Journal of Human Kinetics volume 72/2020, 51-59 DOI: 10.2478/hukin-2019-0124
Section I – Kinesiology

Muscle Recruitment Pattern of The Hamstring Muscles in Hip Extension and Knee Flexion Exercises

by
Osamu Yanagisawa[1], *Atsuki Fukutani*[2]

We aimed to compare dynamic exercise performance between hip extension exercises with different knee angles and between knee flexion exercises with different hip angles, and to investigate the recruitment pattern of the hamstrings in each exercise. Seven men performed 4 isokinetic exercises (3 maximal concentric contractions at 30°/s (peak torque) and 30 maximal concentric contractions at 180°/s (total work)): hip extension with the knee fully extended (HEke) and with the knee flexed at 90° (HEkf) and knee flexion with the hip fully extended (KFhe) and with the hip flexed at 90° (KFhf). The recruitment pattern of the hamstrings was evaluated in each exercise using magnetic resonance imaging (T2 calculation). The HEke condition showed significantly greater peak torque than the HEkf condition ($p < 0.05$). The KFhf condition had significantly greater peak torque and total work values than the KFhe condition ($p < 0.05$). Although the biceps femoris long head, semitendinosus, and semimembranosus had significantly increased post-exercise T2 values in the HEke ($p < 0.05$), KFhe, and KFhf conditions ($p < 0.01$), the T2 increase values were significantly greater under the KFhf than the HEke condition ($p < 0.05$). The semitendinosus showed a significantly greater T2 increase value than other muscles under both KFhe and KFhf conditions ($p < 0.05$). Performance of hip extension and knee flexion exercises increases when the hamstring muscles are in a lengthened condition. The hamstring muscles (particularly the semitendinosus) are more involved in knee flexion than in hip extension.

Key words*: magnetic resonance imaging, T2 relaxation time, isokinetic exercise, biceps femoris, semitendinosus, semimembranosus.*

Introduction

The hamstring muscles consist of the long (BF-L) and short (BF-S) head of the biceps femoris, semitendinosus (ST), and semimembranosus (SM). The BF-L, ST, and SM lie across both the hip and knee joints as a biarticular muscle, whereas the BF-S is a uniarticular muscle that crosses only the knee joint. Based on this gross anatomy, the hamstring muscles are frequently treated as a muscle unit, such as hip extensors (except for the BF-S) or knee flexors. On the other hand, the hamstring muscles are not same in muscle configuration and architecture. The BF-S and ST are regarded as fusiform muscles with a relatively long muscle fiber length (FL), while the BF-L and SM are classified as pennate muscles with a relatively large pennation angle and physiological cross-sectional area (Chleboun et al., 2001; Kellis et al., 2010, 2012; Woodley and Mercer, 2005). The fusiform muscle is thought to be advantageous in muscle contraction velocity, while the pennate muscle is thought to be advantageous in muscle force generation (Lieber and Friden, 2000; Woodley and Mercer, 2005). In addition, the medial hamstrings (ST and SM) have more distal attachments than the lateral ones (BF-L and -S), indicating that the former has more advantageous moment arm than the latter in the production of knee flexion torque (Herzog and Read, 1993). Considering the close relationships between muscle architecture and function (Fukunaga et al.,

---

[1] - *Faculty of Business Information Sciences, Jobu University, 634-1, Toyazuka-machi, Isesaki, Gunma, Japan.*
[2] - *Faculty of Sport and Health Science, Ritsumeikan University, 1-1-1, Noji-higashi, Kusatsu, Shiga, Japan.*

Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 72/2020 in April 2020.

1996) and between moment arm and joint torque, the anatomical feature of individual muscles may lead to functional differences in the hamstring muscles in hip extension and knee flexion.

