

**Relationships between cross sectional area of lower limb muscles and forward
velocity on underwater undulatory swimming**

Running Title: CORRELATION BETWEEN MUSCLE AND UUS VELOCITY

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Abstract

This study aimed to investigate the relationship between cross-sectional area (CSA) of lower limb muscles and UUS velocity on swimmers. Eighteen male swimmers at the regional to national level participated in this study. Kinematic data during maximum-effort UUS were collected using an underwater motion capture system to determine the mean UUS velocity. T1-weighted cross-sectional magnetic resonance (MR) images of the lower limb muscles were acquired using a 3T MR imaging system to determine the CSA of 17 muscles on the swimmers' right side. Relationships between UUS velocity and the CSA of lower limb muscles were examined using correlation coefficients. A positive significant correlation was found between CSA of rectus femoris and UUS velocity (absolute value: $r = 0.475$ $p = 0.046$, relative value: $r = 0.548$ $p = 0.019$). However, UUS velocity was not significantly correlated to CSA of other lower limb muscles ($r = -0.445 \sim 0.469$). These results suggest that the CSA of rectus femoris has a moderate relationship between UUS velocity among the lower limb muscles, regardless of the body size. Revealing the relationships between muscle size and UUS velocity can provide an important insight regarding which lower limb muscles should be strengthened to enhance UUS performance for swimmers, coaches and researchers.

- 41 **Keywords:** magnetic resonance image equipment, lower limb muscle, swimming
- 42 performance, motion capture system

競泳選手における下肢筋の断面積と水中ドルフィンキック泳速度の関係

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要旨

本研究は、競泳選手における下肢筋群の CSA と UUS 速度との関係を明らかにすることを目的とした。本研究では、18 名の地方大会から全国大会出場レベルの男子競泳選手を対象とした。最大努力での UUS の運動データを水中モーションキャプチャシステムで取得し、UUS の平均泳速度を算出した。下肢筋群の T1 強調磁気共鳴画像 (MRI) は 3T MRI 装置を用いて取得し、対象者の右脚の 17 個の骨格筋の CSA を算出した。両指標の相関関係をピアソンの積率相関係数を用いて算出した。その結果、大腿直筋の CSA と UUS の泳速度との間に有意な正の相関関係が認められた (絶対値: $r = 0.475$ $p = 0.046$, 相対値: $r = 0.548$ $p = 0.019$)。一方、他の下肢筋の CSA と UUS 速度の間に有意な相関は認められなかった ($r = -0.445 \sim 0.469$)。よって、体格の大きさに関わらず下肢の筋の中でも大腿直筋の CSA が高い UUS の速度発揮に関連することが示唆された。骨格筋サイズと UUS の速度との関係の解明は、競泳選手、指導者、研究者に UUS 速度を高めるための有益な情報を提供できる可能性がある。

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64 キーワード：磁気画像診断装置，下肢筋横断面積，泳パフォーマンス，モーシ

65 ョンキャプチャシステム

Introduction

Swimmers were permitted to propel underwater up to 15 m after start and turn, especially butterfly, backstroke and freestyle events (1); therefore, they generally performed the underwater undulatory swimming (UUS) during these phases. Swimmers can maintain their high swimming velocity produced by the push-off start during the underwater phase following a turn compared to surface swimming (2), as they can avoid wave drag during UUS (3). Furthermore, a previous study suggested that producing high velocity during the start and turn phases is significantly associated with improved overall race performance (2). Although the underwater phase after the start and turn consists of both a glide and an underwater kick phase, previous studies have highlighted the importance of producing high velocity through UUS during these phases (2, 4). These findings suggest that UUS is one of the important factors for achieving their great race time.

Some athletes require large muscle size to achieve great sports performance. This may be because many outstanding sports performances are significantly related to muscle strength, which is influenced by factors such as neural activation levels (5) and large muscle cross-sectional area (CSA) (6). Swimming velocity is determined by the balance between the propulsive and braking fluid forces generated by swimmer's motion. Thus, previous studies have investigated the relationship between swimming performance and muscle size. The large muscle thickness of thigh and arm muscles were significantly

related to the fast front crawl time (7, 8). Moreover, one repetition maximum of bench press, squat and lat pull down back were significantly correlated with high swimming velocity (9, 10). These findings indicate that large muscle size, which is related to greater muscle strength, may be one of the factors contributing to achieving the high swimming velocity. Muscle size can be measured by ultrasonography or magnetic resonance (MR) imaging. MR imaging allows measurement of CSA for both superficial and deep muscles. Therefore, the relationships between CSA including all relevant muscles and swimming performance can be revealed using this method.

