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Different morphology and function of hip extensor muscles between sprint runners and sprint cyclists

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During a specific task, the whole-body motion favors those with muscles suited for its execution; in addition, it leads to adaptations in muscle morphology and function of muscles. Thus, the well suited and/or adapted muscles are particularly crucial for enhancing performance in each competitive sport. Here, we compared muscle morphology, strength, and EMG activity during isometric maximal voluntary contraction (MVC) at multiple hip angles in runners and cyclists with similar sagittal motion (but different ranges of motion) during competition. Ten sprint track runners and ten sprint track cyclists performed the MVC test of hip extension, and magnetic resonance images of the buttocks and thighs were acquired. Maximum hip extension torque and surface electromyography (EMG) signals from the gluteus maximus (GM) biceps femoris long head (BFlh) and semitendinosus (ST) muscles were assessed during the MVC test at six hip flexion angles (45°, 60°, 75°, 90°, 105°, and 120°). Muscle volumes were determined using magnetic resonance images. Cyclists had a significantly higher MVC torque normalized by the muscle volume than that observed in runners at a hip flexion angle of 120°. At hip flexion angles of 105° and 120°, the normalized root mean square of the EMG signal in cyclists was significantly higher than in runners. Torque-angle relationship in hip extension differed between runners and cyclists, with cyclists generating greater extension torque by increasing GM muscle EMG activity in the flexed position. This may differ in the neuromuscular adaptation to and/or suitability for specific tasks of hip extensor morphology and function in runners and cyclists.

Keywords Magnetic resonance image, Anatomical cross-sectional area, Hip extension torque, Muscle excitation

Abbreviations

ACSA	Anatomical cross-sectional area
BFlh	Biceps femoris long head
BFls	Biceps femoris short head
COM	Center of mass
EMG	Electromyography
GM	Gluteus maximus
MRI	Magnetic resonance image
MVC	Maximal voluntary contraction
RMS	Root mean square
SM	Semimembranosus
ST	Semitendinosus

Activation of skeletal muscles initiates movement in related body segments, ultimately generating whole-body motion. During a specific task, the whole-body motion favors those with muscles suited for its execution; in addition, it leads to adaptations in muscle morphology and function of muscles[1–5]. Thus, the well suited and/or adapted muscles are particularly crucial for enhancing performance in each competitive sport.

In sports science, task-specific muscle morphology and function can be elucidated through comparisons of muscular characteristics among different types of athletes[3,6,7]. In the body, relatively large muscles close to the center of mass (COM) function as force generators and influence sports performance[8–11]. In particular, the

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muscles around the hip joint that extend the leg backward play a crucial role in numerous whole-body motions. Therefore, various studies have been conducted to investigate their hip extensor morphology[8,12–19]. Regardless of the movement patterns, both hip and knee extensor muscles have been shown to be associated with faster forward movement performance such as running[11,18] and cycling[16]. While previous studies have investigated the moment-angle relationship in knee extension[3,7], no research has clarified this relationship in hip extension.

For sprint runners, who specialize 100-m, 200-m, and 400-m events, an important task is to achieve a high maximum running speed by pushing off the ground and maintaining it until the finish line[20,21]. Running speed is primarily generated by an exercise in which the lower limb is repeatedly extended and flexed in the sagittal plane at a high rate[22]. Repeated competition-specific exercises and daily training lead to adaptation to specific muscle profiles associated with a task[15]. Therefore, runners have significantly greater hip and thigh muscle mass compared to that in the general population, adapted to and/or suited for running motion[11,13,17,19]. Hip extension plays a vital role in achieving high running speed. Previous studies have reported significant development in the gluteus maximus (GM) muscle, responsible for hip extension, and the posterior thigh muscles[11,13,17,19].

Similar to running, cycling is an exercise involving repeated extension and flexion of the lower limbs in the sagittal plane. During cycling, the crank power required to move the COM is generated by the hip and knee extension torques[23]. Therefore, cyclists as well as runners have been reported to have morphologically larger GM and thigh musculature than those in the general population[24]. However, in these sports, the same lower limb extensor strength may be applied in varying postures. For instance, the hip flexion angle at which the maximum hip extension torque is observed is approximately 100° for cyclists[25] and 40° for runners[26], indicating that cyclists adopt a more flexed position. A recent previous study reported that protocols involving muscle contraction from a state of greater stretch resulted in significantly greater muscle hypertrophy than those starting from a position of less stretch[27]. Based on these findings, the morphological characteristics of muscles may differ between running and cycling even though their modes of locomotion are similar. However, the morphological characteristics of the muscles of the two athletes (runners and cyclists) with similar movement tasks have not yet been examined.

The magnitude of muscular force depends on the force-length relationship[28], which is affected by the joint angle. Classically, muscle fiber length and structure are similar between individuals[29]. However, several previous studies have reported slight variations in the force-length relationship of muscles[3,30]. Herzog et al. discovered that the rectus femoris muscle exhibits different characteristics in its force-length relationship between runners and cyclists[3], suggesting adaptations to their chronically imposed functional tasks. Adaptation of muscle force-length relationships to the task would also be expected in the hip extensor muscle groups that generate propulsive forces during both running and cycling. Specifically, cyclists have been reported to have a maximum hip flexion angle of 122°, indicative of a pronounced degree of flexion[31]. Hip flexion causes stretching of the GM and posterior thigh muscles; thus, the hip flexor muscles may be used in a relatively more stretched position in cyclists than in runners.