The FL of a muscle is also an important factor that affects the joint function. Skeletal muscle fibers have an optimal length to produce the largest contraction force (Gordon et al., 1966). The FL of each hamstring muscle is affected by the positions of the hip joint (except for the BF-S) as well as the knee joint. Previous studies (Guex et al., 2012; Kwon and Lee, 2013; Mohamed et al., 2002; Worrell et al., 2001) have revealed that isometric hip extension and knee flexion forces significantly increase as the FLs of the hamstring muscles are lengthened by flexing the hip joint and/or extending the knee joint. Additionally, some studies have reported that the activation patterns of the hamstring muscles during hip extension or knee flexion vary with the changes in the hip and/or knee joint angles (Jeon et al., 2016; Kwon and Lee, 2013; Lunnen et al., 1981; Onishi et al., 2002; Mohamed et al., 2002), but the results are not consistent. Moreover, the variation in the recruitment pattern of the hamstring muscles with changes in muscle FL has not been fully investigated in dynamic hip extension and knee flexion exercises. One of possible reasons is that the examination of recruitment patterns among different joint angles by surface electromyography has a methodological limitation. Specifically, once the joint angle (muscle fiber length) changes, the diameter of the muscle fiber also changes because muscle volume is virtually constant (Abbott and Baskin, 1962). Due to this geometric property, the number of muscle fibers under the electromyographic electrode can change as a function of the joint angle, which makes it difficult to evaluate the recruitment pattern among different joint angles.

Considering the above limitation, T2 relaxation time (T2 value) in magnetic resonance imaging (MRI) may be useful to clarify the muscle recruitment pattern among different joint angles. The T2 value is an imaging variable that reflects the level of water content within tissue and elevates by temporally increased intramuscular water resulting from repetitive muscle contractions. Thus, the T2 value has been utilized to noninvasively determine the pattern of muscle use that occurs during exercise (Cagnie et al., 2008; Yanagisawa et al., 2003). In fact, several studies examined the muscle activation level by measuring the changes in the T2 value induced by muscle contractions (Adams et al., 1992; Fisher et al. 1990). Thus, the T2 value would be useful to clarify whether the recruitment pattern of the hamstring muscles differs dependent on the different joint angles.

The purpose of this study was to compare dynamic exercise performance (joint torque production) between hip extension exercises with different knee angles and between knee flexion exercises with different hip angles. Additionally, we aimed to investigate the recruitment pattern of the hamstring muscles among above-mentioned exercises using MRI. We hypothesized that the performance of dynamic hip extension and knee flexion exercises would be superior when the hamstring muscles are in a lengthened condition and that the recruitment pattern of the hamstring muscles would differ in dynamic hip extension and knee flexion exercises with different hip and knee angles.

Methods

Participants

This study included 7 healthy men (age, 23.4 ± 2.1 years; body height, 170.0 ± 5.7 cm; body mass, 66.4 ± 10.5 kg) who did not regularly perform lower extremity exercises. The right lower extremity was dominant in all the participants, defined as the preferred kicking leg. All the participants were free of lower extremity pain at the time of the experiment and did not have a history of hip and knee joint disorders or thigh muscle strain. They were instructed to refrain from physical exercises for 2 days before the measurements were taken.

This study was approved by our institutional review board and followed the ethical guidelines of the Declaration of Helsinki. Prior to the examination, all participants were given a brief description of the study, the examination procedures, and the potential risks. Written informed consent was obtained from each participant, and their rights were fully protected.

Isokinetic exercise

A training session was scheduled to familiarize participants with the testing protocol using an isokinetic dynamometer (Biodex system 3, Biodex Medical Systems, Inc., NY, USA). We informed participants of the characteristics of the isokinetic dynamometer and the way isokinetic exercise was being used in our study through their use of the dynamometer.

The main testing session consisted of 4 isokinetic exercises; 1) hip extension with the knee fully extended (HEke), 2) hip extension with the knee flexed at 90° (HEkf), 3) knee flexion with the hip fully extended (KFhe), and 4) knee flexion with the hip flexed at 90° (KFhf). Participants performed all of the 4 exercises in randomized order completing 1 exercise a day with 3 day rest interval between subsequent sessions. Each exercise condition was comprised of 3 maximal concentric contractions at 30°/s (maximal muscle strength test) and 30 successive maximal concentric contractions at 180°/s (maximal muscle endurance test). The exercise at 30°/s was performed before the exercise at 180°/s considering the effect of muscle fatigue that may occur following 30 repetitive contractions.