In UUS, swimmers propel underwater through downward and upward movement of the lower limbs; therefore, they may necessarily have the large lower limb muscle size to produce the forward high velocity. Previous studies have reported that high angular velocities of the hip, knee, and ankle joints are significantly related to high UUS velocity (11-13). Mechanically, these high joint angular velocities in the lower limbs increase toe vertical velocity and kick frequency, both of which are important parameters for achieving high UUS velocity (14-16). From a hydrodynamic perspective, the high feet velocity generates greater propulsive fluid force, resulting in increased UUS velocity (17). Based on these previous studies (11-16), swimmers would require great lower limb muscle strength to correspond the large propulsive fluid force applied to their feet. Thus, the large lower limb muscle size is likely to be related to the high UUS velocity; however, it has never been investigated. Understanding the relationship between muscle size and

UUS velocity can provide fundamental insights for training and swimming science. The current results, therefore, offer valuable information for swimmers, coaches, and researchers regarding which lower limb muscles should be strengthened to enhance UUS performance. The purpose of this study, therefore, was to investigate the relationship between the lower limb muscle sizes and the velocity of UUS on swimmers. The high toe vertical velocities, which the most important factor to produce the high UUS velocity may be produced by the hip flexion and knee extension during downward kick, whereas the corresponding velocity may be induced by the hip extension and knee flexion during upward kick (14-16). Therefore, the present study hypothesized that the large CSA of lower limb hip and knee flexion/extension muscles are related to the high UUS velocity.

Materials & Methods

Participants

Eighteen college male swimmers participated in this study (age; 20.7 ± 1.2 years, body height; 1.72 ± 0.06 m, body mass; 67.0 ± 7.5 kg). The participants included four butterfly, three backstroke, two breaststroke, six freestyle and two individual medley swimmers. World Aquatics Point Score of swimmers' personal best for long course was 573.15 to 774.81. We calculated the minimum sample size using G*power before conducting the experiment (18). The sample size was determined as 13 with the assumption of $1-\beta = 0.80$ power and $\alpha = 0.05$ significance level and correlation $\rho = 0.70$

using two-tailed test. The p level was determined based on a previous study that reported correlation coefficients ranging from 0.639 to 0.802 between muscle CSA and sprint running time (19), and the standard interpretation of correlation coefficient (20). Written informed consent was obtained from the participants before conducting the experiment. This study was approved by the Ethics Committee of Ritsumeikan University (BKC-LSMH-2022-061) and was conducted in accordance with the guidelines of the Declaration of Helsinki.

Experimental setting and data collection

The swimming trial was conducted in an indoor pool (25 m $\times$ 7 lanes, depth: 1.35 m, water temperature: 30 °C). The fifteen reflective makers were attached to the participants' body. The landmarks were as follows: both of anterior superior iliac spine, posterior superior iliac spine, greater trochanter, right side of the midpoint of thigh, lateral femoral epicondyle, medial femoral epicondyle, midpoint of lower leg, lateral malleoli, medial malleoli, calcaneus, epiphysis of the first metatarsal, epiphysis of the fifth metatarsal (Fig. 1). After 10 min self-selected warm-up, participants performed three 20 m UUS trials at their maximal effort using a push-off start with 3 min rest between trials to avoid fatigue (13). The three-dimensional coordinate data of reflective markers were collected by underwater motion capture system with six cameras at sampling rate of 100 Hz (Qualysis, Sweden) (Fig. 2). Swimmers were instructed to maintain their body more

than 0.75 m from water surface to avoid the wave drag effect and to hold their breath during UUS trials (3).

