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Original Article

Measurement of the cross-sectional area of the hamstring muscles during initial and stretch positions with gravity magnetic resonance imaging

Dai Nakaizumi, RPT, MS[1, 2)*], Hitoshi Asai, RPT, PhD[3)],
Pleiades Tiharu Inaoka, RPT, PhD[3)], Naoki Ohno, PhD[4)], Tosiaki Miyati, PhD[4)]

[1)] Division of Health Sciences, Graduate School of Medical Sciences, Kanazawa University: 5-11-80 Kodatsuno, Kanazawa, Ishikawa 920-0942, Japan
[2)] Department of Rehabilitation, Kanazawa Red Cross Hospital, Japan
[3)] Department of Physical Therapy, Graduate Course of Rehabilitation Science, School of Health Sciences, College of Medical, Pharmaceutical, and Health Sciences, Kanazawa University, Japan
[4)] Faculty of Health Sciences, Institute of Medical, Pharmaceutical and Health Sciences, Kanazawa University, Japan

Abstract. [Purpose] We aimed to investigate the change rate in the cross-sectional area of each hamstring component to evaluate muscle extensibility and to contribute to the studies on hamstring strain prevention. [Participants and Methods] Fifteen healthy young males volunteered to participate in this study. They performed a knee extension test. For the measurements, we used multi-posture magnetic resonance imaging (gravity magnetic resonance imaging), the open shape of which allows performing body scanning in various positions. We measured the maximum cross-sectional area of the hamstring during the initial and stretch positions from the obtained images. Then, for each muscle, we calculated the maximum cross-sectional area change rate relative to the initial position. [Results] For all hamstring muscles, the maximum cross-sectional area during stretching was significantly smaller than that in the initial position. The maximum cross-sectional area change rate of the semimembranosus was significantly smaller than that of the other 3 muscles (there were no significant differences among these 3 muscles). [Conclusion] The results suggest that the semimembranosus has higher resistance to morphological change than the other muscles, which could be an important limiting factor for the extensibility of the hamstring muscle group.
Key words: Cross-sectional area of hamstring muscles, Gravity MRI, Hamstring strain

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INTRODUCTION

The hamstring muscles are composed of the biceps femoris short head (BFsh), the biceps femoris long head (BFlh), the semitendinosus (ST) and, the semimembranosus (SM). Hamstring muscle strain, ranging from mild to very severe, is one of the most common types of sports injury[1, 2)]. Based on the mechanisms of injury, two different types of hamstring strain have been described[3–5)]. Hamstring strain that occurs during high-speed running, in which the BFlh is most commonly involved, typically occurs at the proximal muscle-tendon junction[3, 6)]. The other hamstring strains occur in the setting of excessive lengthening of the hamstring and more commonly occur in dancers. This hamstring strain commonly involves the proximal free tendon of the SM, close to the ischial tuberosity[7)] and is frequently associated with poor hamstring flexibility[8)]. Thus,

*Corresponding author. Dai Nakaizumi (E-mail: weile2117@gmail.com)

maintaining and improving hamstring flexibility is necessary for prevent the occurrence and recurrence of hamstring strains.

The BFlh and the SM are unipennate muscles, while the BFsh and the SM are fusiform muscles; the differences in muscle architecture affect passive tension, and the structural features as pennate muscles develop passive tension with a shorter muscle length. On the other hand, when the muscles are closer to the fusiform muscles, greater passive tension develops in the extended position[9]. As mentioned above, it has been reported that the hamstring strain frequency is high in the BFlh and the SM, and the strain frequency differs among the hamstring muscles[3–8]. The differences in the muscle architecture and strain predominance in these muscles also suggest differences in the morphological changes of each muscle during hamstring extension. Previous studies have reported a strong linear relationship between the shear elastic modulus measured by ultrasonic shear wave elastography and the amount of muscle elongation[10, 11]. However, although ultrasonic shear wave elastography enables the assessment of differences in the degree of hamstring elongation[12–14], the shear elastic modulus and change of muscle morphology cannot be determined.

Poisson's ratio, also known as the Poisson coefficient, is the ratio of transverse contraction strain to longitudinal extension strain in a stretched bar. The Poisson's ratio of muscle tissue is approximately 0.49 and is similar to that of an incompressible substance, such as rubber[15]. Since incompressible substances have a constant volume before and after deformation[16], it is expected the cross-sectional area will shrink as the muscle stretches and thus it is possible that the extent of muscle stretch can be represented by the degree of change (contraction) of the cross-sectional area. Thus, the degree of change in the cross-sectional area of the hamstring from the initial position to the position at stretch may be an objective indicator of the hamstring flexibility.