This study aimed to determine the task-specific strategies of athletes in two sagittal plane tasks (running and cycling) performed at different joint angle ranges. The specific purpose was to determine the differences in the volumes of hip extensor muscles and their activations at various joint angles during the strength test between runners and cyclists. We hypothesized that (1) cyclists who chronically produce the maximum extension torque in a more flexed position would have larger hip extensor muscle volumes than those in runners, and (2) compared to runners, cyclists would have greater hip extension torque and higher hip extensor muscle activations in a more flexed position.

Results

Body characteristics

Body masses of runners and cyclists were 63.6 ± 4.4 kg and 71.6 ± 3.5 kg, respectively (Table 1), and a significant difference was observed between them ($Z = 2.857$, $P < 0.002$). Other characteristics, including height, thigh length, and muscle length of the SM, ST, BFlh, BFsh, and GM were not significantly different between the groups (Table 1).

	Runners	Cyclists	*P*
Age [year]	21.0 ± 0.6	19.8 ± 1.2	n.s.
Height [m]	1.71 ± 0.06	1.72 ± 0.02	n.s.
Mass [kg]	63.6 ± 4.4	71.6 ± 3.5	0.002
Thigh length [cm]	40.7 ± 1.7	41.2 ± 1.2	n.s.
Muscle length [cm]			
Semimembranosus	26.8 ± 2.1	26.1 ± 1.5	n.s.
Semitendinosus	31.2 ± 2.5	30.8 ± 1.5	n.s.
Biceps femoris long head	26.4 ± 2.0	25.9 ± 1.8	n.s.
Biceps femoris short head	23.9 ± 2.4	24.1 ± 1.2	n.s.
Gluteus maximus	28.1 ± 1.4	27.3 ± 1.7	n.s.

Table 1. Morphological characteristics of participants. Values are mean ± standard deviation. *n.s.* not significant.

Muscle volume

The medians (and quantiles) of the absolute and normalized muscle volumes are presented in Table 2. The absolute and normalized muscle volumes of the ST in runners were significantly higher than those in cyclists (absolute: $Z = -2.561$, $P = 0.005$; normalized: $Z = -3.152$, $P = 0.001$). In contrast, the absolute and normalized muscle volumes of the SM, BFlh, BFsh, and GM were not significantly different between the two groups.

Hip extension torque during MVC test

Absolute hip extension torque is demonstrated in Fig. 1. A Friedman test demonstrated a significant main effect of the group in absolute hip extension torque ($\chi^2 = 9.504$, $P = 0.002$); significant differences were observed between the two groups in 90° and 120° conditions (90°: $Z = 1.773$, $P = 0.038$; 120°: $Z = 1.839$, $P = 0.033$). The Friedman test also yielded significant effects, highlighting the angle condition as the primary factor ($\chi^2 = 61.305$, $P < 0.002$). Both groups demonstrated significantly higher values for the conditions at 60° and above than those observed for conditions at 45° (all conditions $Z = -2.889$, $P < 0.001$ in runners and cyclists). Cyclists displayed significantly higher values for the above 75° conditions than for 60° condition (at 75°: $Z = -2.712$; 90°: $Z = -2.712$; 105°: $Z = -2.801$; 120°: $Z = -2.801$, all conditions $P < 0.003$), with 120° condition displaying higher values than the 75° condition ($Z = -2.801$, $P = 0.003$). In runners, the absolute hip extension torque was higher in the 105° condition than that in the 60° condition ($Z = -2.889$, $P = 0.002$).

For the normalized hip extension torques (Fig. 2), a significant main effect of hip extension angle condition on the hip torque normalized by muscle volume was observed in cyclists ($\chi^2 = 12.332$, $P < 0.001$). No significant main effects were observed for either variable in the runners. The Mann–Whitney *U* test demonstrated that the hip extension torque normalized by the muscle volume of cyclists was significantly higher than that of runners in the 120° condition ($Z = 2.495$, $P = 0.006$). There was not a significant main effect of hip extension angle condition on the hip torque normalized by body mass.

RMS of EMG signals during MVC test

A Friedman test revealed a significant main effect of group in normalized muscle EMG activity of GM ($\chi^2 = 6.603$, $P = 0.010$); significant differences were noted between the two groups in the 105° and 120° condition (105°: $Z = 1.904$, $P = 0.028$; 120°: $Z = 1.773$, $P = 0.038$; Fig. 3).

Discussion

This study examined the hypothesis that differences in specific hip-extensor muscle morphology and function between runners and cyclists, who move forward as a daily specialized tasks under different sagittal plane joint angle ranges. Our findings were as follows: the ST muscle volume of runners was significantly larger than that of cyclists. In contrast, no significant differences were identified between the two groups in terms of the muscle volumes of the other hip extensor muscles. Both the absolute and muscle volume-normalized values of the hip extension torque of cyclists were significantly higher than those of runners in the flexed position. At the same time, cyclists demonstrated a significantly higher RMS of the EMG signals of the GM muscle in the flexed position relative to runners. The results of this study suggest that runners and cyclists might adapt to specific tasks that require the exertion of a large hip extension torque while maintaining an optimal flexed position.

A previous study reported that repeated contractions from more stretched states produced greater muscle hypertrophy in the hamstrings during resistance training[27]. In this study, we hypothesized that cyclists would have a significantly greater hip extensor muscle volume than that observed in runners. This is because both groups engaged in specialized maximal-effort exercises for similar durations, with cyclists operating in a maximum hip flexion position of 122°[31], which is higher than the 100° observed in runners[26]. However, no significant differences were observed in any of the muscles in this study, except for ST (Table 2). However, these results do not support our first hypothesis.