T1-weighted cross-sectional MR images of lower limb muscles were collected by 3T MR image equipment (Magnetom Skyra; Siemens Healthcare). The scanning range was between xiphoid process and right foot of participants. The scanning condition of trunk was as follows: field of view, 420×420 mm; matrix, 512×512 ; slice thickness, 5 mm; TR, 140 ms; TE, 2.46 ms; gap, 5 mm. The scanning condition of right leg was as follows: field of view, 260×260 mm; matrix, 512×512 ; slice thickness, 5 mm; TR, 700 ms; TE, 11 ms; gap, 5 mm (21). The scanned muscles were as follows: psoas major (PM), gluteus maximums (GM), adductor longus (AL), adductor brevis (AB), adductor magnus (AM), rectus femoris (RF), vastus lateral (VL), vastus internal (VI), vastus medial (VM), biceps femoris short head (BFS), biceps femoris long head (BFL), semitendinosus (ST), semimembranosus (SM), tibialis anterior (TA), extensor digitorum longus (EDL) gastrocnemius (GAS) and soleus (SOL). Participants were instructed in prone positions for scanning all muscles except the GM, whereas they were offered in supine positions for scanning the GM. When scanning was conducted in prone position, participants fully extended their hip and knee joints with the ankle joint at 90 degrees. Participants kept fully extending their hip, knee and ankle joints when they were scanned in supine positions. These scanning positions were based on a previous study (22).

The body fat-free mass (FFM) of participants was obtained to normalize muscle CSA by body composition analyzer (InBody770, InBody).

Data analysis

The three-dimensional coordinate data during UUS were smoothed by the fourth-order Butterworth low pass filter with a cut-off frequency of 6 Hz (23). The x, y and z axes were defined as the long, short and vertical axis of the pool lane, respectively (Fig. 2). A kick cycle was defined from the instance of the highest right epiphysis of the fifth metatarsal marker to the instance of the next highest corresponding marker (13, 17). The x component of velocity for midpoint of greater trochanter was determined as a UUS velocity. The kick frequency was determined as the reciprocal of the duration of each kick cycle. The kick length was calculated from the mean UUS velocity and kick frequency for each cycle. The vertical amplitude was defined as the difference between the highest and lowest positions of the epiphysis of the fifth metatarsal. The maximum toe vertical velocity was obtained for both the upward and downward kick phases. Average value was calculated from three continuous kick cycles and adopted to the analysis (24).

The CSA of scanned lower limb muscles were determined from cross-sectional images of right side by image processing software (Horos Project). The CSA of PM was measured at the middle level of the L4 and L5. The CSA of GM was measured at the greater trochanter level. The CSA of AL, AB and AM were measured at proximal 30 %

of the thigh length. The CSA of RF, VL, VI and VM were measured at 50 % of the thigh length. CSA of BFS, BFL, ST and SM were measured at proximal 70 % of the thigh length. CSA of TA, EDL, GAS and SOL were measured at proximal 30 % of the shank length. These CSA measurements were conducted based on previous studies (22, 25) (Fig. 3). The CSA of adductor muscles (ADD) was measured as summed of AL, AB and AM. The CSA of quadriceps femoris (QF) was obtained as summed of RF, VL, VI and VM. The BFS, BFL, ST and SM were summed to obtain the CSA of hamstrings (HAM). The CSA of dorsal (DF) and planter (PF) flexor muscle were determined as summed of TA and EDL, and GAS and SOL, respectively. The CSA measurement was repeated by the same examiner on another day and the mean values of the twice processing was used for statistical analysis. To exclude the effect of body mass and fat, these muscle CSA were normalized by two-thirds power of participants' FFM (26, 27). The mean value of intraclass correlation coefficient (ICC) and coefficient variance (%CV) of each CSA of lower limb muscles were determined. The ICC (1, 2) values ranged from 0.784 to 0.999 and the %CV values ranged from 0.8 % to 5.8%, indicating high measurement reliability.

Statistical analysis

Analyzed data are presented as mean $\pm$ standard deviation. The normality of collected data was confirmed using Shapiro-Wilk test. 88.6 % (39 of 44 measures) of all collected data were normally distributed. Previous studies conducted parametric

statistical tests when more than 90 % of the variables were normally distributed to maintain consistency (28-30). Differences between the corresponding values in previous studies and the present study may be due to differences in the number of the outcome measures and sample size. The number of normally distributed variables in this study was similar to those reported in previous studies (28-30); therefore, correlation coefficients in the present study were also determined using parametric statistical tests to maintain consistency. The correlation coefficients between UUS velocity and lower limbs CSA were determined using Pearson's correlation coefficient. The correlation coefficients between UUS velocity and lower limbs CSA were determined using Pearson's correlation coefficient. In this study, the correlation coefficient for 0.00-0.10, 0.10-0.39, 0.40-0.69, 0.70-0.89 and 0.90-1.00 indicates "negligible", "weak", "moderate", "strong" and "very strong", respectively (20). The significance level was set at $p < 0.05$. All statistical analysis was conducted by SPSS statistics ver. 29 (IBM Corp, Armonk, NY, USA).

