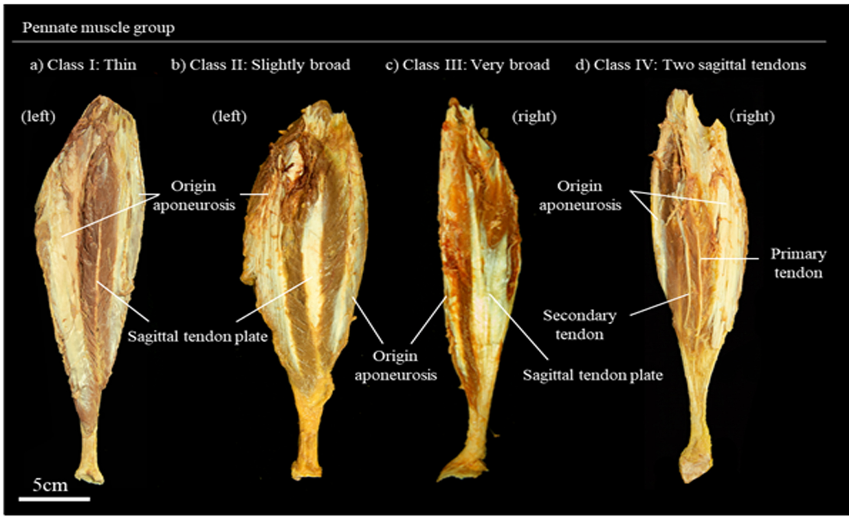
Fig. 1. Anterior view of a soleus muscle and sagittal tendon plate. The maximum length of the soleus muscle (mm) (A), the maximum length of the soleus muscle belly (mm) (B), the medial lobe length of origin aponeurosis (mm) (C), the lateral lobe length of origin aponeurosis (mm) (D), the length of the sagittal tendon plate (mm) (E), the lowermost end height of the medial lobe of pennate muscle (mm) (F), the lowermost end height of the lateral lobe of pennate muscle (mm) (G), the maximum breadth of the soleus muscle (mm) (a), the maximum breadth of the pennate muscle (mm) (b), the minimum breadth of calcaneao tendon (Achilles' tendon) (mm) (c), the free end breadth of calcaneal tendon (mm) (d) and the maximum breadth of the sagittal tendon plate (mm) (*) were measured.

the lateral lobe of pennate muscle: the distance between the distal free end of the calcaneal tendon and the lowermost end of the lateral lobe; a) the maximum breadth of the soleus muscle: the maximum breadth running at right angles to the long axis of the muscle, b) the maximum breadth of the pennate muscle: the maximum breadth of the pennate muscle part running at right angles to the long axis of the muscle; c) the minimum breadth of calcaneal tendon: the breadth running at right angles to the long axis of the tendon part between the lowermost end of the pennate muscle bundle and the free end of Achilles' tendon; d) the free end breadth of Achilles' tendon: the breadth of calcaneal tendon at the free end, and *) the maximum breadth of the sagittal tendon plate: the maximum breadth running at right angles to the long axis of the sagittal tendon plate (Fig. 1). Moreover, the pennation angles and the pennate fiber bundle lengths were measured in the medial and lateral sides at three different heights. These were evaluated at proximal 1/3 height, median 1/2 height, and distal 1/3 height relative to the maximum muscle length of soleus muscle (A). The measurement of each item was represented as a mean ± standard deviation.

Statistical analysis. IBM SPSS analytic software (version 25, International business Machines Corp. NY, USA) was used for the statistical analysis. A Shapiro–Wilk test was performed as a test of normality. A Mann–Whitney U test was performed to evaluate sexual and bilateral differences in the morphological measurement. Meanwhile, to investigate the occurrence frequency of each classification type, differences in the population rate in each item were evaluated using cross tabulation with chi-squared test. At the same time, a chi-squared test was performed to investigate the independence between populations regarding the occurrence frequency of each sagittal tendon plate classification type. The statistical significance level was set at < 5 %.

RESULTS

Construction of the morphological classification model for the sagittal tendon plate on anterior surface of the soleus muscle. Based on the previous reports (Loetzke & Trzenschik, 1969; Trzenschik & Loetzke, 1969; Agur *et al*., 2003; Olewnik *et al*., 2020), the soleus muscle specimens were roughly divided into those in which some pennate structure was visible on the anterior surface (pennate muscle group) and those without (non-pennate muscle group). Then, specimens in the pennate muscle group were divided into four classes based on the shape of the sagittal tendon plate, which were different in the breadth (thin, slightly broad, and very broad) and number (one or two) (Fig. 2). Based on