	Runners	**Cyclists**	***P***
Absolute muscle volume [cm^3]			
Semimembranosus	243.4 (228.7, 264.3)	270.9 (239.8, 290.8)	n.s.
Semitendinosus	248.9 (223.9, 293.1)	210.3 (197.4, 228.9)	0.005
Biceps femoris long head	235.6 (197.5, 258.0)	210.6 (199.3, 228.9)	n.s.
Biceps femoris short head	103.7 (97.6, 116.2)	114.8 (100.8, 124.4)	n.s.
Gluteus maximus	1049.7 (989.0, 1151.1)	1089.0 (989.1, 1197.9)	n.s.
Normalized muscle volume [$cm^3 \cdot kg^{-1} \cdot m^{-1}$]			
Semimembranosus	2.08 (1.95, 2.48)	2.16 (1.89, 2.42)	n.s.
Semitendinosus	2.29 (2.23, 2.47)	1.70 (1.55, 1.81)	0.001
Biceps femoris long head	2.01 (1.62, 2.34)	1.76 (1.52, 1.87)	n.s.
Biceps femoris short head	0.96 (0.90, 1.06)	0.97 (0.79, 1.02)	n.s.
Gluteus maximus	9.77 (9.05, 10.26)	9.10 (8.06, 9.59)	n.s.

Table 2. Absolute and normalized values of muscle volumes of runners and cyclists. Value are medians (lower quartile, upper quartile). Comparison between groups was examined using the Mann–Whitney *U* test ($P < 0.05$).

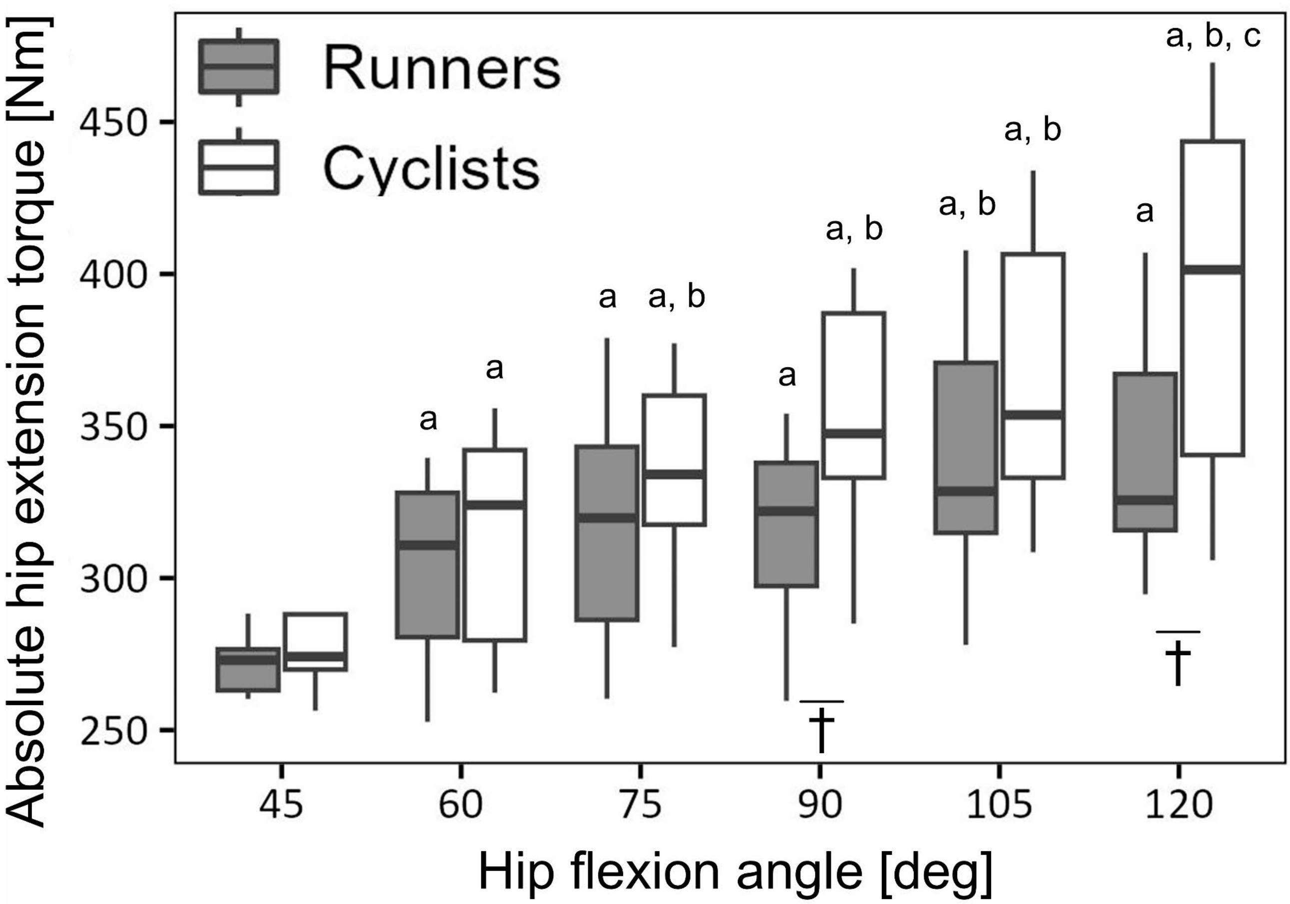

Fig. 1. Absolute hip extension torque performed on maximal voluntary contraction test with six hip flexion angle conditions. $^{a}P < 0.01$ indicates a significant difference from 45° condition; $^{b}P < 0.01$ indicates a significant difference from 60° condition; $^{c}P < 0.01$ indicates a significant difference from 75° condition; $^{\dagger}P < 0.05$ indicates a significant difference between groups.