Muscle flexibility is generally assessed by the maximum range of motion in a joint or series of joints. However, it has been proposed that it is not appropriate to evaluate muscle flexibility by the range of motion since the measurement of a range of motion is influenced by several factors, including pain and stretch tolerance[17, 18]. The reliability and validity of assessing muscle flexibility in the range of motion will be high if there is a relationship between the measurement of the range of motion and changes in muscle morphology.

T_1-weighted magnetic resonance imaging (MRI) is generally used to measure the cross-sectional area of muscles[19–21]. T_1-weighted imaging is generally considered to be the most accurate non-invasive modality to assess muscle morphology. In most studies using MRI to measure the cross-sectional area of muscles[19–21], the measurement is performed in a resting condition. To the best of our knowledge, no studies have measured the cross-sectional area of muscles at stretch. This is due in part to the fact that regular MRI equipment obtains images with the patient lying in the supine position since MRI scanners do not allow scanning in arbitrary body positions.

The straight leg raise (SLR) and knee extension with hip flexed in supine positions are generally to assess hamstring flexibility[22, 23]. Since MRI images cannot be obtained from patients lying in these two positions using regular MRI scanners, we used a novel magnetic resonance imaging system that can obtain images in any posture "gravity MRI"[24], which can hold any position, allowing for images to be acquired in postures that were impossible in the past. We used gravity MRI to measure the cross-sectional area of the hamstring at stretch and compared the area with that at rest and examined the relationship between the change and the range of motion of the lower limb joint.

The purpose of this study was to investigate the change rate of the cross-sectional area of each component of the hamstring muscles between the initial position and stretch position and to investigate the relationship between the change rate of the cross-sectional area of the hamstring in these two positions and the knee extension angle.

We hypothesized that in each of the hamstring muscles, the cross-sectional area in the stretch position would become smaller than that in the initial position, that the maximum cross-sectional area change rate would differ in each of the hamstring muscles, and that the maximum cross-sectional area change rate would be correlated with the knee extension angle.

PARTICIPANTS AND METHODS

The study population included 15 healthy young men. The height, weight and age of the participants were 172.1 ± 5.0 cm, 65.7 ± 6.9 kg and 22.0 ± 1.3 years, respectively. The participants were free from neurological and orthopedic impairments. All participants gave their written informed consent to participate in this study, which followed a protocol revised and approved by the institutional ethics committee of Kanazawa University in accordance with the Declaration of Helsinki (No. 797-1).

A gravity MRI system, the open shape of which allows the body scanning in various positions (0.4T, Hitachi Healthcare, Tokyo, Japan), was used to measure the cross-sectional area of the hamstring. All images obtained by MRI were recorded on a computer (Dell Japan Inspiron 1300; Dell Japan, Kawasaki, Japan). The ImageJ software program (National Institutes of Health, Bethesda, Maryland, USA) was used to measure the cross- sectional area of each muscle.

The maximum knee extension angle was measured as follows: 1) the participants lay on a table in the supine position, with the hip and knee joints of the examined side at 90° of flexion; 2) while keeping the hip at 90° of flexion, the knee of the tested side was passively extended until the maximal range of motion was reached (measurement was performed using goniometer). The knee extension angle was defined as the angle between the longitudinal axis of the fibula and the longitudinal axis of the femur. The maximal range of motion was defined as the point at which the examiner felt confirmed resistance or the subject confirmed that the maximum knee extension had been reached[25, 26]. Boyce et al. reported that the sustained extension of the