Results

The mean value of FFM for participants was 57.1 ± 5.6 (kg). Table 1 and 2 represents the absolute and relative values of CSA for analyzed muscles and kinematic data during UUS, respectively. A positive significant moderate correlation was found between the absolute and relative CSA of RF and UUS velocity (Table 3). The CSA of PM, GM, AL, AB, AM, VL, VI, VM, BFS, BFL, ST, SM, TA, EDL, GAS, SOL, ADD,

QF, HAM, DF and PF were not significantly correlated to the mean value of UUS velocity (Table 3).

Discussion

This study investigated the relationships between the CSA of lower limb muscles and UUS velocity on regional to national level male swimmers. A positive significant moderate correlation was found between the absolute and relative CSA of RF and UUS velocity; however, CSA of other muscles were not significantly related to the corresponding velocity. Therefore, the hypothesis of this study was partly supported. These results indicate that the CSA of RF has the relationship with UUS velocity among the lower muscles, regardless of body size.

A moderate positive correlation was found between UUS velocity and both the absolute and relative values of RF CSA (Table 3). The hip flexion and knee extension were found during the downward kick on UUS, and the muscle activation of RF was also found during the corresponding phases (31). A previous study reported that RF activation became stronger during the downward kick as swimmers produce the high UUS velocity compared to moderate effort (32). Previous studies suggested that the high UUS velocity was induced by the high swimmers' toe velocity during downward kick (11, 13). The reason could be that the high toe vertical velocity induces an increase in the propulsive fluid force applied to the swimmers' feet during UUS (11, 13). An increase in propulsive

fluid force is induced by changes in vortex structure caused by the generation of large momentum in the flow field during UUS (33). Mechanically, the higher their toe vertical velocity during the downward kick is induced by the quick hip flexion and knee extension on UUS. Moreover, a previous study suggested that the human with large muscle size could activate their muscles stronger than the human who have small muscle size (6). To summarize these studies and the current results, the swimmers with large CSA of RF might be able to perform the UUS with high toe velocity since they could achieve the quick hip flexion and knee extension during the downward kick. In addition, although a large RF size may contribute to producing greater propulsive fluid force, a larger muscle size could also increase the braking fluid force during UUS. A previous study suggested that swimmers with larger muscle size exhibit a trade-off between propulsive and braking fluid forces (34). Therefore, the negative effect of a large CSA of the RF on braking fluid force may affect its positive effect on propulsive fluid force, which could explain the moderate correlation observed with UUS velocity. This result indicates that a large RF size, regardless of body size, may have a greater positive effect on producing high UUS velocity than the negative effect associated with generating braking fluid force.

No significant correlation was found between muscle CSA and UUS velocity, excepting the CSA of RF for current swimmers. The PM contributes to the hip flexion during downward kick on UUS. The QF excepting RF induces the knee extension during downward kick on UUS. During the upward kick, the HAM and GM contribute to the hip

extension (31, 32). The ADD may induces the hip flexion, extension and adduction during one kick cycle during UUS. The DF and PF muscles were used to maintain planter flexion angles by co-activation during UUS (31). However, a previous study suggested that the QF, HAM, ADD, DF and PF may not be utilized more than RF during UUS with swimmers' nearly maximum effort (32). Therefore, these muscle sizes may not be a significant factor to achieve the high UUS velocity. On the other hand, the high muscle activation was found for GM during upward kick on UUS with high forward velocity (32). Previous studies reported that the lower limb motion during the upward kick was significantly related to achieve the high UUS velocity (11, 13). The reason was indicated by a systematic review (35) as follows: 1) the study (11) had high validation in competitive levels, 2) the only high-level swimmers (World Aquatic Point Score > 800) may be able to achieve the high upward kick performance during UUS (13). Also, a systematic review suggested only swimmers with highly competitive level can improve their swimming velocity of UUS with increasing kick frequency (14). The competitive level of the current swimmers was regional to national level according to the previous study (35); therefore, the differences of competitive level also may lead to the differences in correlation between muscle size and UUS velocity. Moreover, the validation of the corresponding level was lower than previous studies (11, 13). Hence, no significant correlation was found between the CSA of GM and UUS velocity in the current study. For the same reason as RF, PM size might also induce the high UUS velocity during

downward kick; however, the current results showed no significant correlation (Table 3). These suggest that the muscle sizes of lower limb muscle excepting the RF may not be significant determinant to produce the high UUS velocity for current swimmers' competitive level.