Ema et al. reported that the volumes of ST and BFsh muscles in cyclists were higher than those in non-athletes[8]. Moreover, several previous studies have reported that the hip extensor muscle volumes are significantly higher in runners than in non-athletes[13,17,19]. In particular, the GM, ST, and BFlh of elite runners have been shown to be significantly higher than those of sub-elite runners[11]. A recent longitudinal study reported a significant increase in ST muscle volume following 12 months of sprint training for elite runner[15]. In this study, runners had significantly larger absolute and normalized volumes of ST muscle than those in the cyclists (Table 2). Therefore, the muscle morphology, in particular, ST muscle volume in runners might exhibit competition-specific adaptations compared to that in cyclists.

A previous study reported hip extensor muscle EMG activity with changes in running speed using high-density surface EMG[32]. Their results demonstrated significant muscle EMG activity beyond MVC in the BFlh and ST muscles during the stance and swing phases of high-speed sprinting, indicating that muscle activity occurred at an intensity that could not be assessed during general strength training[33]. The fusiform architecture of the ST muscle is designed to enable rapid muscle action[34]. Runners are required to perform a hip extension-flexion motion at high speeds considering that the step frequency can reach a maximum of about 4.12 Hz during a 400-m event[21]. In contrast, in cyclists, the frequency of motion in a 1000 m event is approximately 2.1 Hz[35], which is less than that in runners. Additionally, during the latter half of swing phase in sprint running, the ST muscle performs eccentric contraction[36], which greatly contributes to the muscle hypertrophy[37]. Thus, the specific hypertrophy of the ST muscle observed in runners might be the result of adaptation to specific high-frequency tasks and eccentric contraction.

In this study, the hip extension torque and muscle volume were measured in two types of athletes (400 m runners and 1 km time trial cyclists). At a hip flexion angle of 90° with a 90° knee flexion angle, a hip extension torque is reported to be 4.65 Nm/kg for the healthy young males[38]. The participants in this study had greater hip extension torque, which was approximately 9.65% for runners and 7.13 for cyclists higher than that reported by Tayashiki et al.[38]. This suggests that hip extensor muscles of runners and cyclists contribute to the greater