On the day of each testing session, participants performed a 10 min warm-up (5 min static stretching for the hamstring muscles followed by 5 min exercise on a cycle ergometer at a self-regulated moderate intensity). The rotation axis of the dynamometer was aligned with the greater trochanter of the femur in hip extension exercises and the lateral epicondyle of femur in knee flexion exercises. The inferior margin of the lever arm shin-pad was placed approximately 2 cm superior to the knee joint fissure in hip extension exercises and to the medial malleolus in knee flexion exercises. The straps of the isokinetic dynamometer were tightened around the chest, pelvis, and distal aspect of thigh (only during knee flexion exercises) for stabilization during exercise. Gravity correction was performed at the beginning of each testing session according to the manufacturer's recommendations. Participants were instructed to extend the hip or flex the knee as hard as possible throughout the fully defined range of motion (hip extension: 0° -70°, knee flexion: 5° -105°) at every trial. Five sub-maximal repetitions and 1 maximal repetition were performed before each test to familiarize them with the velocity and sensations of the dynamometer. Participants were required to fold their arms across their chest to minimize extraneous body motion during measurement. Then, they performed 3 maximal repetitions at 30°/s and 30 maximal repetitions at 180°/s in hip extension or knee flexion. Visual feedback from the Biodex computer monitor was not provided, but they were verbally encouraged to work as hard as possible from the first to the last repetition. In each testing session, we assessed maximal muscle strength by adopting the peak torque value of 3 repetitions at 30°/s and the maximal muscle endurance by using total work value in 30 repetitions at 180°/s.

MRI

Axial MR images of the right thigh were obtained with the participant in the prone position before and after the muscle endurance test using a 1.5 Tesla MR system (Signa Excite XIV, GE Healthcare UK Ltd., Buckinghamshire, UK) with an 8 channel body array coil to evaluate the recruitment pattern of the hamstring muscles during each exercise. During the 4 testing sessions, we could perform the MRI measurement in 5 min after each exercise because the exercises were performed near the MRI room. The imaging sequence (spin-echo type) for calculating the muscle T_2 value was as follows: repetition time, 2,000 ms; echo time, 20, 40, 60, and 80 ms; 128 × 128 matrix; number of excitations, 1; field of view, 240 mm; slice thickness, 10 mm; scan time, 4 min 40 s. The scan position was proximally 50% of the length between the ischial tuberosity and the head of fibula and was marked on the participant's skin with semi-permanent ink for ensuring the same scan position during repeated MRI measurements.

A region of interest was drawn around the BF-L and -S, ST, and SM using the FuncTool 2 software program (GE Healthcare) built into the MR device, with special care taken to avoid inclusion of subcutaneous fat, fascia, blood vessels, or bony anatomy on an image with a 20 ms echo time. Next, the regions of interest of each muscle were copied onto the 40, 60, and 80 ms echo time images. The signal intensity for each echo time and for each muscle, was determined. Then, T_2 value was calculated via the following equation: $Sn = S0 \exp(-TE/T_2)$, where Sn represents the signal intensity at each echo time, S0 is signal intensity at 0 ms, and TE is echo time.

Statistical Analysis

The mean and standard deviation (SD) were calculated for all variables. Performance data regarding hip extension between the HEke and HEkf conditions and knee flexion between the KFhe and KFhf conditions were compared using a paired t-test. In addition, T_2 values before and after each exercise were compared using a paired t-test in individual muscles; the BF-S was excluded from the analysis of the HEke and HEkf conditions because this muscle does not lie across the hip joint. Moreover, significant differences between the 4 exercise conditions were evaluated by one-way repeated measures analysis of variance with a Bonferroni's test in each muscle; a paired t-test was used in the analysis of the BF-S. Similarly, one-way repeated measures analysis of variance with a Bonferroni's test was used to evaluate significant differences between the muscles under each exercise condition. The level of statistical significance was set at $p < 0.05$ for all analyses.