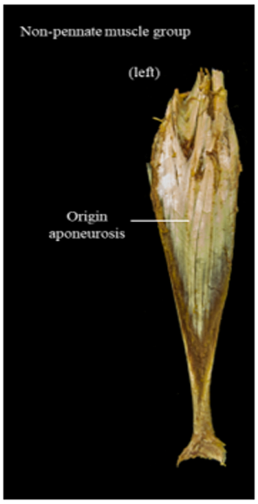


Fig. 2. Differences in the breadth and number of sagittal tendon plates. The image shows the Class I (a), Class II (b), Class III (c), and Class IV (d) sagittal tendon plates in the pennate muscle group and non-pennate muscle-shaped soleus muscle in non-pennate muscle group.

these differences in both "breadth" and "number", the specimens were classified into four classes: Class I (one tendon, thin), Class II (one tendon, slightly broad), Class III (one tendon, very broad), and Class IV (two tendons, thin). In particular, for Class I–III, the percentage of the "the maximum breadth of the sagittal tendon plate" relative to the "the maximum breadth of the soleus muscle" was calculated (the maximum breadth of the sagittal tendon plate to the maximum breadth of the soleus muscle), and a scatter diagram was plotted. As a result, it was plausible to divide the sagittal tendon plate specimens into three classes, with breath ratios of 10 % and 20 % being the cutoff zones (coefficient correlation: $p > 0.05$) (Fig. 3). Accordingly, they were classified into Class I (< 10 %), Class II (≥ 10 %, < 20 %), and Class III (≥ 20 %). Furthermore, each Class were classified into three types based on the position where the sagittal tendon plate joined the calcaneal tendon: the median tendon type, the lateral tendon type, and the medial tendon type (Fig. 4). Particularly, the Class IV specimens were divided into the median, lateral, and medial tendon types based on the side on which the tendon bundles of both primary and secondary tendons joined the Achilles' tendon. Based on these classification criteria, the soleus muscle classification model consisting of a total of 13 divisions was constructed (Fig. 5).

Evaluation of the occurrence frequency for each division of the sagittal tendon plates in Japanese soleus muscles. In the 458 unilateral soleus muscles from the 234 specimens, the sagittal tendon plates were classified as per the classification model shown in Fig. 5. A pennate structure on the anterior surface was observed in 91.7 % of the soleus muscles (male: 92.00 %; female: 91.47 %). No bilateral or sexual differences in the occurrence frequency were noted.

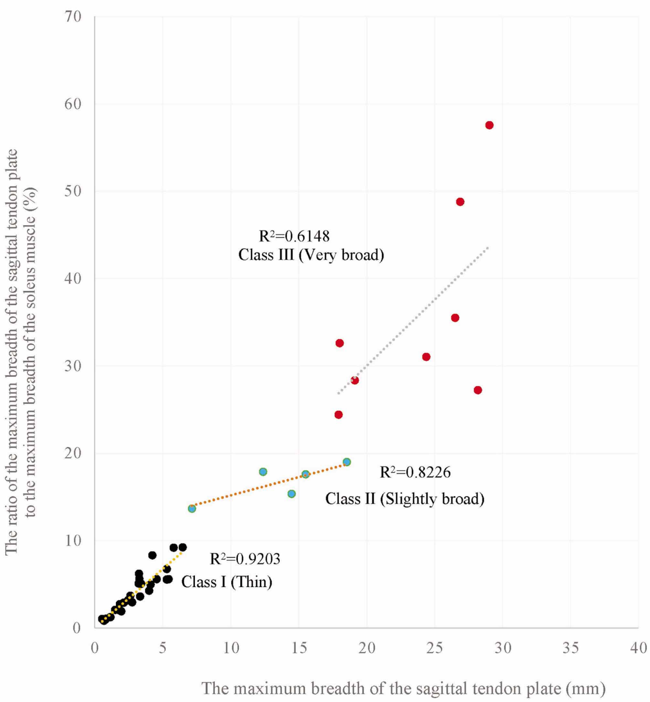


Fig. 3. Relationships between the ratio of the maximum breadth of the sagittal tendon plate to the maximum breadth of the soleus muscle and the sagittal tendon plate types. The scatter diagram shows that the sagittal tendon plates are divided into three classes based on their breadth ratio. Class I was < 10 %, Class II was ≥ 10 % and < 20 %, and Class III was ≥ 20 %. No significant differences were noted in the correlation coefficient. N = 46 unilateral muscles.