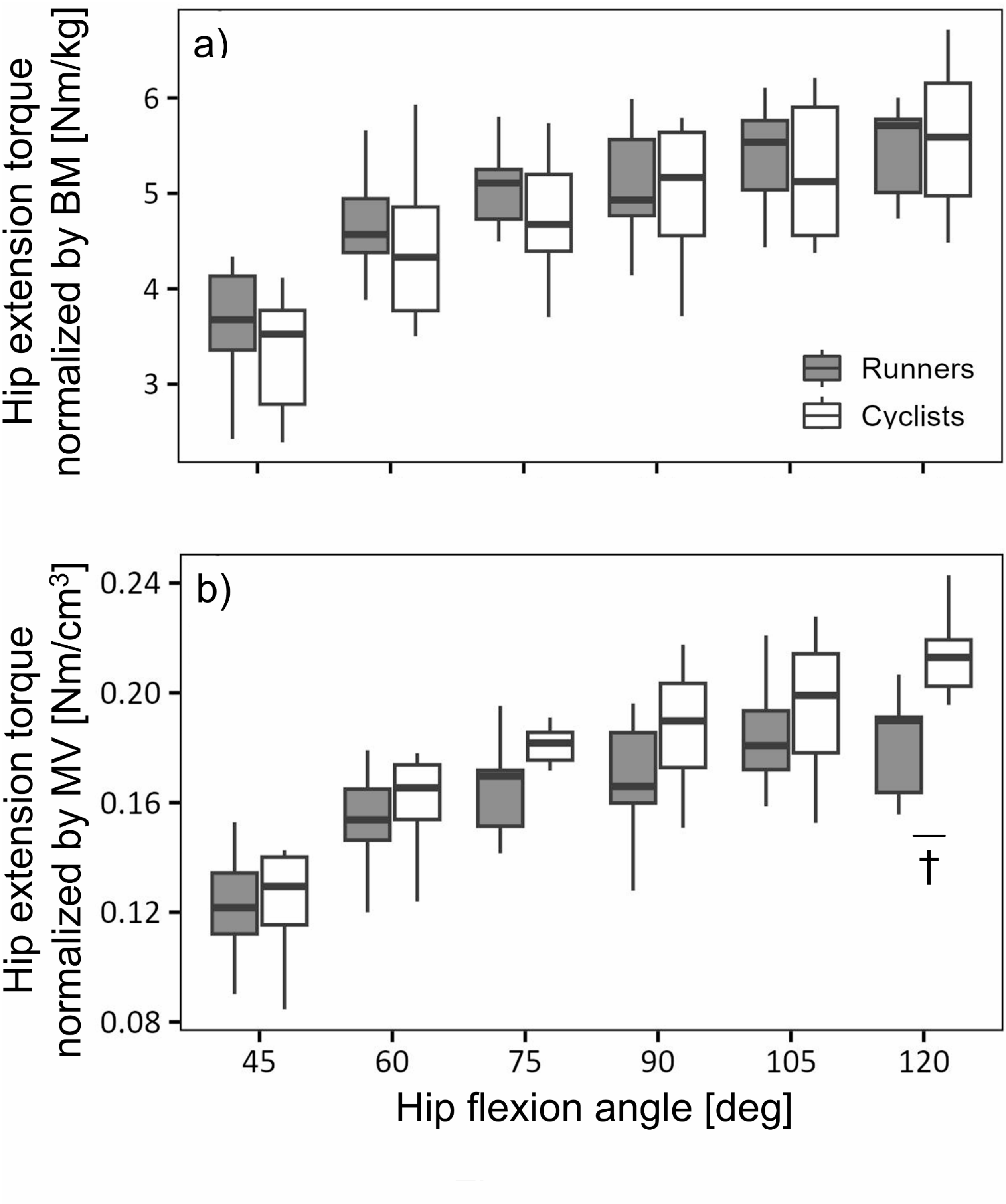

Fig. 2. Hip extension torques normalized by body mass (BM, panel **a**) and muscle volume (MV, panel **b**) performed on maximal voluntary contraction test with six hip flexion angle conditions. †$P < 0.01$ indicates a significant difference between groups.

hip extension torque than those of healthy young males. Hip extension movement plays an important role in the competitive performance of runners and cyclists and the acquisition of whole-body translational velocity. Therefore, the findings of this study suggest that the participants in this study were athletes who specifically adapted to and/or suited for hip extension exercises in the sagittal plane.

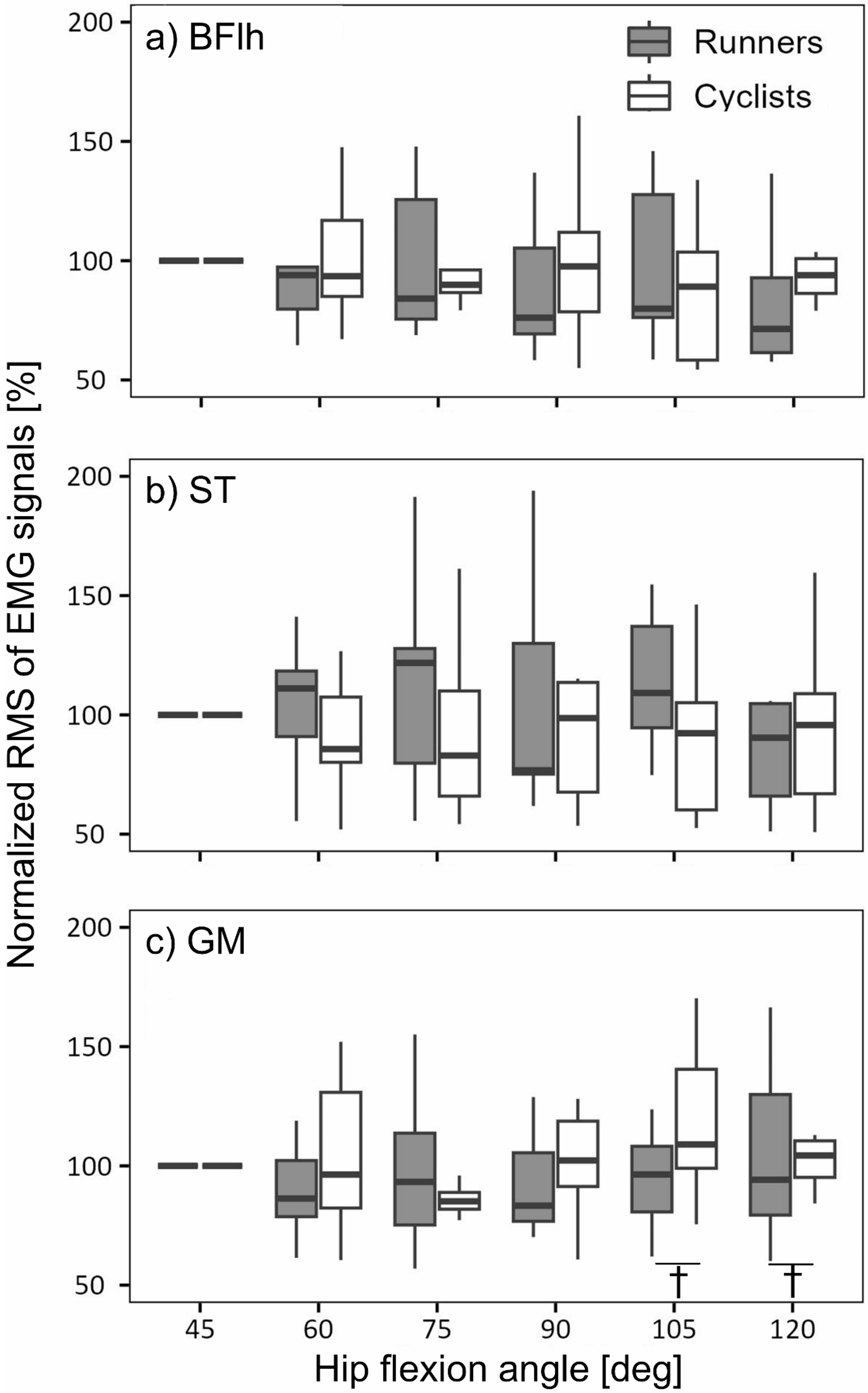

Fig. 3. Normalized root mean squire (RMS) of electromyography (EMG) signals in biceps femoris long head (BFlh, panel **a**), semitendinosus (ST, panel **b**), and gluteus maximus (GM, panel **c**) muscles during the isometric maximal voluntary contraction test performed under six hip flexion angle conditions. $^{\dagger}P < 0.05$ indicates a significant difference between groups.