The current study has three important limitations regarding the interpretation of the results. The current results are specific to regional to national level swimmers according to the previous study (35). Moreover, the kinematic parameters during UUS were similar to those reported or swimmers of the corresponding level in previous studies (15) (Table 2); therefore, the current results may be applicable to these levels but not to swimmers of other levels. A previous study suggested that the important kinematic parameters of UUS for producing the high UUS velocity were different among competitive levels (14). Therefore, differences in competitive level may also lead to variations in the correlation between muscle size and UUS velocity. To address this limitation, future studies should investigate the relationship between muscle size and UUS velocity in swimmers of different competitive levels. Second, the present study could not determine whether the large size of RF was due to training effects or congenital factors. Therefore, longitudinal studies, such as training interventions, should be conducted in the future to clarify the importance of a large CSA of RF for achieving high UUS performance.

Conclusion

This study investigated the relationships between the muscle CSA of lower limb and UUS velocity on swimmers. A positive significant correlation was found between the absolute and relative CSA of RF and UUS velocity; however, CSA of other muscles were not significantly correlated with corresponding velocity. These results suggest that the CSA of RF has relationship with UUS velocity among the lower limb muscles, regardless of body size.

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Disclosure statement

The authors declare no conflict of interest.

Contributions

Experiment conception and design: HT. Data collection: HT, TT and TS. Data analysis: HT. Wrote the manuscript: HT. Reviewed and revised the manuscript: TT, TS and TI. All authors have approved to submit the manuscript.

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Tables

Table 1. Mean and standard deviation value of the absolute and relative cross-sectional area of lower limb muscles. PM: psoas major, GM: glute maximum, ADD: adductor muscles, AM: adductor maximum, AB: adductor brevis, AL: adductor longus, QF: quadriceps femoris, RF: rectus femoris, VL: vastus lateral, VI: vastus interval, VM: vastus medial, HAM: hamstrings, BFS: biceps femoris short head, BFL: biceps femoris long head, ST: semitendinosus, SM: semimembranosus, DF: dorsal flexor muscle, TA: tibialis anterior, EDL: extensor digitorum longus, PF: planter flexor muscle, GAS: gastrocnemius, SOL: soleus.

	Absolute (cm ²)			Relative (cm ² /kg ^{2/3})		
	Mean	±	SD	Mean	±	SD
PM	16.91	±	2.13	1.14	±	0.14
GM	53.80	±	7.04	3.63	±	0.41
ADD	53.19	±	9.26	3.59	±	0.43
AL	16.41	±	3.22	2.15	±	0.24
AB	4.85	±	1.45	0.33	±	0.10
AM	31.92	±	4.44	1.11	±	0.20
QF	75.19	±	9.26	5.07	±	0.47
RF	7.09	±	1.29	0.48	±	0.08
VL	27.93	±	4.49	1.88	±	0.27
VI	22.30	±	3.39	1.50	±	0.19
VM	17.85	±	2.89	1.20	±	0.16
HAM	27.13	±	4.08	1.83	±	0.27
BFS	5.81	±	0.77	0.39	±	0.06
BML	5.16	±	1.57	0.35	±	0.11
ST	4.50	±	1.47	0.30	±	0.10
SM	11.66	±	1.83	0.79	±	0.12
DF	10.11	±	1.28	0.68	±	0.08
TA	7.16	±	1.10	0.49	±	0.08
EDL	2.96	±	0.46	0.20	±	0.03
PF	43.86	±	4.90	2.96	±	0.29
GAS	22.07	±	3.25	1.49	±	0.19
SOL	21.82	±	2.40	1.48	±	0.16

434 Table 2. The kinematic data during underwater undulatory swimming

	Mean	±	SD
Swimming velocity (m/s)	1.39	±	0.12
Kick frequency (Hz)	2.29	±	0.19
Kick length (m/kick)	0.61	±	0.05
Kick amplitude (m)	0.48	±	0.04
Vertical toe velocity (m/s)			
Downward kick	-2.38	±	0.17
Upward kick	1.99	±	0.19