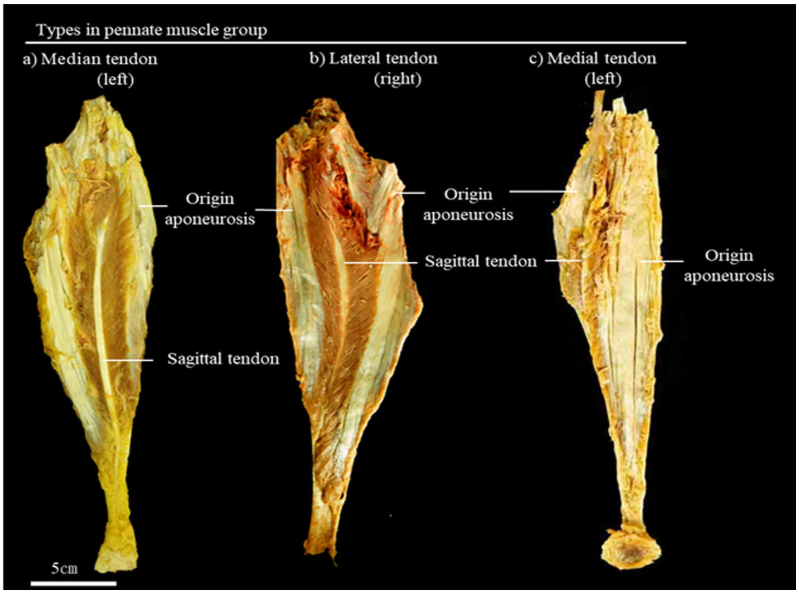
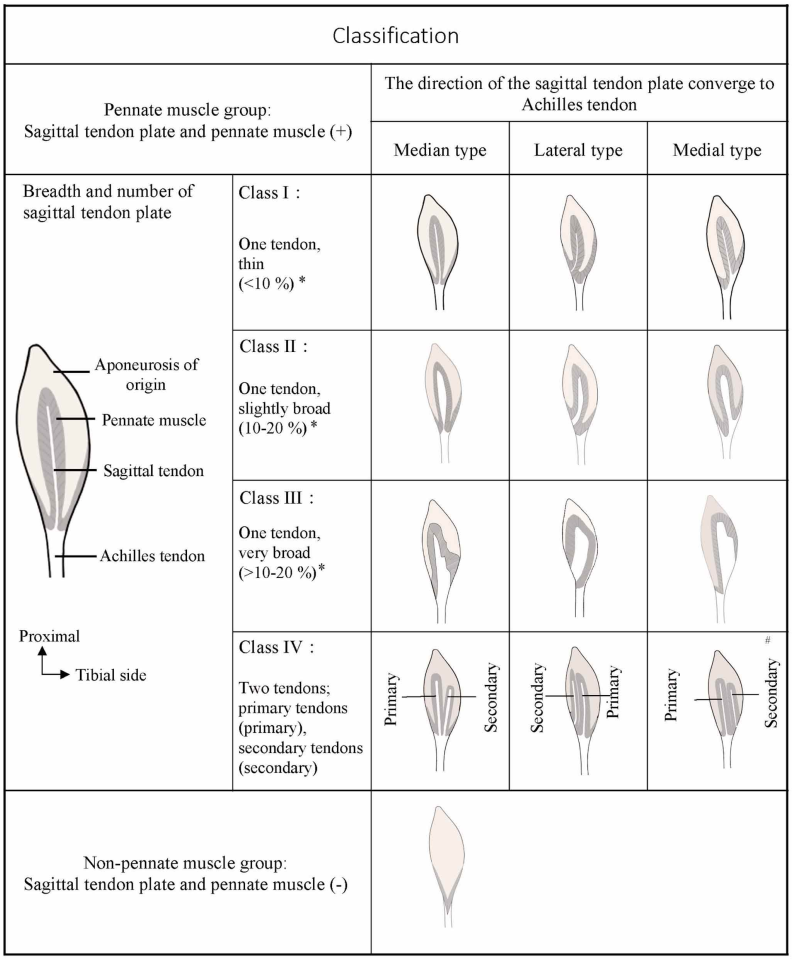


Fig. 4. Joining site between the sagittal tendon plate and the calcaneal tendon (Achilles tendon). The image shows the median tendon type (a), lateral tendon type (b), medial tendon type (c).



Subsequently, the occurrence frequencies of Class I–IV sagittal tendon plate were evaluated (Table I). Class I accounted for 80.57 % of all specimens (male: 79.0 %; female: 81.78 %), which was significantly higher than Class II, III, and IV ($p < 0.001$). Moreover, the occurrence frequency of the median tendon type in Class I was significantly higher than those of the lateral and medial tendon types ($p < 0.001$). Between the lateral and medial tendon types, the occurrence frequency of the lateral tendon type was significantly higher than that of the medial tendon type ($p < 0.001$). The occurrence frequency of Class II was 4.59 % (male: 6.50 %; female: 3.10 %). Overall, the median tendon type accounted for 3.49 %, which was significantly higher than the occurrence frequencies of the lateral and medial tendon types ($p = 0.003$ and $p < 0.001$). Class III accounted for 5.46 % overall. In Class III, the medial tendon type occurred most frequently, but no significant differences were noted in the three different tendon types. The occurrence frequency of Class IV was the lowest, with only five cases noted among all the evaluated specimens (1.09 %). Like Class III, no significant differences were noted among the three tendon types.