Based on findings that muscle hypertrophy adapts differently depending on the muscle stretch length during resistance training[27] and that muscle force-length relationships adapt to and/or suit for specific tasks[3,7], we postulated a second hypothesis that the torque-angle relationship of hip extension varies between runners and cyclists. The data on the torque-angle relationship in this study support our second hypothesis. Comparing the absolute values of hip extension torque, a trend of increasing torque was observed in cyclists with increasing flexion angles, whereas no change was observed in runners with flexion angles > 60° (Fig. 1). The cyclist produces maximum hip extension torque when the crank is at approximately 90° and the hip angle is approximately 100°[25]. In contrast, runners generate hip extension torque from the late swing phase to mid-stance with hip flexion angles ranging from 20–70°[26,39]. Therefore, cyclists may adapt to generate hip extension torque in a relatively more flexed hip position, whereas runners may adapt to generate hip extension torque in a relatively less flexed hip position, which is potentially reflected in the results of this study. This difference of angle-torque relationship according to athletic characteristics has been reported in several previous studies investigating knee extensors[3,7], and our results demonstrated similar characteristics in the hip extensors of cyclists and runners.

Muscle strength is closely associated with the muscle size[40]. In the 120° hip flexion condition, the extension torque normalized by the absolute muscle volume was significantly higher in cyclists than in runners (Fig. 2). This result did not reflect the volume of the ST muscle, which was smaller in cyclists than in runners. The ST muscle is a fusiform muscle, which is advantageous for generating contraction force at the higher contraction velocities. Therefore, the larger ST muscle size of runners may reduce its contribution to generate the hip extension torque during an isometric strength test. On the other hand, during hip extension in the flexed position, compared with runners, cyclists exhibited significantly higher activation of the GM muscle (Fig. 3). These results suggest that cyclists increase muscle excitation, that is, motor unit recruitment and firing frequency, to generate significant extension torque at the flexed hip position. A similar finding has been reported that highly trained athletes can significantly increase the EMG amplitude of the rectus femoris muscles and improve knee extension strength[41].

There are some limitations in this study. The first is that we measured EMG amplitude of hip extensor muscle according to the SENIAM method, in which the EMG electrode was attached at the midpoint of the muscles. This approach may have resulted in the absence of the innervation zone locations of the analyzed muscles. Some previous studies reported that with the innervation zone locations of the ST, BFlh, and GM clustered in the proximal region, with no innervation zone locations at intermediate positions[42,43]. In contrast, other reported that the location of the innervation zones is difficult to detect with high-density surface EMG in pinnate muscles such as the BFlh[44]. In addition, the muscle activity during the MVC differs in a region-specific manner[33,45,46]. Considering these factors, the EMG activity in this study must be interpreted carefully. The second limitation is that muscle strength was measured under isometric conditions, which differ from the dynamic hip flexion and extension movements involved in athletic activities such as running and cycling. Future studies should investigate the relationship between sport-specific muscle volume distribution and the force-velocity or torque-angular velocity characteristics of the hip extensors to better understand their functional relevance in dynamic performance. Third limitation is that moment arms of hip extensor muscles were not measured so as to evaluate the effect of muscle EMG activation on generating the extension moment. It has a direct effect on the moment production capacity of the muscles; however, that measurement may be challenging. This is because, unlike the knee and ankle joints, where tendons extend across the joints, the hip extensor muscles, such as the thick gluteus maximus, cross the hip joint, making it difficult to determine how to define the moment arm. A final limitation is that magnitudes of the external forces applied to feet varied between runners and cyclists. Runners are required to continuously support their body mass and to propel their center of mass against gravity with each step. The differing mechanisms of force generation by the lower-limb muscles, involving the hip extensors, in response to these external forces may influence muscle hypertrophy. Consequently, the biomechanical demands of running and cycling diverge, leading to distinct adaptations in the involved musculature.

In conclusion, the present study demonstrates that the torque-angle relationship in hip extension differs between runners and cyclists, with cyclists generating greater extension torque by increasing GM muscle EMG activity in the flexed position. The observed differences in the torque-angle relationship of the muscle between runners and cyclists complement previous findings by Herzog et al.[3] and Savelberg and Meijer[7], which suggest that muscle EMG activity plays a role in shaping this relationship. In addition, ST muscle volume in runners was significantly larger than those in cyclists. This difference in ST muscle volume may be more relevant to dynamic conditions, such as eccentric and concentric contractions, rather than the isometric contractions measured in this study. Although this study does not directly associate the difference in ST muscle volume with distinct functional roles in hip extension, it suggests a potential influence on dynamic hip extension tasks. Thus, our results provide evidence of adaptation to and/or suitability for specific tasks of hip extensor morphology and function.