Results

Table 1 displays the peak torque and total work values in isokinetic hip extension and knee flexion exercises. The HEke condition showed a significantly greater peak torque than the HEkf condition ($p < 0.05$). The peak torque value of the KFhf condition was significantly greater than that of the KFhe condition ($p < 0.05$). The KFhf condition showed a significantly greater total work value than the KFhe condition ($p < 0.05$).

Table 2 shows T_2 values of the hamstring muscles before and after isokinetic hip extension and knee flexion exercises. The BF-L, SM, and ST had significantly increased post-exercise T_2 values under the HEke condition ($p < 0.05$). The hamstring muscles had significantly increased post-exercise T_2 values under both KFhe and KFhf conditions ($p < 0.01$). The hamstring muscles showed increased signal intensity on a T_2-weighted image after the KFhf exercise (Figure 1).

Table 1

Exercise performance data regarding isokinetic hip extension and knee flexion exercises

	Hip extension exercise (30°/s)	Hip extension exercise (180°/s)
	Peak torque (Nm)	Total work (J)
HEke	204.9 ± 35.1*	4448.1 ± 672.3
HEkf	182.7 ± 29.6	4202.6 ± 857.7
	Knee flexion exercise (30°/s)	Knee flexion exercise (180°/s)
	Peak torque (Nm)	Total work (J)
KFhe	79.7 ± 11.4	1705.9 ± 348.8
KFhf	90.6 ± 15.4*	2310.6 ± 514.1*

HEke: hip extension with the knee fully extended, HEkf: hip extension with the knee flexed at 90°
KFhe: knee flexion with the hip fully extended, KFhf: knee flexion with the hip flexed at 90°
Asterisks show significant differences between HEke and HEkf or between KFhe and KFhf in each exercise performance ($p < 0.05$)*
Data = mean ± SD

Table 2

T2 values of the hamstring muscles before and after isokinetic hip extension and knee flexion exercises

	HEke		HEkf		KFhe		KFhf	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
BF-S					28.4 ± 1.1	34.7 ± 1.2**	29.0 ± 1.4	34.3 ± 0.5**
BF-L	28.8 ± 1.1	30.2 ± 1.3*	29.1 ± 1.6	29.3 ± 1.9	28.6 ± 1.1	32.2 ± 1.2**	28.9 ± 1.1	33.7 ± 1.3**
ST	28.0 ± 1.2	29.0 ± 1.4*	28.1 ± 1.7	28.6 ± 2.1	27.9 ± 1.0	36.7 ± 1.3**	28.0 ± 1.7	36.1 ± 1.2**
SM	28.3 ± 0.9	29.3 ± 0.8*	28.6 ± 1.3	28.7 ± 1.7	28.5 ± 1.0	30.5 ± 1.1**	28.5 ± 1.1	33.3 ± 1.5**

HEke: hip extension with the knee fully extended, HEkf: hip extension with the knee flexed at 90°
KFhe: knee flexion with the hip fully extended, KFhf: knee flexion with the hip flexed at 90°
BF-L = long head of biceps femoris, BF-S = short head of biceps femoris, ST = semitendinosus, and SM = semimembranosus
Asterisks show significant changes before and after exercise ($p < 0.05$, **$p < 0.01$)*
Data = mean ± SD, Unit: ms