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Table 3. Correlation coefficient between the absolute and relative cross-sectional area of lower limb muscles and swimming velocity during underwater undulatory swimming. PM: psoas major, GM: glute maximum, ADD: adductor muscles, AM: adductor maximum, AB: adductor brevis, AL: adductor longus, QF: quadriceps femoris, RF: rectus femoris, VL: vastus lateral, VI: vastus interval, VM: vastus medial, HAM: hamstrings, BFS: biceps femoris short head, BFL: biceps femoris long head, ST: semitendinosus, SM: semimembranosus, DF: dorsal flexor muscle, TA: tibialis anterior, EDL: extensor digitorum longus, PF: planter flexor muscle, GAS: gastrocnemius, SOL: soleus.

	Swimming velocity			
	Absolute (cm ²)		Relative (cm ² /kg ^{2/3})	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
PM	0.413	0.088	0.469	0.050
GM	-0.155	0.538	-0.078	0.760
ADD	0.001	0.996	0.090	0.723
AL	0.051	0.842	0.111	0.660
AB	0.081	0.750	0.153	0.544
AM	-0.061	0.811	0.008	0.976
QF	-0.170	0.559	-0.064	0.801
RF	0.475*	0.046	0.548*	0.019
VL	0.066	0.794	0.183	0.468
VI	-0.164	0.515	-0.304	0.438
VM	-0.445	0.064	-0.438	0.069
HAM	0.241	0.335	0.307	0.215
BFS	-0.039	0.877	0.020	0.939
BFL	0.299	0.228	0.316	0.202
ST	0.307	0.215	0.354	0.150
SM	0.050	0.844	0.119	0.638
DF	-0.260	0.298	-0.183	0.468
TA	-0.114	0.570	-0.080	0.753
EDL	-0.310	0.211	-0.283	0.255
PF	0.010	0.970	0.115	0.648
GAS	0.120	0.634	0.238	0.342
SOL	-0.149	0.555	-0.075	0.767

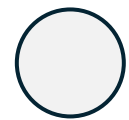
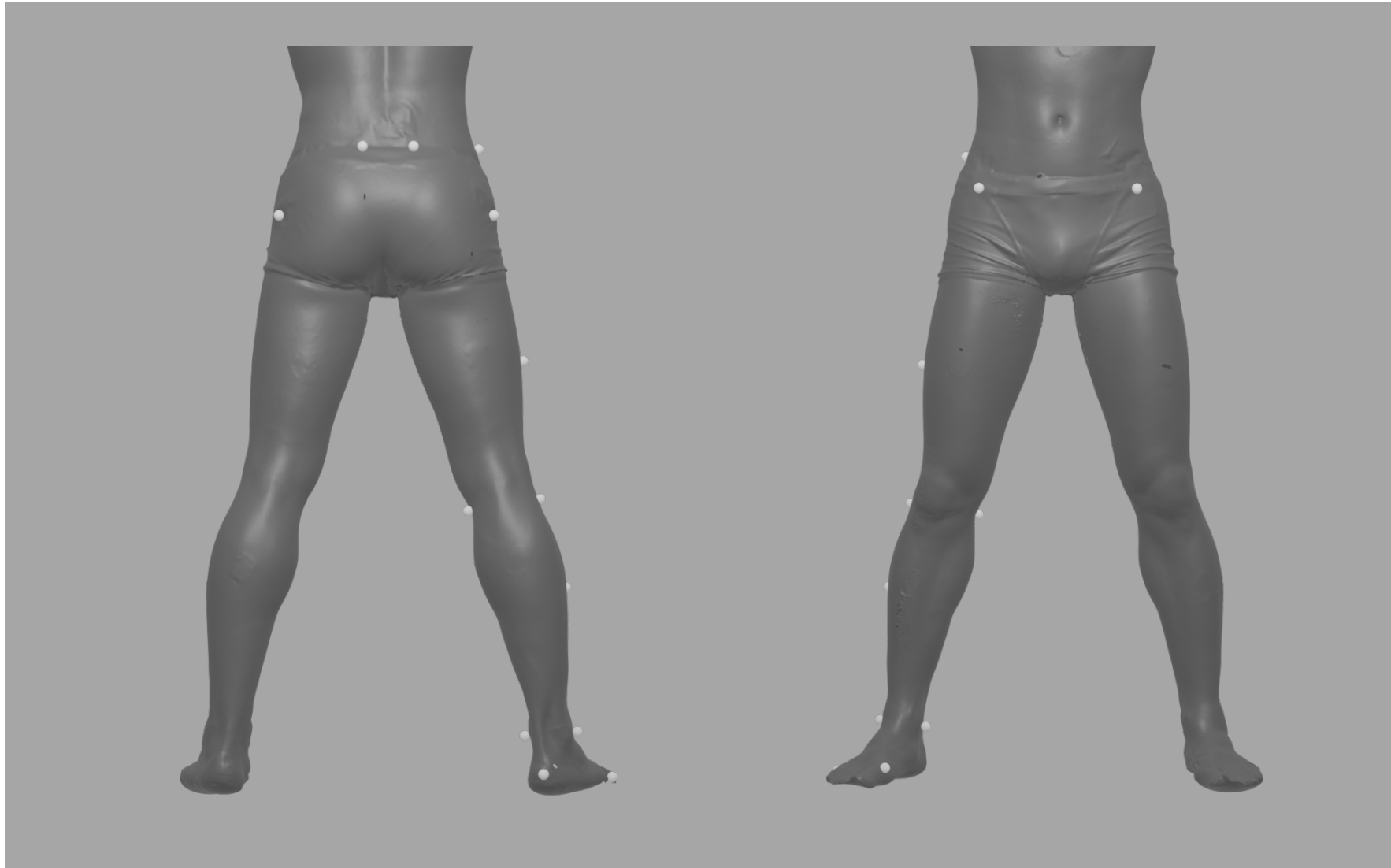
*: $p < 0.05$

