



Original Article

Morphological changes in the long axis of the lower leg muscles during isometric contraction in the sitting position

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Abstract. [Purpose] To compare the changes in the muscle cross-sectional area (MCSA) along the long axis of the lower leg muscles at rest and during ankle plantar flexors isometric contraction and to obtain basic information regarding the movement of lower leg muscles during ankle plantar flexors contraction. [Participants and Methods] Sixteen healthy young female participants (20.9 ± 1.2 years) were asked to sit with their ankles in a neutral ankle position. Images were obtained at rest and during isometric contraction of the ankle plantar flexors using gravity magnetic resonance imaging. The MCSAs of the triceps surae and tibialis anterior were measured. [Results] The middle region of the soleus muscle had a lower MCSA on contraction than at rest. In addition, the medial head of the gastrocnemius had a lower MCSA on contraction than at rest in the distal quarter. Moreover, the tibialis anterior had a lower MCSA at rest than on contraction in the middle region. [Conclusion] The area to be used as an indicator and the movement to be induced differ depending on the muscle during isometric contraction of the triceps surae.

Key words: Muscular dynamics, MRI, Lower leg muscle

(This article was submitted Jul. 30, 2020, and was accepted Sep. 9, 2020)

INTRODUCTION

Injuries such as fractures of the ankle joint and lower leg (crus) tend to cause limited range of motion in ankle dorsiflexion and decreased strength of the ankle plantar flexor muscle. As a result, many issues may arise when carrying out daily activities, such as walking and climbing stairs. Hayashi et al.¹⁾ stated that if there is sliding amidst muscles or between muscles and other tissues during contraction, it can lead to pain and limited range of motion, as well as muscle weakness due to the lack of tension transfer to the periphery during contraction. Therefore, information on normal muscle dynamics during contraction is important for comparison with abnormal findings to aid physical therapy interventions for muscle strengthening. In general, when contraction occurs, there is an overall increase in muscle cross-sectional area (MCSA) and muscle thickness. The relationship between muscle activity and muscle thickness has been investigated by obtaining ultrasound images of various muscles, such as the lumbar multifidus, tibialis anterior, and biceps muscles²⁾. In particular, there are many studies on the lower trunk muscle^{3, 4)}, and it has been reported that the increase in muscle activity demonstrated by electromyography is related to muscle thickness in low level contraction of the lumbar multifidus⁵⁾. However, changes in muscle thickness and MCSA involve several factors, including extensibility of muscle and fascia, muscle contraction pattern, neural factors, and muscle extracellular tissue. Therefore, changes in muscle thickness as seen on ultrasound images are not typically considered an indicator of muscle activity⁶⁾. Additionally, the muscle measurement portion is another factor that makes it difficult to evaluate muscle thickness as an indicator of muscle activity. Kinugasa et al.⁷⁾ reported that the MCSA decreases when the

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muscle is stretched in the longitudinal direction, because the muscle volume is constant. Similarly, it is presumed that when the muscle contracts, the portion where the MCSA increases due to contraction and the portion where the MCSA decreases due to stretching are occurred in the longitudinal direction of the muscle. Therefore, to capture muscle dynamics, wide-area image information that includes the entire muscle is required. Magnetic resonance imaging (MRI) can obtain wide-area morphological information. However, it is generally difficult to evaluate in the antigravity position due to the structure of this device. It has been reported that in the decubitus position, the measurement is different from that obtained in the antigravity position, because it is affected by deflection and displacement due to gravity⁸). In recent years, with the development of vertical open MRI, it has become possible to obtain wide-area image information in the antigravity position, and it is used in many fields^{9, 10}). In our previous study, the muscle dynamics of the lower leg muscles were investigated in the stretching and shortening positions, in the antigravity position¹¹); however, the muscle dynamics during contraction of the ankle plantar flexor, which is often a problem, have not yet been clarified. Therefore, the purpose of this study was to obtain basic information on muscle dynamics due to contraction of the ankle plantar flexor muscles by comparing the MCSA of the lower leg muscles at rest and at contraction, in the antigravity position.

PARTICIPANTS AND METHODS

The participants were 16 healthy young females without reported pain during daily activities; more specifically, the study focused on the dominant legs of the participants that they would use to kick a ball. Mean (\pm standard deviation) age, height, and weight were 20.9 ± 1.2 years, 160.3 ± 5.7 cm, and 53.4 ± 5.3 kg, respectively. None of the participants had a history of orthopedic problems of the legs or vertebrae. The protocol for this study was approved by the Ethics Committee of Kanazawa university (approval number: 687). Before the study, we explained the objective and content of the study to the participants and informed them that the data obtained from this study would be used solely for the purpose of this study, assuring them that the data would be handled strictly in confidence to prevent dissemination of personal information. In addition, we obtained written informed consent from all the participants.