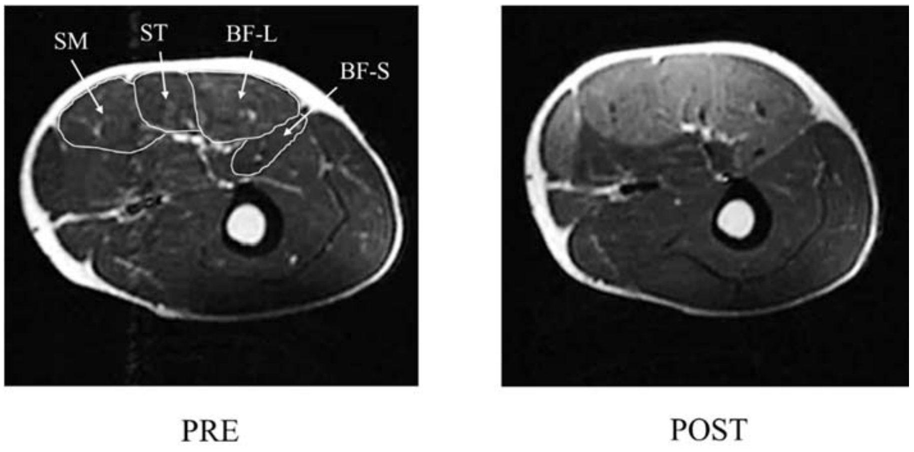

Figure 1

Axial MR T_2-weighted images (repetition time = 2,000 ms, echo time = 80 ms) of the right thigh before and after knee flexion exercise with the hip flexed at 90°in a representative subject
The BF-L and -S, ST, and SM showed increased signal intensity on post-exercise T_2-weighted MR image. BF-L = long head of biceps femoris, BF-S = short head of biceps femoris, ST = semitendinosus, and SM = semimembranosus.

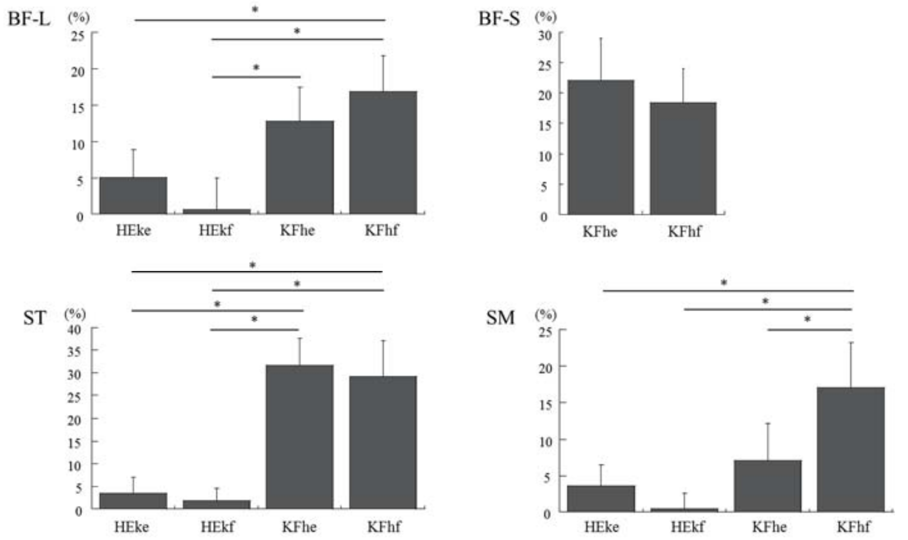

Figure 2

The rate of change in the T_2 values of the hamstring muscles before and after hip extension and knee flexion exercises

BF-L = long head of biceps femoris, BF-S = short head of biceps femoris, ST = semitendinosus, and SM = semimembranosus. HEke = hip extension with the knee fully extended, HEkf = hip extension with the knee flexed at 90°, KFhe = knee flexion with the hip fully extended, and KFhf = knee flexion with the hip flexed at 90°. Asterisks show significant difference between exercise conditions ($p < 0.05$). Data = mean ± SD.*