Methods
Participants
Eleven male track runners (major disciplines: 400 m dash, personal record: 49.46 ± 1.56 s, year of competitive experience: 7.1 ± 2.1 year) and eleven male track cyclists (major disciplines: 1000 m time trial, personal record: 66.784 ± 2.525 s, year of competitive experience: 5.0 ± 1.0 year) participated in this study (Table 1). All of them were of a level that would allow them to compete in national university games. Both groups had a specific competition duration of approximately 50–60 s for each event. Therefore, both groups can be considered athletes who utilize similar energy supply systems (mainly the yield of glycolysis) to perform their exercises. Additionally, runners can be characterized as a group that generates peak hip extension torque at less flexed hip angles, while cyclists can be characterized as a group that generates peak hip extension torque at more flexed hip angles. Following an explanation of the testing procedures, the participants provided written informed consent before participating in the study. The experimental procedures were approved by the Ethics Committee of Nippon Sport Science university (approval number: 021-H124) and conducted in accordance with the Declaration of Helsinki.

Experimental design

The participants visited the laboratory on three separate days. At the first visit, the participants performed the familiarization task of the isometric maximal voluntary contraction test (MVC test) for hip extension. The main MVC test was performed during the second visit. Magnetic resonance images (MRIs) of the buttocks and thighs were acquired during the third visit to the laboratory. The participants were instructed to refrain from performing any strenuous physical activity or drinking alcohol for 24 h before the study.

Measurements of MVC's torque and root mean square (RMS) of electromyographic (EMG) signals

The MVC test was performed using an isokinetic dynamometer (Biodex Multi-Joint System 4; Biodex Medical Systems, Shirley, NY, USA). They performed the MVC test twice under each of the six hip flexion angle conditions (45°, 60°, 75°, 90°, 105°, and 120°). Participants were seated in a supine position with a parallel backrest and their right thighs were secured using an attachment connected to an input shaft equipped with a strain gage to measure torque. In this study, the hip flexion angle was defined as the angle formed by the pelvic vector connecting the superior posterior iliac spine to the superior anterior iliac spine and the femoral vector connecting the greater trochanter to the femoral condyle. The hip flexion angles could be monitored and accurately adjusted in the dynamometer, moving the shaft slowly. The thigh and shank were stabilized using an L-shaped metal frame to maintain a 90° knee joint angle throughout the test (Fig. 4a), ensuring that changes in the knee joint did not affect EMG activity[47]. In addition, to prevent changes in pelvic angle during the MVC test, participants were secured to the seat with a fabric belt (Fig. 4b). In all conditions, only the right leg was used, and the order of the six conditions was determined randomly. When the difference between the first and second measurements exceeded 5.0%, a third measurement was performed, and the trial with the average value across all trials was selected for analysis[36]. Prior to the MVC measurements, a practical and warm-up session consisting of a few submaximal isometric strength tests of hip extension at the three hip flexion positions of 45°, 90°, and 120° to familiarize the participants with the task required and allow for warm-up. To evaluate the EMG activity of the hip extensor muscles during MVC, surface EMG was recorded from the BFlh, ST, and GM muscles using surface EMG electrodes (DL-142; S&ME, Tokyo, Japan) at 1000 Hz. The electrode locations for the BFlh, ST, and GM were determined according to the recommendations of SENIAM[48]. The EMG signals were filtered using a fourth-order Butterworth filter (bandwidth was 20–400 Hz). The RMS was calculated in the selected 0.5 s of peak MVC torque (± 0.25 s) for evaluation of the strength of surface EMG signals in each channel. The RMS of the EMG signals in all conditions was normalized with respect to that in the 45° condition for comparison between the two groups. Hip extension torques were normalized by the body mass (hip extension torque normalized by body mass) and sum of absolute values of SM, ST, BFlh, BFsh, and GM muscle volumes (hip extension torque normalized by muscle volume).

Measurement of muscle volume and anatomical cross-sectional area (ACSA)

MRI scans for the right-side buttock and thigh (echo time: 2.3 ms, repetition time: 294.4 ms, field of view: 450 mm, slice thickness: 10 mm, interval: 10 mm, flip-angle: 80°, matrix: 320 × 192) were obtained using a 1.5-T MR scanner system (Echelon OVAL; Hitachi Medico Inc., Tokyo, Japan). The participants were positioned supine on the MRI table during the scan. A polyurethane cushioning material was placed over the back of the waist and lower legs to prevent deformation of the back of the thighs and a band brace was used to secure both the right and left legs to prevent external rotation. In addition, the cushioning material was placed over the lower ribs, pelvis, and patella to prevent pressure from the spinal coil positioned over the upper part of the body. The edges of the semimembranosus (SM), semitendinosus (ST), biceps femoris long head (BFlh), biceps femoris short head (BFsh), and GM muscles were manually outlined by the same researcher using the Osiris software (The University Hospital of Geneva, Switzerland). Care was taken to exclude visible adipose

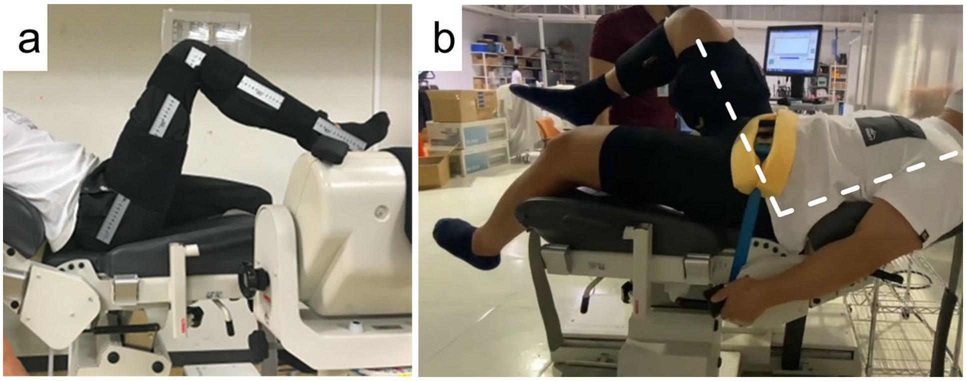

Fig. 4. Fixation method for knee joint and pelvis during the isometric maximal voluntary contraction (MVC) measurement. (**a**) The knee joint was fixed at 90° using a rectangular metal plate secured with nylon straps during the MVC measurement. (**b**) The pelvis was stabilized with an adjustable belt to minimize movement and ensure consistent positioning throughout the MVC measurement (90° hip flexion angle condition). The backrest was inclined at 20°.