Fig. 5. Classification of soleus sagittal tendon plates based on their morphological characteristics. The sagittal tendon plate of human soleus muscle were roughly divided based on the presence/absence of a sagittal tendon plate into the pennate muscle group and non-pennate muscle group, and we proposed a total of 13 classification divisions based on two aspects of the pennate muscle: (1) the breadth and number of sagittal tendon plates and (2) the joining point of the distal part of sagittal tendon plates to the Achilles tendon. *Ratio of the maximum breadth of the sagittal tendon plate to the maximum breadth of the soleus muscle (%). #It was evaluated based on the report by Kimura *et al.* (2021) (illustrated), but none was observed in this study. N = 458 unilateral muscles.

Detailed analysis of the soleus muscle and the sagittal tendon plate. For the 46 unilateral muscles from the 23 cadavers in above specimens, further detailed morphological measurements were conducted (Table II). In all the items, no significant bilateral differences were noted in either males or females. When the same sides were compared between males and females, the maximum length of the soleus muscle (right: $p = 0.003$; left: $p = 0.003$) and the maximum length of the soleus muscle belly (right: $p = 0.005$; left: $p = 0.045$) were significantly longer in male than in female. In the medial lobe length of origin aponeurosis (right: $p = 0.003$), lateral lobe length of origin aponeurosis (left: $p = 0.028$), the maximum breadth of the soleus muscle (right: $p = 0.016$), and the minimum breadth of calcaneal tendon (left: $p = 0.006$), significant differences were noted on only one side, with the measurements in males being significantly larger than measurements in females for all items. Neither males nor females exhibited any significant differences in the pennation angles on the medial and lateral sides between right and left at each level, proximal 1/3, median 1/2, and distal 1/3, nor were there any significant sexual differences. The fiber bundle length of pennate muscle on the medial and lateral sides did not differ significantly between the right and left in either males or females. Meanwhile, significant sexual differences in the fiber bundle length of pennate muscle on the medial side were noted at the proximal 1/3 on the left side ($p = 0.005$) and the median 1/2 on both sides (right: $p = 0.039$; left: $p = 0.011$), with males exhibiting larger measurements for all items. In the fiber bundle length of pennate muscle on the lateral side, significant differences were noted at the median 1/2 on the left side ($p = 0.033$) and the distal 1/3 of the left side ($p = 0.003$), and the measurements were larger in males.

When the pennation angle was evaluated focusing on the morphological type of the sagittal tendon plate, the medial tendon type had a significantly lower value than the median and lateral tendon type at proximal 1/3 of the pennation angle on the medial side ($p = 0.0057$ and 0.0053, respectively) (Table III). Also, the median tendon type had a significantly higher value than the medial tendon type and lateral tendon type at median 1/2 of the pennation angle on the medial side ($p = 0.0097$ and 0.0144, respectively).

Table I. Occurrence frequency of each division for the sagittal tendon plate in the soleus muscle.

Classification class & type for the sagittal tendon plate in pennate muscle group	Males						Females						Total (n=458)		
	Right (n=100)		Left (n=100)		Both (n=200)		Right (n=129)		Left (n=129)		Both (n=258)				
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	
Class I	81	81.0	77	77.0	158	79.00	109	84.5	102	79.1	211	81.78	369	80.57	***
Median tendon type	49	49.0	46	46.0	95	47.50	64	49.6	63	48.8	127	49.22	222	48.47	###
Lateral tendon type	18	18.0	19	19.0	37	18.50	33	25.6	27	20.9	60	23.26	97	21.18	###, &&&
Medial tendon type	14	14.0	12	12.0	26	13.00	12	9.3	12	9.3	24	9.3	50	10.92	###, &&&
Class II	6	6.0	7	7.0	13	6.50	4	3.1	4	3.1	8	3.10	21	4.59	***
Median tendon type	5	5.0	6	6.0	11	5.50	2	1.6	3	2.3	5	1.94	16	3.49	$$, $$$
Lateral tendon type	1	1.0	1	1.0	2	1.00	1	0.8	1	0.8	2	0.78	4	0.87	$$
Medial tendon type	0	0.0	0	0.0	0	0.00	1	0.8	0	0.0	1	0.39	1	0.22	$$$
Class III	6	6.0	7	7.0	13	6.50	7	5.4	5	3.9	12	4.65	25	5.46	***
Median tendon type	1	1.0	2	2.0	3	1.50	3	2.3	1	0.8	4	1.55	7	1.53	
Lateral tendon type	2	2.0	2	2.0	4	2.00	1	0.8	1	0.8	2	0.78	6	1.31	
Medial tendon type	3	3.0	3	3.0	6	3.00	3	2.3	3	2.3	6	2.33	12	2.62	
Class IV	0	0.0	0	0.0	0	0.00	1	0.8	4	3.1	5	1.94	5	1.09	***
Median tendon type	0	0.0	0	0.0	0	0.00	0	0.0	4	3.1	4	1.55	4	0.87	
Lateral tendon type	0	0.0	0	0.0	0	0.00	1	0.8	0	0.0	1	0.39	1	0.22	
Medial tendon type	0	0.0	0	0.0	0	0.00	0	0.0	0	0.0	0	0.00	0	0.00	
Non-pennate muscle group	7	7.0	9	9.0	16	8.00	8	6.2	14	10.9	22	8.53	38	8.30	