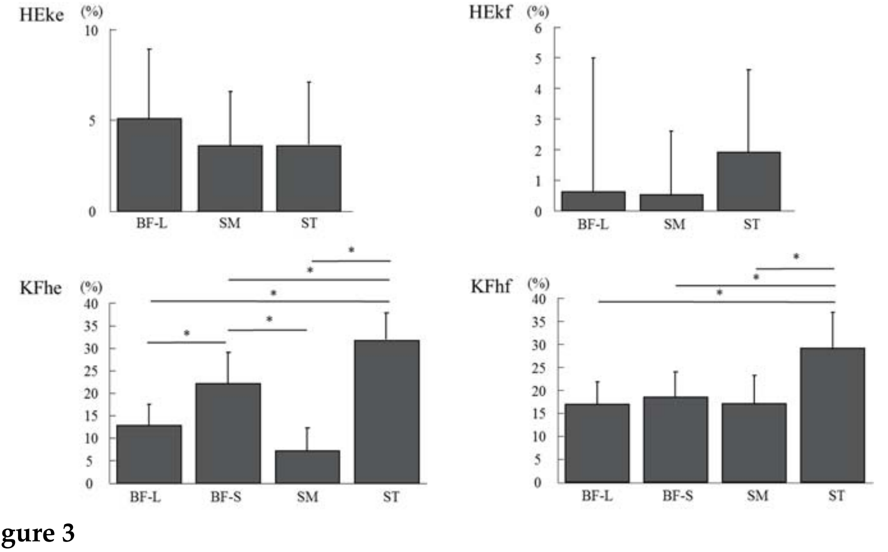

Figure 3

The rate of T_2 increase in the hamstring muscles before and after hip extension and knee flexion exercises

HEke = hip extension with the knee fully extended, HEkf = hip extension with the knee flexed at 90°, KFhe = knee flexion with the hip fully extended, and KFhf = knee flexion with the hip flexed at 90°. BF-L = long head of biceps femoris, BF-S = short head of biceps femoris, ST = semitendinosus, and SM = semimembranosus. Asterisks show significant difference between muscles ($p < 0.05$). Data = mean ± SD.*

Figure 2 displays the comparison of T_2 increase values among the 4 exercise conditions in each muscle. The BF-L showed significantly greater T_2 increase value in the KFhf condition than both HEke and HEkf conditions, and in the KFhe condition than the HEkf condition ($p < 0.05$). The T_2 increase values of the ST were significantly greater in the 2 knee flexion exercises compared to the 2 hip extension exercises ($p < 0.05$). Moreover, the SM had the greatest T_2 increase value under the KFhf condition compared to the other conditions ($p < 0.05$).

T_2 increase values of the hamstring muscles under each exercise condition are shown in Figure 3. The ST showed significantly greater T_2 increase value than other muscles under the KFhe condition ($p < 0.05$). Additionally, the BF-S had a significantly greater T_2 increase value than the BF-L and SM ($p < 0.05$). T_2 increase values of the ST were significantly greater than other muscles under the KFhf condition ($p < 0.05$).

Discussion

The HEke condition showed a significantly greater peak torque than the HEkf condition. The BF-L, ST, and SM were lengthened under the HEke condition, which possibly made the FL of these muscles better for force production during the hip extension exercise (Chleboun et al., 2001; Kwon and Lee, 2013; Watanabe et al., 2016). Kwon and Lee (2013) also demonstrated that maximal torque in isometric hip extensions was greater when the BF-L, ST, and SM were in a lengthened position by extending the knee. Significantly increased T2 values of the BF-L, ST, and SM suggest that the muscle fibers within these muscles were greatly recruited during the HEke exercise. Previous studies (Jeon et al., 2016; Kwon and Lee, 2013) also revealed that electromyography activities of the BF-L and ST during the hip extension exercise were significantly higher at the knee angle of 0° than 90°. However, the T2 increases of the BF-L, ST, and SM under the HEke condition were relatively small. Considering that the hamstring muscles have a larger moment arm at the hip joint than at the knee joint (Visser et al., 1990), the mechanical advantage might lead to lower metabolic demand (relatively small T2 increase) during exercise.