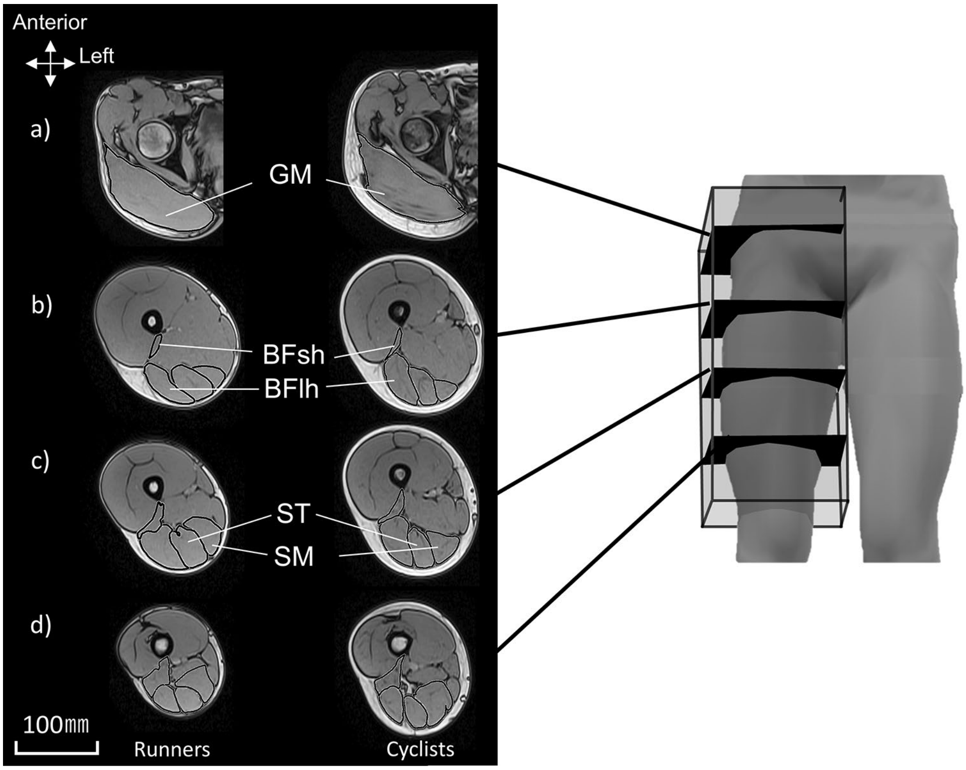

Fig. 5. An example of a magnetic resonance image of the right foot of a runner and a cyclist. (**a**) This image displays the maximum area of the gluteus maximus (GM) muscle obtained from the analysis. (**b**–**d**) These images display magnetic resonance images of each part of the thigh (**b** 70%, **c** 50%, **d** 30% of the distal thigh length). *SM* semimembranosus, *ST* semitendinosus, *BFlh* biceps femoris long head, *BFsh* biceps femoris short head.

tissue and connective tissue incursions. Representative MRI scans for measuring the ACSAs of the buttock and thigh muscles are displayed in Fig. 5. The intra-investigator effect was validated by outlining the maximum circumferential circumference of each muscle twice, resulting in a coefficient of variation of 1.5 ± 1.8% and an intraclass correlation coefficient of 0.99. The volume of each muscle was determined by adding the ACSA to the slice thickness (10 mm). Thigh length was determined by measuring the length from the head of the greater trochanter to the articular cleft of the knee joint using sagittal MRI. To minimize the impact of body size on the differences in muscle size between runners and cyclists, normalized muscle volumes were calculated using absolute muscle volumes were divided by body height and mass.

Statistical analysis
All the analyses were performed using MATLAB (version 9.8, Math Works, Natick, MA, USA). A Shapiro-Wilk test was performed on the data obtained in this study to examine normality. However, in the case of rejection, a Friedman test was performed. In the case of a significant Friedman test p-value (< 0.05), the Wilcoxon signed-rank test was used to assess significant changes in the hip flexion angle conditions within the MVC torque and EMG. The Mann–Whitney *U* test was used to compare participant characteristics, MVC torque, EMG, and muscle morphology data. Statistical significance for multiple comparisons was adjusted using Bonferroni correction to avoid alpha-level inflation. All parameters are presented as medians with 25th and 75th percentiles.

Data availability
The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Received: 30 October 2024; Accepted: 10 April 2025
Published online: 11 May 2025

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Acknowledgements
The authors acknowledge the participants for their participation and the coaches for their cooperation.

Author contributions
YY, TN, NW, WF, MM and MO conceived and designed research; YY., NW and OM performed experiments; YY, NW and MO analyzed data; YY and OM interpreted results of experiments; YY and OM prepared figures; YY drafted manuscript; YY, NW and MO edited and revised manuscript; All authors read and approved the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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