***: Class I was significantly higher than the other types. ###: Among Class I, the median tendon type was significantly higher than the medial tendon type and the lateral tendon type. &&&: The lateral tendon type was significantly higher than the medial tendon type. $$: Among Class II, the median tendon type was significantly higher than that of lateral tendon type. $$$: Among Class II, the median tendon type was significantly higher than that of medial tendon type. $$p < 0.01, ***, ###, &&&, $$$p < 0.001.

Table II. Morphological measurements of the soleus muscle.

Measurement items# (For details refer to Fig. 1)	Males						Females					
	Right			Left			Right			Left		
	n	Mean	±SD	n	Mean	±SD	n	Mean	±SD	n	Mean	±SD
A Maximum length of the soleus muscle	7	337.08**	22.26	7	339.61**	23.46	16	300.67**	18.60	16	297.54**	21.23
B Maximum length of the soleus muscle belly	7	289.37**	18.76	7	278.47*	27.94	16	254.63**	21.34	16	249.44*	28.86
C Medial lobe length of origin aponeurosis	7	218.91**	20.84	7	218.49	34.35	16	169.35**	55.83	16	174.72	58.33
D Lateral lobe length of origin aponeurosis	7	230.16	31.81	7	238.43*	31.37	15	202.55	27.70	16	205.76*	25.67
E Length of the sagittal tendon plate	6	150.09	36.90	5	145.63	47.97	16	148.23	18.90	14	144.10	30.42
F Lowermost end height of the medial lobe of pennate muscle	7	50.29	6.51	7	58.57	26.28	16	53.98	19.58	16	59.45	34.54
G Lowermost end height of the lateral lobe of pennate muscle	7	66.12	15.45	7	62.03	16.57	16	61.50	26.64	16	66.96	36.69
a Maximum breadth of the soleus muscle	7	87.41*	9.05	7	85.28	9.74	15	70.49*	15.56	16	74.08	16.71
b Maximum breadth of the pennate muscle	6	38.66	8.01	5	41.24	10.17	16	36.94	8.46	14	35.21	7.48
c Minimum breadth of Achilles tendon	7	12.92	2.69	7	14.75**	1.20	16	11.58	2.05	16	12.00**	2.78
d Free end breadth of Achilles tendon	7	20.90	3.32	7	21.25	2.72	15	20.18	3.21	16	22.45	6.68
* Maximum breadth of the sagittal tendon plate	6	4.97	6.84	5	8.36	10.19	15	9.89	8.64	14	8.61	9.97
Pennation angle on the medial side (°)												
- proximal 1/3	6	29.44	9.63	4	27.65	13.80	16	28.91	13.24	12	29.53	10.02
- median 1/2	6	41.40	10.06	5	41.35	8.01	15	37.89	14.00	12	38.98	11.05
- distal 1/3	6	30.98	8.92	4	31.86	9.23	14	34.60	8.60	12	36.03	11.09
Pennation angle on the lateral side (°)												
- proximal 1/3	6	32.20	11.51	4	22.85	10.31	16	27.35	13.25	13	28.87	5.62
- median 1/2	6	33.97	10.07	5	31.64	10.96	15	32.15	11.35	14	37.82	10.07
- distal 1/3	6	29.29	9.11	5	34.22	4.56	14	34.34	10.66	14	32.15	7.94
Fiber bundle length of pennate muscle on the medial side (mm)												
- proximal 1/3	6	24.39	5.51	4	34.91**	4.31	16	21.21	7.72	12	20.16**	6.44
- median 1/2	6	24.30*	2.58	5	26.45*	3.18	15	19.89*	5.57	12	17.92*	6.30
- distal 1/3	6	22.04	8.29	4	20.72	4.56	14	15.36	4.87	12	16.88	4.88
Fiber bundle length of pennate muscle on the lateral side (mm)												
- proximal 1/3	6	28.64	7.06	4	31.47	5.60	16	25.21	9.05	13	25.29	8.23
- median 1/2	6	25.02	5.14	5	30.92*	8.11	15	23.74	8.06	14	20.99*	7.41
- distal 1/3	6	24.01	10.77	5	30.42**	8.68	14	18.52	9.53	14	16.55**	6.94

#: all length and breadth are expressed in millimeters. *p < 0.05, **p < 0.01: items with significant differences between males and females on the same side.