The KFhf condition showed a significantly greater peak torque and total work values than the KFhe condition. According to the results of post-exercise T2 values, the hamstring muscles were activated during knee flexion exercises, regardless of the hip joint angle. However, the BF-L, ST, and SM were more lengthened under the KFhf condition than under the KFhe condition. This state possibly led to better exercise performance under the KFhf condition. The peak torque of knee flexion becomes greater with an increasing hip flexion angle, regardless of the muscle contraction mode or velocity (Bohannon et al., 1986; Guex et al., 2012; Lunnen et al., 1981; Worrell et al., 1989). The FL of the hamstring muscles is more sensitive to changes in the hip position with the knee position constant compared to changes in the knee position with the hip position constant (Chleboun et al., 2001; Visser et al., 1990).

The BF-L, ST, and SM showed significant differences in the rate of T2 increase among 4 exercise conditions. Since a T2 increase strongly depends on the mean force generated by a muscle during exercise (Fisher et al., 1990), greater mean force production during exercise translates into greater T2 elevations in the active muscles. Post-exercise T2 elevation has also been shown to correlate with integrated electromyography activity during exercise (Adams et al., 1992). In the present study, the findings of post-exercise T2 elevation suggest that the BF-L, ST, and SM were more involved in knee flexion than hip extension. Previous studies (Schoenfeld et al., 2015; Worrell et al., 2001) also obtained similar results though electromyography activities of the hamstring muscles. Worrell et al. (2001) observed very marked electromyography activity of the gluteus maximus and very low electromyography activity of the hamstring muscles during isometric hip extension exercise regardless of the hip angle. Jacobs et al. (1996) also showed, using Hill-based muscle models, that the relative contribution of the BF-L and ST to hip extension during the jumping and sprinting push-off phases was relatively low. Taking these findings into consideration, it is possible that the gluteus muscles, especially the gluteus maximus which has the largest muscle volume, was preferentially recruited as the main extensor of the hip joint instead of the hamstring muscles during hip extension exercise (Jeon et al., 2016; Kwon and Lee, 2013; Worrell et al., 2001). Moreover, the present study showed that the recruitment of the ST during knee flexion exercise was the greatest among the hamstring muscles. Therefore, the contribution of the ST to the production of knee flexion torque might be the greatest among the hamstring muscles.

The present study has some limitations. MRI measurements are not affected by cross-talk from the surrounding muscles that is occasionally observed in surface electromyography measurements. However, unlike electromyography measurements, MRI cannot evaluate the extent of muscle activity at a specific joint angle in the range of motion. Additionally, the range of motion in hip extension and knee flexion exercises was limited by the property of the dynamometer and/or the flexibility of the hamstring muscles. Thus, there is a possibility that exercise performance and muscle recruitment pattern change are dependent on the range of motion. This point should be evaluated in future studies. Moreover, the small sample size is a limitation of our study.

In conclusion, performance of dynamic hip extension and knee flexion exercises becomes high when the hamstring muscles are in a lengthened condition. The BF-L, ST, and SM are more involved in knee flexion compared to hip extension. In particular, the ST is most recruited among the hamstring muscles during knee flexion exercise.

Acknowledgements

This study was supported by a Grant-in-Aid for Scientific Research (C) from Japan Society for the Promotion of Science.

References

Abbott BC, Baskin RJ. Volume changes in frog muscle during contraction. *J Physiol*, 1962; 161: 379-391

Adams GR, Duvoisin MR, Dudley GA. Magnetic resonance imaging and electromyography as indexes of muscle function. *J Appl Physiol*, 1992; 73(4): 1578-1583

Bohannon RW, Gajdosik RL, LeVeau BF. Isokinetic knee flexion and extension torque in the upright sitting and semireclined sitting positions. *Phys Ther*, 1986; 66(7): 1083-1086

Cagnie B, Dickx N, Peeters I, Tuytens J, Achten E, Cambier D, Danneels L. The use of functional MRI to evaluate cervical flexor activity during different cervical flexion exercises. *J Appl Physiol*, 2008; 104(1): 230-235

Chleboun GS, France AR, Crill MT, Braddock HK, Howell JN. In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. *Cells Tissues Organs*, 2001; 169(4): 401-409

Fisher MJ, Meyer RA, Adams GR, Foley JM, Potchen EJ. Direct relationship between proton T2 and exercise intensity in skeletal muscle MR images. *Invest Radiol*, 1990; 25(5): 480-485