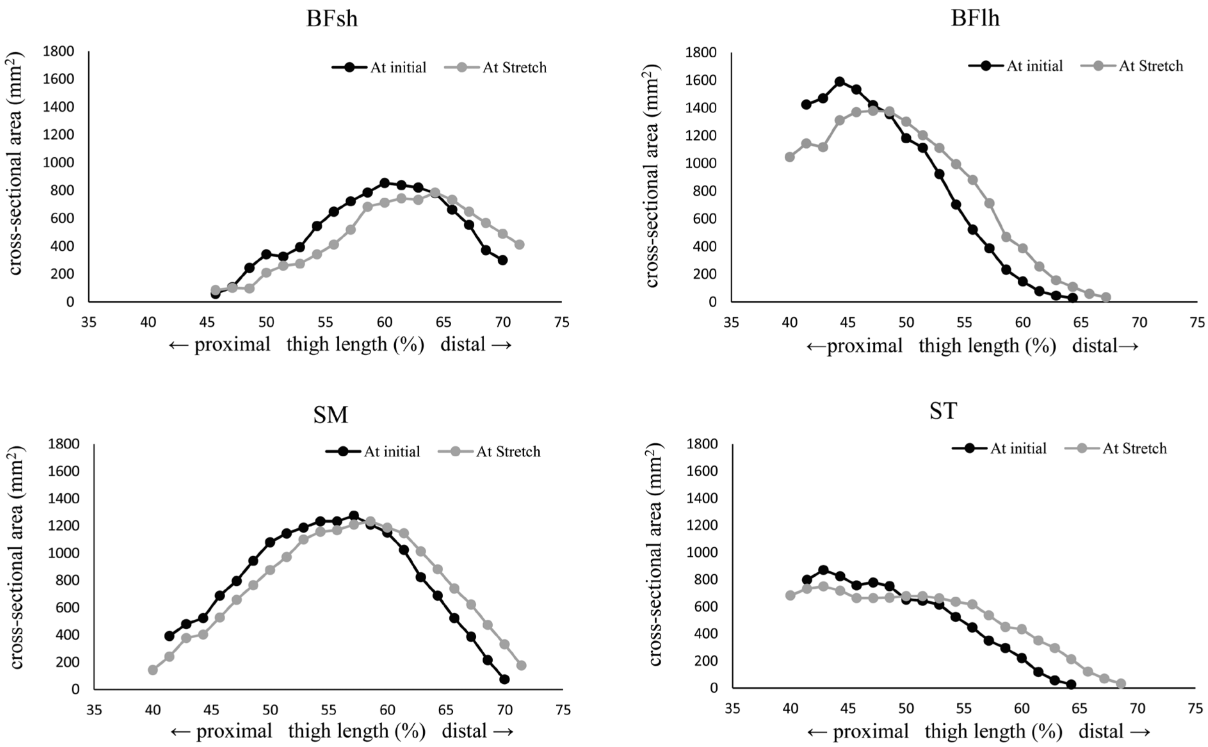

Fig. 1. The cross-sectional area of hamstring muscles (typical data).
The horizontal axis represents the slice location according to the percentage of thigh length.
The slice location was calculated considering the greater trocanter as 0% and lateral femoral epicondyle as 100%.
Muscle maximum cross-sectional area was confirmed after cross-sectional area plotting for each participant.
BFsh: biceps femoris short head; BFlh: biceps femoris long head; ST: semitendinosus; SM: semimembranosus.

hamstrings for 15 seconds would expand the range of motion[27)]. Thus, taking into consideration the fact that the measurement itself extends the hamstrings and influences the range of motion, the maximal range of motion in the knee extension test was held for less than 5 seconds.

The measurement of the muscle cross-sectional area was performed as follows: a gravity MRI system was used to scan T_1-weighted images of the right thigh. The following imaging parameters were used: slice plane, axial; pulse sequence, RF-spoiled steady state gradient echo; field of view, 240 mm; repetition time, 27.5 ms; echo time, 8.9 ms; flip angle, 16 degrees; slice thickness, 5 mm; slice interval, 0 mm; matrix size, 288 × 192; number of signals averaged, 1; receiver bandwidth, 23.2 kHz; and scan time, 3 min 20 s. The images were taken in the following positions: 1) the initial position (supine position with the hip and knee flexed to 90°); and 2) the stretch position (supine position, hip flexed to 90°, and the knee extended to the maximal range of motion without pain, where it could be kept for at least 5 minutes). Since 3 minutes and 20 seconds are required to acquire each MR image, the stretch position for imaging was established as previously described with consideration for fatigue and pain, and to reduce—as much as possible—body movement during image acquisition. Before imaging, the participants were fitted with a marker located on 50% of the thigh length (the midpoint between the greater trochanter and the lateral femoral epicondyle). A coil was wound around the marker. The slice showing 50% of the thigh length was identified based on the reflected marker from obtained image, and the cross-sectional area of the BFsh, the BFlh, the ST and the SM muscles were outlined every 5 mm proximal and distal to the marked slice ranging at least 43% to 64% (Fig. 1). All of the manual segmentation measurements were completed by the same examiner. The maximum cross-sectional area of each muscle was determined from the measured muscle cross-sectional area.

To examine the reproducibility of the muscle cross-sectional area measurements, the same examiner measured the cross-sectional area twice at intervals of 1week or more in on the images of the maximum cross-sectional area level in seven participants.