Figure captions

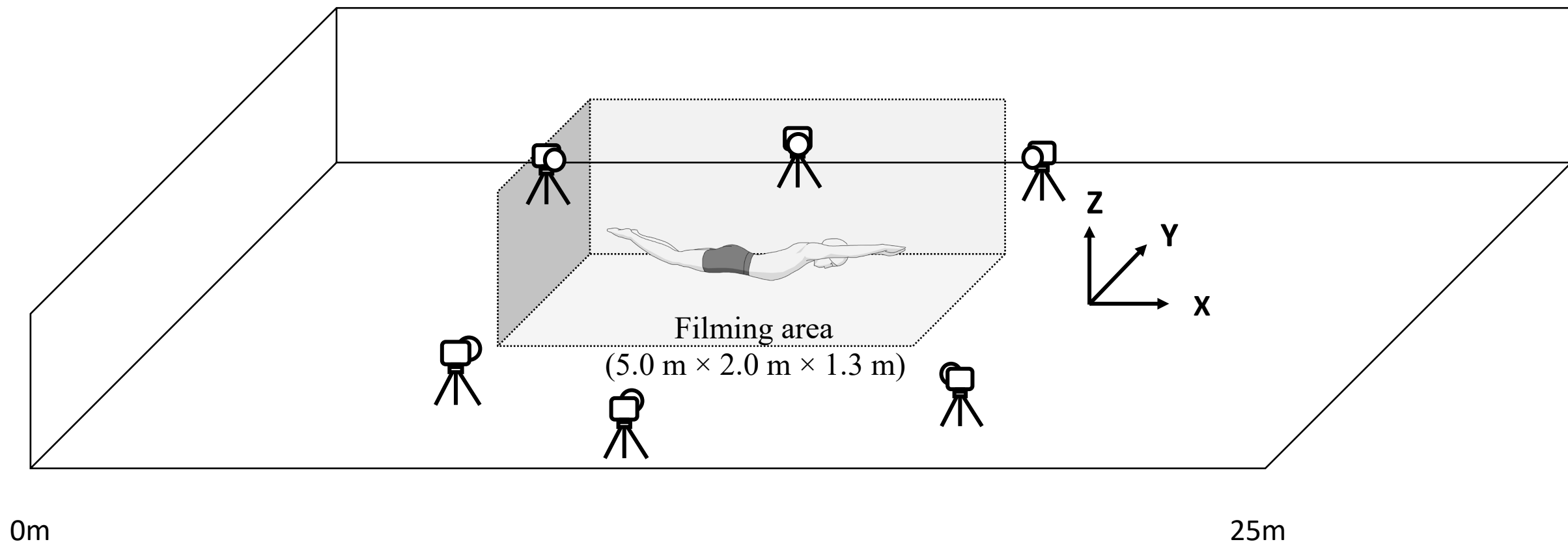
Figure 1. The marker set of this study.