In the antigravity position, the sitting position is more stable and easier to hold than the standing position, during imaging. Therefore, the sitting position was selected as the measurement position. Each participant was positioned on a chair, knee flexion at 90° , lower legs perpendicular to the floor, and ankle dorsiflexion at 0° . The chair had a backrest, and the seat height was adjusted by placing a plate on the chair to make the knee flexion 90° . The thighs were fixed with cushions and bands, and the participants were instructed to remain as motionless possible during the measurement. In addition, the thighs were pressed at the upper extremities to prevent flexion of the hip joint.

Measurement was performed under 2 conditions: resting (RES) and ankle plantar flexor isometric contraction (CON). The isometric contraction of the ankle plantar flexor muscle was performed by holding the neutral position of the ankle against the load in the ankle dorsiflexion direction with a rubber band (Fig. 1). The length of the rubber band was adjusted to 50% of the maximum ankle plantar flexor strength. In order to set the load, the maximum ankle plantar flexor strength was measured using a hand-held dynamometer (μ Tas F-200, Anima Co., Ltd., Tokyo, Japan) in the same sitting position used for the MRI measurement.

The muscle strength was measured by placing the heel on the floor in the neutral position of the ankle joint and fixing the lower end of the sensor pad of the handheld dynamometer to the first metatarsal head. The maximum isometric contraction was performed for 3 seconds after the start signal, and the average value of 3 measurements was used as the maximum plantar flexion strength value.

Using Gravity MRI (Hitachi Healthcare, Ltd., Tokyo, Japan), which is a vertical open MRI, horizontal T1-weighted images were obtained from the fibular head to 290 mm distal at 10 mm intervals. The imaging parameters were as follows: slice plane axial, pulse sequence RF-spoiled steady state gradient echo, field of view 280 mm, repetition time 110.0 ms, echo time 8.6 ms, flip angle 35 degrees, slice thickness 10.0 mm, slice interval 10.0 mm, matrix size 256×256 , number of signals averaged 2, receiver bandwidth 20.6 kHz, and scan time 4 min 32 s. The MCSAs of the soleus muscle (SOL), gastrocnemius

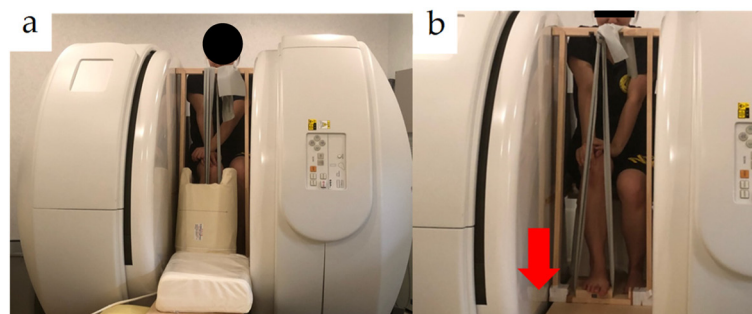


Fig. 1. The isometric contraction of the ankle plantar flexor muscle (a, measurement position; b, inside the coil).

medial head (GM), gastrocnemius lateral head (GL), and tibialis anterior (TA) were measured using the Image J image analysis program (Fig. 2). For all measurements, the examiner was blinded to one other person who was not the author.

For the comparison of the MCSA at each condition, 5 points—endmost muscle belly, most proximal and most distal, and 1/4 proximal, middle, and 1/4 distal—were extracted for each muscle. Additionally, the measured values of the muscle that showed the greatest MCSA were used for statistical analysis.

All statistical analyses were carried out using SPSS ver.19 (IBM SPSS Statistics, Japan IBM, Tokyo, Japan). Values of $p < 0.05$ were considered significant. For comparison of the MCSA between RES and CON, the paired t-test was used after confirmation of normality by the Shapiro-Wilk test. All data are expressed as mean \pm standard deviation.

RESULTS

Table 1 shows the MCSA values at RES and CON for each muscle. The SOL was significantly lower at CON than at RES in the middle portion of the muscle. The GM was also significantly lower at RES than at CON in the most proximal portion of the muscle. In addition, in the 1/4 distal portion of the muscle, at RES was significantly greater than at CON. The GL was not significantly different at all portions. The TA was significantly lower at RES than at CON in the middle portion of the muscle.

Comparison of the areas where the MCSA revealed the maximum value showed no significant difference between RES and CON in all muscles.