DISCUSSION

In this study, we proposed a total of 13 classification divisions for the human soleus muscle sagittal tendon plate based on the following two factors: (1) the joining site with the distal part to the calcaneal tendon and (2) the breath and number. In another study, Uweda (1926) discussed mutations in the aponeurosis of insertion, aponeurosis of origin, and sagittal tendon plate in the soleus muscle. Later, Loetzke *et al*. classified 165 unilateral soleus muscles from European cadavers into 10 types based on the combination of the breadth of the sagittal tendon plate and the placement of the pennate muscle (Loetzke & Trzenschik, 1969). Loetzke & Trzenschik (1969) reported only one case of Class III (0.6 %) as with our classification, but they did not report any non-pennate muscle type and reported only the median type of Class IV. Olewnik *et al*. (2020) focused on the number of pennate muscle bundles appearing on 80 unilateral soleus muscles from European cadavers and proposed a four-type classification system. However, they did not show how the sagittal tendon plate joint to the calcaneal tendon. Our study included 458 unilateral soleus muscles, which constituted the largest sample size so far. Therefore, as far as we know, we constructed a more comprehensive

Table III. Angles of pennation and fiber buldle lengths of pennate muscle in each type of sagittal tendon plate.

Measurement item Corresponds to signs in Fig. 1	Median tendon type n	 Mean	 ±SD	Lateral tendon type n	 Mean	 ±SD	Medial tendon type n	 Mean	 ±SD
Pennation angle on the medial side (°)									
- proximal 1/3	21	31.25**	11.34	12	30.08##	9.56	3	10.60**,##	5.40
- median 1/2	20	44.56*,&&	11.44	13	34.81*	9.04	4	27.73&&	4.82
- distal 1/3	20	34.78	10.31	13	34.40	6.79	2	29.07	20.81
Pennation angle on the lateral side (°)									
- proximal 1/3	22	30.75	11.18	12	25.93	8.80	3	22.46	6.88
_ median 1/2	23	34.79	8.11	13	35.18	13.80	3	34.06	10.76
- distal 1/3	23	34.37	9.34	13	30.71	7.75	4	34.83	6.96
Fiber bundle length of pennate muscle on the medial side (mm)									
- proximal 1/3	21	23.60	6.88	12	21.31	7.29	3	28.76	14.36
- median 1/2	20	20.50	5.90	13	21.16	5.97	4	21.71	8.03
- distal 1/3	20	18.08	6.62	14	18.46	4.58	2	16.25	0.13
Fiber bundle length of pennate muscle on the lateral side (mm)									
- proximal 1/3	22	25.37	7.56	12	27.90	9.31	3	29.09	11.03
- median 1/2	23	24.11	8.01	13	22.76	4.74	3	20.82	9.63
- distal 1/3	22	20.82	9.63	13	18.06	8.33	4	19.96	15.95

**: Pennation angle on the medial side was significantly lower in medial tendon type than median tendon type at proximal 1/3 level. ##: Pennation angle on the medial side was significantly lower in medial tendon type than lateral tendon type at proximal 1/3 level. *: Pennation angle on the medial side was significantly higher in median tendon type than lateral tendon type at median 1/2 level. &&: Pennation angle on the medial side was significantly higher in median tendon type than medial tendon type at median 1/2 level. *$p < 0.05$, **, ##, &&$p < 0.01$.

classification model for the sagittal tendon plate of human soleus muscle. One of key points in this study it is that we quantified the breadth of the sagittal tendon plate of soleus muscle. The quantification of sagittal tendon plate dimensions will help improve the reliability of accumulated data in the clinical setting. It has been suggested that the forces applied on the calcaneus bone by the soleus muscle via the calcaneal tendon differ depending on the breadth and the insertion angle (pennation angle) of the sagittal tendon plate (Trzenschik & Loetzke, 1969; Loetzke & Trzenschik, 1969; Agur *et al*., 2003; Olewnik *et al*., 2020). Therefore, the quantified classification of sagittal tendon plates is expected to serve as a basis for evaluating differences in the maximum output and the speed of recovery from injury.