The maximum cross-sectional area change rate of each muscle relative to initial position was calculated from the following formula. Rate of change=[(maximum muscle cross-sectional area at initial position − maximum muscle cross-sectional area at stretch) / maximum muscle cross-sectional area at initial position] ×100.

In order to investigate the reproducibility of the cross-sectional area measurement, intraclass correlation coefficients (ICC [1, 1]) was calculated. Spearman's rank correlation coefficient was used to determine the relationship between the maximum

Table 1. Maximum cross-sectional area reproducibility and the maximum cross-sectional area change rate per muscle

Muscle	Condition				Change rate (%)
	At initial		At stretch		
	ICC	95%CI	ICC	95%CI	
BFsh	0.984	0.923–0.997	0.997	0.983–0.999	6.7 ± 3.4
BFlh	0.985	0.978–0.997	0.997	0.987–1.000	8.6 ± 2.8
ST	0.996	0.978–0.999	0.982	0.912–0.997	10.1 ± 4.4
SM	0.964	0.828–0.994	0.993	0.965–0.999	2.3 ± 0.8 *

At initial: supine position with the hip and knee flexed to 90°.
At stretch: supine position, hip flexed to 90°, and the knee extended to the maximal range of motion without pain, where it could be kept for at least 5 minutes.
ICC: intraclass correlation coefficients [1, 1]; 95%CI: 95% confidence interval; BFsh: biceps femoris short head; BFlh: biceps femoris long head; ST: semitendinosus; SM: semimembranosus.
*p<0.05.

Table 2. Maximum cross-sectional area (mm^2)

	At initial	At stretch
BFsh	775.2 ± 161.2	722.3 ± 150.3*
BFlh	1,350.2 ± 245.4	1,235.4 ± 234.3*
ST	968.0 ± 234.7	870.1 ± 217.9*
SM	1,315.4 ± 254.6	1,286.5 ± 252.9*

*Significantly different compared to at initial.
At initial: supine position with the hip and knee flexed to 90°.
At stretch: supine position, hip flexed to 90°, and the knee extended to the maximal range of motion without pain, where it could be kept for at least 5 minutes.
BFsh: biceps femoris short head; BFlh: biceps femoris long head; SM: semimembranosus; ST: semitendinosus.

Table 3. Correlation between the maximum cross-sectional area and the stretch position angle

		BFsh	BFlh	ST	SM
Stretch position angle	r	0.288	0.403	0.461	0.300
	p value	0.299	0.136	0.084	0.277

BFsh: biceps femoris short head; BFlh: biceps femoris long head; SM: semimembranosus; ST: semitendinosus.

knee extension angle and stretch position angle. The Wilcoxon signed-rank test was used to determine the difference in the maximum cross-sectional area at the initial position and at stretch. Spearman's rank correlation coefficient was used to determine the relationship between the stretch position angle and the maximum cross-sectional area change rate of each muscle. Bonferroni correction was applied to investigate the difference in the maximum cross-sectional area change rate per muscle. The significance level was set at 5%. All data were analyzed using the SPSS software program (ver. 23, IBM, SPSS Tokyo, Japan).

RESULTS

The reproducibility of the cross-sectional area measurement is shown in Table 1. The ICC [1, 1] was 0.964–0.996 at the initial position and 0.082–0.997 at the stretch position.

The maximal knee extension angle was 157.7 ± 9.4° and the stretch position angle was 148.0 ± 10.0°. Spearman's rank correlation coefficient indicated a strong correlation between the maximum knee extension angle and stretch position angle (r=0.911, p<0.001).

The maximum cross-sectional area at the initial and at stretch positions are shown in Table 2. The maximum cross-sectional area at stretch was significantly smaller than in the initial position for all hamstring muscles.

The maximum cross-sectional area change rate per muscle was shown in Table 1. The SM maximum cross-sectional area change rate was significantly smaller in comparison to the other three muscles, and no significant differences were found among these three muscles.

Table 3 shows Spearman's rank correlation coefficient between the stretch position angle and the maximum cross-sectional area change rate of each muscle. There was no significant correlation for any of the hamstring muscles.

DISCUSSION

The current study investigated the relationship between the cross-sectional area change rate of the hamstring at initial and stretch positions and the knee extension angle and the changes in the cross-sectional area of each component of the hamstring muscles at the initial and stretch positions.

In the investigation of the reproducibility of the cross-sectional area measurement, the ICC [1, 1] was 0.964–0.996 for the initial position and 0.982–0.997 for the stretch position. Since 'good reliability' is defined by an ICC of ≥0.7[28, 29], the reproducibility of the cross-sectional area measurement in this study can be considered reliable.