Fukunaga T, Roy RR, Shellock FG, Hodgson JA, Edgerton VR. Specific tension of human plantar flexors and dorsiflexors. *J Appl Physiol*, 1996; 80(1): 158-165

Gordon AM, Huxley AF, Julian FJ. Variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol*, 1966; 184(1): 170-192

Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *J Athl Train*, 2012; 47(4): 390-395

Herzog W, Read LJ. Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *J Anat*, 1993; 182(Pt 2): 213-230

Jacobs R, Bobbert MF, van Ingen Schenau GJ. Mechanical output from individual muscles during explosive leg extensions: the role of biarticular muscles. *J Biomech*, 1996; 29(4): 513-523

Jeon IC, Hwang UJ, Jung SH, Kwon OY. Comparison of gluteus maximus and hamstring electromyographic activity and lumbopelvic motion during three different prone hip extension exercises in healthy volunteers. *Phys Ther Sport*, 2016; 22: 35-40

Kellis E, Galanis N, Kapetanos G, Natsis K. Architectural differences between the hamstring muscles. *J Electromyogr Kinesiol*, 2012; 22(4): 520-526

Kellis E, Galanis N, Natsis K, Kapetanos G. Muscle architecture variations along the human semitendinosus and biceps femoris (long head) length. *J Electromyogr Kinesiol*, 2010; 20(6): 1237-1243

Kwon YJ, Lee HO. How different knee flexion angles influence the hip extensor in the prone position. *J Phys Ther Sci*, 2013; 25(10): 1295-1297

Lieber RL, Friden J. Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve*, 2000; 23(11): 1647-1666

Lunnen JD, Yack J, LeVeau BF. Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Phys Ther*, 1981; 61(2): 190-195

Mohamed O, Perry J, Hislop H. Relationship between wire EMG activity, muscle length, and torque of the hamstrings. *Clin Biomech*, 2002; 17(8): 569-579

Onishi H, Yagi R, Oyama M, Akasaka K, Ihashi K, Handa Y. EMG-angle relationship of the hamstring muscles during maximum knee flexion. *J Electromyogr Kinesiol*, 2002; 12(5): 399-406

Schoenfeld BJ, Contreras B, Tiryaki-Sonmez G, Wilson JM, Kolber MJ, Peterson MD. Regional differences in muscle activation during hamstrings exercise. *J Strength Cond Res*, 2015; 29(1): 159-164

Visser JJ, Hoogkamer JE, Bobbert MF, Huijing PA. Length and moment arm of human leg muscles as a function of knee and hip-joint angles. *Eur J Appl Physiol Occup Physiol*, 1990; 61(5-6): 453-460

Watanabe K, Otsuki S, Hisa T, Nagaoka M. Functional difference between the proximal and distal compartments of the semitendinosus muscle. *J Phys Ther Sci*, 2016; 28(5): 1511-1517

Woodley SJ, Mercer SR. Hamstring muscles: architecture and innervation. *Cells Tissues Organs*, 2005; 179(3): 125-141

Worrell TW, Karst G, Adamczyk D, Moore R, Stanley C, Steimel B, Steimel S. Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *J Orthop Sports Phys Ther*, 2001; 31(12): 730-740

Worrell TW, Perrin DH, Denegar CR. The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *J Orthop Sports Phys Ther*, 1989; 11(3): 104-107

Yanagisawa O, Niitsu M, Yoshioka H, Goto K, Itai Y. MRI determination of muscle recruitment variations in dynamic ankle plantar flexion exercise. *Am J Phys Med Rehabil*, 2003; 82(10): 760-765

Corresponding author:

Osamu YANAGISAWA
Faculty of Business Information Sciences, Jobu University, 634-1,
Toyazuka-machi, Isesaki, Gunma, Japan 372-8588
Phone: +81- 270-32-1011, FAX: +81-270-**32**-1126,
E-mail: yanagisawa@ic.jobu.ac.jp