The distal part of the sagittal tendon plate has a dynamically important concerning the transmission direction of the tensile force from the soleus muscle. In this study, we observed that the occurrence frequency of a median tendon type in Class I was the highest. Meanwhile, the presence of lateral and medial tendon types was also confirmed. The sagittal tendon plate is a part of the tendon of insertion and transmits the tensile force generated by the soleus muscle to the calcaneal bone. If that transmission pathway shifts toward either the inner or outer side, it is possible that the direction of motion may be deviated. This will constitute a critical challenge in rehabilitating patients with a chief complaint of ankle joint disorder. Since the sagittal tendon plate can be evaluated with MRI and ultrasonography (Balius *et al*., 2013; De-la-Cruz-Torres & Romero-Morales, 2021), it will be possible to evaluate the distal joining site of the sagittal tendon plate to Achilles' tendon using the classification model developed in this study, which will be helpful in determining the therapeutic strategy. In order to perform plantar flexion in the ankle joint without deviating inversion or eversion, it is possible to selectively strengthen the peroneal muscle group with plantar flexion/eversion effects and conduct motor learning, to further act on the ankle joint to promote a more plantar flexion/inversion direction for the medial tendon type. Conversely, for the lateral tendon type, it is possible to selectively strengthen the flexor digitorum longus muscle and the flexor hallucis longus muscle with plantar flexion/eversion effects and conduct motor learning, to act on the ankle joint to promote a more plantar flexion/eversion direction. It is worth noting that our research clarified the relationship between pennation angle and the morphological type of the sagittal tendon plate, the median, medial, and lateral tendon types (Table III). We hope that our classification model will contribute to basic studies and clinical applications in the future.

We compared the occurrence frequencies of Class I–IV of the sagittal tendon plate of Japanese soleus muscle as shown in Fig. 5 and Table I with the data from these previous studies [(populations from Olewnik *et al*. (2020) (the country or rural areas in Central Europe) and Loetzke & Trzenschik (1969) (the urban or metropolitan areas in Central Europe)] (Fig. 6). By comparison, it is noted that the results reported by Loetzke & Trzenschik (1969) had a higher occurrence frequency of Class I. However, the results reported by Olewnik *et al*. (2020). show that the frequencies of Classes III, IV, and the non-pennate group (Types 2, 3, and 4 in their report) were higher than those in our study and the population reported by Loetzke & Trzenschik (1969). In our study, Class I–IV of the sagittal tendon plate of human soleus muscle are a classification system based on the breadth and number of sagittal tendon plates. In humans, the shape of the sagittal tendon plate is almost completely matured in the fetal stage (Jager & Moll, 1951). This suggests that embryologic factors may be involved in variations in the breadth and number of sagittal tendon plates as seen in Class I–IV. Therefore, the differences in the breadth and number of sagittal tendon plates in different regions (the population in this study, that of the study by Olewnik *et al*. (2020), and that of the study by Loetzke & Trzenschik (1969) may reflect the differences in embryologic factors in the different populations. However, we have not compared populations in different regions (between the population in this study and the populations in the preceding studies) in terms of the occurrence frequencies of the median tendon type, lateral tendon type, and medial tendon type in Classes I–IV of the sagittal tendon plate. Unlike the breadth and number of sagittal tendon plates, the occurrence frequencies of the median, lateral, and medial tendon types may be affected by dynamic factors after birth (Faller, 1942; Loetzke & Trzenschik, 1969; Trzenschik & Loetzke, 1969). It may be possible that different lifestyle habits between Japanese people and the Western population result in considerable differences in the occurrence frequencies of the respective classification types. Regarding the morphological analysis of the sagittal tendon plate of human soleus muscle, further comprehensive evaluation factoring in ethnicities and regions will be necessary.