In this study, the correlation coefficient between the maximum knee extension angle and the stretch position angle was r=0.911, and a strong positive correlation was observed. Thus, the maximum knee extension angle of the individual is well represented by the stretch position angle during the MRI measurement.

The results of this study showed that the maximum cross-sectional area was significantly smaller in the stretch position than in the initial position in all hamstring muscles and the maximum cross-sectional area was found to decrease when the muscle is stretched. These outcomes support the hypothesis that in each hamstring muscles, the cross-sectional area in the stretch position becomes smaller than that in the initial position. In this study, we used "gravity MRI" to measure the cross-sectional area in the initial and stretch positions. The position of the thigh with respect to the direction of gravity is the same in the initial and stretch positions, which eliminates the influence of gravity on morphological changes. Thus, the reduction of the maximum cross-sectional area of each of the hamstring muscles that was shown in this study can be considered to be due to the influence of the stretching of the hamstring muscles. Narici et al. reported that the physiological cross-sectional area of the gastrocnemius and the pennation angle at rest with an ankle joint angle of 90 degrees was smaller than that at 150 degrees (plantar flexion, shorter muscle)[30]. Another study using ultrasound reported a decrease in the fascicle length and pennation angle during BFlh stretching[31, 32]. The results of these studies suggest that morphological changes resulted in a decreased cross-sectional area in a stretched muscle position, which supports the findings of our study[30–32].

The maximum cross-sectional area change rate of the SM was significantly smaller than that of the other three muscles (the BFsh, the BFlh, the ST), and no significant differences were found between the other three muscles. The results of this study supported the hypothesis that the maximum cross-sectional area change rate differs in each hamstring muscle. Although the BFlh and the SM are both unipennate muscles, in this study, the maximum cross-sectional area change rates of the BFlh and SM were significantly different. Thus, the cross-sectional area changes in our study cannot be explained by the muscle architecture classifications. However, if explored in more detail, the SM is reported to have the shortest fascicle length and the largest pennation angle[33]. These two differences in architectural properties may have influenced the difference in the maximum cross-sectional area change rate.

The smaller change in the maximum cross-sectional area of the SM in comparison to the other three muscles may indicate that the SM is the most stretch-resistant (stiff, inflexible) muscle. A previous study that examined each hamstring muscle in the stretch position, similar to this study (knee extension with hip flexed in the supine position), using ultrasonic shear wave elastography reported that the SM was stiffer and more stretched than the BF and ST[12]. In addition, SM strains commonly occur with the excessive lengthening of the hamstring, such as during extreme hip flexion with knee extension[4, 34]. Based on the stiffness and injury rates, the SM appears to have more resistance to morphological change during stretching than the other hamstring muscles. This also suggests that higher resistance of the SM to morphological change is an important limiting factor for the extensibility of the hamstring muscle group.

There was no significant correlation between the stretch position angle and the maximum cross-sectional area change rate for any of the hamstring muscles. The knee extension angle during the stretch position was not identical for each participant because the angle was based on the participant's perception of the stretch and the ability to maintain the position during the imaging time. Our second hypothesis was that the cross-sectional area change rate would be correlated with the knee extension angle because we believed that individuals with higher knee extension angle during the stretch position would have a higher cross-sectional area change in comparison to the initial position. However, the results of this study did not support this hypothesis. Participants with a larger knee extension angle did not have a larger cross-sectional area change rate. A previous study that examined changes of the muscle morphology of the medial gastrocnemius during ankle dorsiflexion with ultrasound reported that in ankle dorsiflexion, passive torque, fascicle length and muscle-tendon unit lengthening varied among individuals[35]. Although gastrocnemius stretching resulted in morphological changes, the amount of change was suggested to vary among individuals. Similarly, the morphology of the hamstring muscles in the initial and stretch positions may vary among individuals. Probably due to these individual differences, the stretch position angle and the maximum cross-sectional area change rate were not correlated for any of the hamstring muscles in this study.

The main limitation of this study was that only two positions were evaluated to analyze the relationship between the stretch angle and the maximum cross-sectional area change rate. Thus, further research evaluating different angles of stretch is required to clarify the individual changes according to stretch intensity. Furthermore, the evaluation of group differences in hamstring extensibility and injury occurrence would be desirable to understand the factors involved in strain injuries and to create effective preventive physical therapy programs.

Funding and Conflict of interest

None.

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