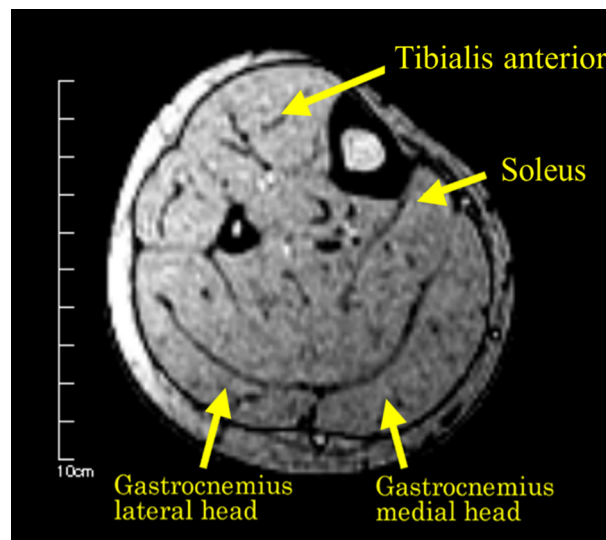


Fig. 2. Lower leg transverse section.

Table 1. The MCSA values at resting and ankle plantar flexor isometric contraction for each muscle (cm²)

	Condition	SOL	GM	GL	TA
MCSA of most proximal region	Resting	1.62 \pm 0.69	4.48 \pm 1.40	1.65 \pm 0.66	0.35 \pm 0.36
	contraction	1.61 \pm 0.94	5.08 \pm 1.89*	1.78 \pm 0.64	0.27 \pm 0.29
MCSA of 1/4 proximal region	Resting	13.96 \pm 2.49	7.99 \pm 1.62	4.93 \pm 1.46	5.54 \pm 0.96
	contraction	13.44 \pm 2.22	8.03 \pm 1.58	4.67 \pm 1.04	5.24 \pm 0.77
MCSA of middle region	Resting	16.27 \pm 3.26	12.39 \pm 2.63	6.89 \pm 1.75	5.78 \pm 1.21
	contraction	15.66 \pm 3.05*	11.96 \pm 2.16	7.02 \pm 1.73	6.01 \pm 1.19*
MCSA of 1/4 distal region	Resting	10.14 \pm 2.73	9.84 \pm 2.90	3.98 \pm 1.46	1.99 \pm 0.62
	contraction	9.57 \pm 2.67	9.35 \pm 2.93*	3.98 \pm 1.66	2.13 \pm 0.88
MCSA of most distal region	Resting	1.73 \pm 1.83	1.20 \pm 1.15	0.22 \pm 0.36	0.37 \pm 0.37
	contraction	1.61 \pm 1.91	1.07 \pm 1.13	0.20 \pm 0.32	0.42 \pm 0.34
The greatest MCSA	Resting	17.32 \pm 2.72	7.44 \pm 1.22	12.95 \pm 2.47	7.93 \pm 1.72
	contraction	17.01 \pm 2.81	7.30 \pm 1.12	13.01 \pm 2.32	7.89 \pm 1.73

*Significant difference compared to resting position ($p < 0.05$).

MCSA: muscle cross-sectional area; SOL: soleus, GM: gastrocnemius medial head; GL: gastrocnemius lateral head; TA: tibialis anterior.

DISCUSSION

This study aimed to obtain essential information on muscle dynamics during the ankle plantar flexor muscles contraction by comparing the MCSA of the lower leg muscles at rest and at contraction, in the antigravity position.

Pappas et al.¹²⁾ reported that change in muscle morphology during contraction is different in the long axis portion of the same muscle. Therefore, when performing muscle thickness measurement using ultrasonography, it is assumed that there is a portion that is measured as a decrease rather than an increase, in muscle thickness, depending on the measurement portion during muscle contraction. Therefore, the results of this study serve as an index for the assessment of the MCSA and muscle thickness of the lower leg muscles during isometric contraction of the ankle plantar flexor muscles in normal muscles, and provide information about muscle dynamics for treatment purposes.

The results showed that there was no significant difference in any of the muscles analyzed between RES and CON, where the MCSA revealed a maximum value. However, when comparing the RES and CON MCSA at the same portion, differences were noted among different muscles and measurement portions. This suggests that when muscle contraction occurs, the MCSA at the same portion changes due to a shift rather than increasing or decreasing as the muscle converges.