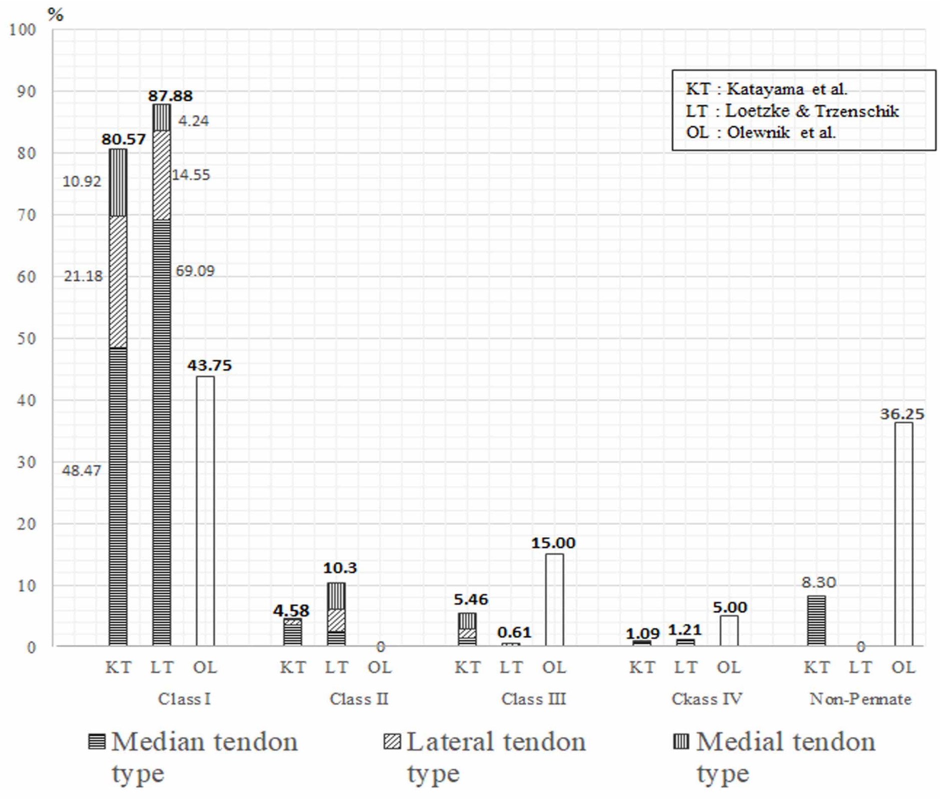


Fig. 6. Differences in the occurrence frequencies of Class I–IV of the sagittal tendon plate between Japanese and populations in other regions. The graph shows the occurrence frequency of Class I, II, III, IV (the pennate muscle group) and the non-pennate muscle group in results by Loetzke & Trzenschik (1969), Olewnik *et al*. (2020) and us. Also data indicate the tendon type (median, lateral, and medial tendon type) in each Class and the non-pennate muscle group except for the results by Olewnik *et al*. (2020) (do not report about each tendon type of the sagittal tendon plate. Data are shown by the while bars). KT: the population data in this study, LT: the population data by Loetzke & Trzenschik (1969). OL: the population data by Olewnik *et al*. (2020). Non-type show represents the non-pennate muscle group.

Our classification model requires further detailed evaluation in the future on several aspects. The important thing is the advanced age of our specimen donors. The mean age of the specimen donors (members of a body donation organization) was 84.00 ± 10.39 years. In this study we did not evaluate the specimen from younger donors and the presence/absence of age-related morphological changes in the sagittal tendon plate of human soleus muscle. Meanwhile, Kimura *et al*. (2021) argued that unlike muscle structures, the basic structure of the connective tissue-derived aponeurosis is developed before birth, which is unlikely to regress or disappear due to its low variability. The sagittal tendon plate of human soleus muscle has been captured by MRI and ultrasonography (Balius *et al*., 2013; De-la-Cruz-Torres & Romero-Morales, 2021). It is expected that the accumulation of data from cross-sectional evaluation of soleus muscle and its sagittal tendon plate from varying ages will bring about important findings for rehabilitation medicine. Further research on the soleus sagittal tendon plate is desired from the perspective of both medical research and clinical medicine.

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KATAYAMA, S.; TAKEUCHI, K.; MIYASO, H.; NATSUYAMA, Y.; KAWATA, S.; YAKURA, T.; LI, Z. L. & ITOH, M. Clasificación morfológica de la lámina tendinosa sagital del músculo sóleo en cadáveres japoneses. *Int. J. Morphol., 41(3)*:1135-1145, 2023.

RESUMEN: El músculo sóleo humano ha atraído la atención de la ciencia del deporte, la medicina de rehabilitación, etc. para mejorar el rendimiento del ejercicio en el entrenamiento, prevenir las lesiones y rehabilitación. La lámina tendinosa sagital del músculo sóleo es particularmente importante en la rehabilitación. Sin embargo, pocos estudios han evaluado en detalle la forma de la placa lámina sagital en el músculo sóleo humano y han intentado clasificar sus variaciones en función de su morfología. Realizamos un análisis detallado de la morfología de las láminas de los tendones sagitales en muestras de músculo sóleo de cadáveres japoneses y construimos un sistema de clasificación basado en la morfología y, además, evaluamos su frecuencia de aparición. Los especímenes se dividieron en aquellos con una lámina de tendón sagital que era visible en la superficie anterior (grupo muscular pennado) y aquellos sin (grupo muscular no pennado). A continuación, según el "número" y el "ancho" de las láminas de los tendones sagitales, las muestras del grupo de músculos pennados se clasificaron en cuatro clases: Clase I (un tendón, delgado), Clase II (un tendón, ligeramente ancho), Clase III (un tendón, muy ancho) y Clase IV (dos tendones delgados). Posteriormente, las muestras se dividieron en tres tipos, según la posición donde la lámina del tendón sagital se unía al tendón calcáneo: tipo de tendón mediano, tipo de tendón lateral y tipo de tendón medial (un total de 13 divisiones). En estas divisiones se clasificaron 458 especímenes de músculo sóleo de indiviuos japoneses, las frecuencias de ocurrencia de Clase I-IV fueron 80,57 %, 4,59 %, 5,46 % y 1,09 %, respectivamente. En la Clase I, el tipo de tendón mediano era más frecuente que los tipos de tendón lateral y medial, representando el 48,47 % del total. Se espera que los tipos de clasificación de la lámina del tendón sagital y sus respectivas frecuencias de aparición, que se reportan en este estudio, sirvan como datos fundamentales para implementar la rehabilitación del músculo sóleo.

PALABRAS CLAVE: Músculo sóleo; Placa de tendón sagital; Clasificación morfológica; Rehabilitación; Cadáver.

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