In the SOL, the MCSA in the middle portion of the muscle decreased during contraction. Regarding changes during isometric contraction of the triceps surae muscle, muscle fiber length is shortened by muscle contraction, and muscle thickness and physiological MCSA are often increased¹³⁻¹⁵⁾. Although the gastrocnemius muscle is located in the shallow part of the SOL, the MCSA in the distal portion of the GM, which is the same as the middle portion of the SOL, decreased during contraction as in the SOL, and the GL showed no change due to contraction. It is unlikely that the gastrocnemius muscle influenced the MCSA by compressing the SOL. Therefore, in this study, it was considered that the SOL did not converge to the middle portion during the contraction, but moved slightly to the proximal or distal portion, resulting in a decrease in the MCSA in the middle portion of the SOL. Therefore, SOL is indexed to the rate of change in decreasing MCSA of the middle portion of the muscle with respect to the contraction in the direction of plantar flexion of the ankle, and the movement acquisition in both the proximal and distal directions may be necessary to perform contraction. However, in this study, the activities of the deep leg muscles, such as the flexors of the toes, were set to be minimal; however, the presence of the deep leg muscles is unknown because measurement of the deep leg muscles was not performed.

During contraction, the GM showed an increase in the MCSA in the most proximal portion and a decrease in the MCSA in the 1/4 distal portion. This suggests that GM shifts distally due to muscle contraction. Therefore, GM is indexed to the rate of change in decreasing MCSA in the 1/4 distal portion, and the acquisition of movement in the proximal direction is required to perform contractions. On the contrary, GL showed no change at any portion during muscle contraction. The SOL has a plantar flexion torque rate that is approximately 3 times that of the gastrocnemius muscle in the ankle joint flexion torque¹⁶⁾. In addition, it was considered that movement of the gastrocnemius muscle was restricted since the measurement position was the knee flexion position. Furthermore, the GL exerts less muscle strength than the GM¹⁷⁾. Therefore, in this study, the GL contributes little to the isometric contraction of the ankle plantar flexor muscle, and the GL muscle contraction is reduced. As a result, it seems that only the GM had a change in muscle morphology. Therefore, it is necessary to investigate GL rigorously in the future.

The TA increased the MCSA during contraction in the middle portion. TA is indexed to the rate of change in the increasing MCSA of the middle portion of the muscle with respect to contraction in the direction of the plantar flexion of the ankle. It is said that antagonistic muscles act in concert during the activity of the agonistic muscles, and are involved in joint stability and motor control¹⁸⁾. Therefore, in this study, although the TA was not directly involved in ankle plantar flexion movement, muscle activity was thought to have occurred by regulating the plantar flexion direction during contraction. In particular, the TA accounts for the majority of ankle dorsiflexion muscle strength in terms of the dorsiflexion torque rate calculated from the physiological MCSA and the moment arm¹⁶⁾. Therefore, even if the activity of the TA was reduced at the time of measurement, the contribution of the TA may have been substantial and the muscle morphology was likely to change. Furthermore, since the TA increased the MCSA in the middle portion, the TA may shift to the middle portion during muscle contraction, unlike the SOL and the GM. The pennation angle of the TA is reduced compared to the SOL¹⁹⁾. Since the bipennate muscle is expected to move less in the longitudinal direction than in the fusiform muscle during contraction, the morphological characteristics of the muscle may have contributed to the muscle dynamics during muscle contraction. Therefore, TA may require the acquisition of converging movements from proximal and distal portions to the middle portion, to contract the ankle plantar flexor muscles.

As a limitation of this study, muscle dynamics were captured based on the MCSA of the muscles, but no evaluation of dynamics in the long axis direction considering tendon flexibility was performed. Narici et al.¹³⁾ stated that tendon tissue flexibility acts as a mechanical buffer during high intensity contractions and reduces the load on the muscle. The tendon is stretched during muscle contraction, and the whole muscle tendon units may be maintained at a certain length. Therefore, in the future, it is necessary to analyze the longitudinal direction of the muscle, including the distance of the tendon movement. In addition, only anatomical MCSA measurement was used in this study, while the physiological MCSA was not evaluated. The bipennate muscle is thought to increase the MCSA and muscle thickness due to an increase in the pennation angle^{13, 14)}, and it is expected that the muscle shape changes during contraction depending on the pennation angle. Therefore, it is

necessary to analyze the morphology while considering the pennation angle in order to investigate a potential relationship between the latter and muscle strength. Furthermore, in this study, the measurement was focused on muscle morphology, so it is unclear how the actual muscle activity occurred. Therefore, it is necessary to analyze the relationship between muscle activity and morphological changes using surface electromyography.

In conclusion, the purpose of this study was to clarify changes in muscle morphology during isometric contraction of the triceps surae using the MCSA as an index. The results of this study suggest that the MCSA increases and decreases depending on the longitudinal direction of the muscle during isometric contraction of the triceps surae. In addition, the area to be used as an indicator and the movement to be induced differ depending on the muscle during isometric contraction of the triceps surae.

Funding

This work was supported by JSPS KAKENHI Grant Number JP20K11204.

Conflict of interest

No potential conflicts of interest are disclosed.

ACKNOWLEDGMENT

The authors thank Ms. Misa Fukushima for her help with this study.

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