Figure 2. Experimental setting. The x, y and z axes of the global coordinate system were defined as a long, short and vertical direction of the pool lane, respectively.

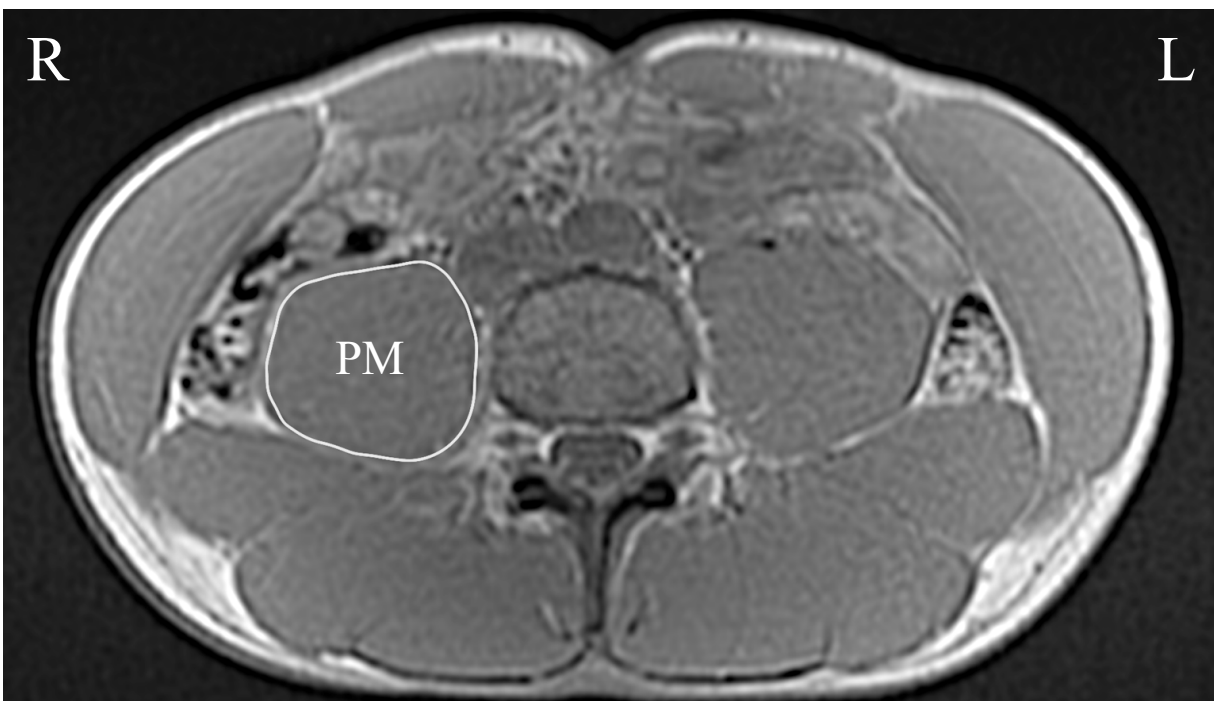
Figure 3. Transversal images of lower limb muscles scanned by magnetic resonance imaging. A: the cross-sectional area (CSA) of psoas major (PM) was obtained at the level between L4 and L5, B: The CSA of glute maximum (GM) was obtained at the level of greater trochanter, C: The CSA of adductor longus (AL), adductor brevis (AB) and adductor magnus (AM) were obtained at the proximal 30% of the thigh length, D: The CSA of rectus femoris (RF), vastus lateral (VL), vastus internal (VI) and vastus medial (VM) were obtained at 50% of the thigh length. E: The CSA of biceps femoris short head (BFS), biceps femoris long head (BFL), semitendinosus (ST) and semimembranosus (SM) were obtained at the proximal 70% of the thigh length, F: The CSA of tibialis anterior (TA), extensor digitorum longus (EDL), gastrocnemius (GAS) and soleus (SOL) were obtained at 30% proximal of the shank length.



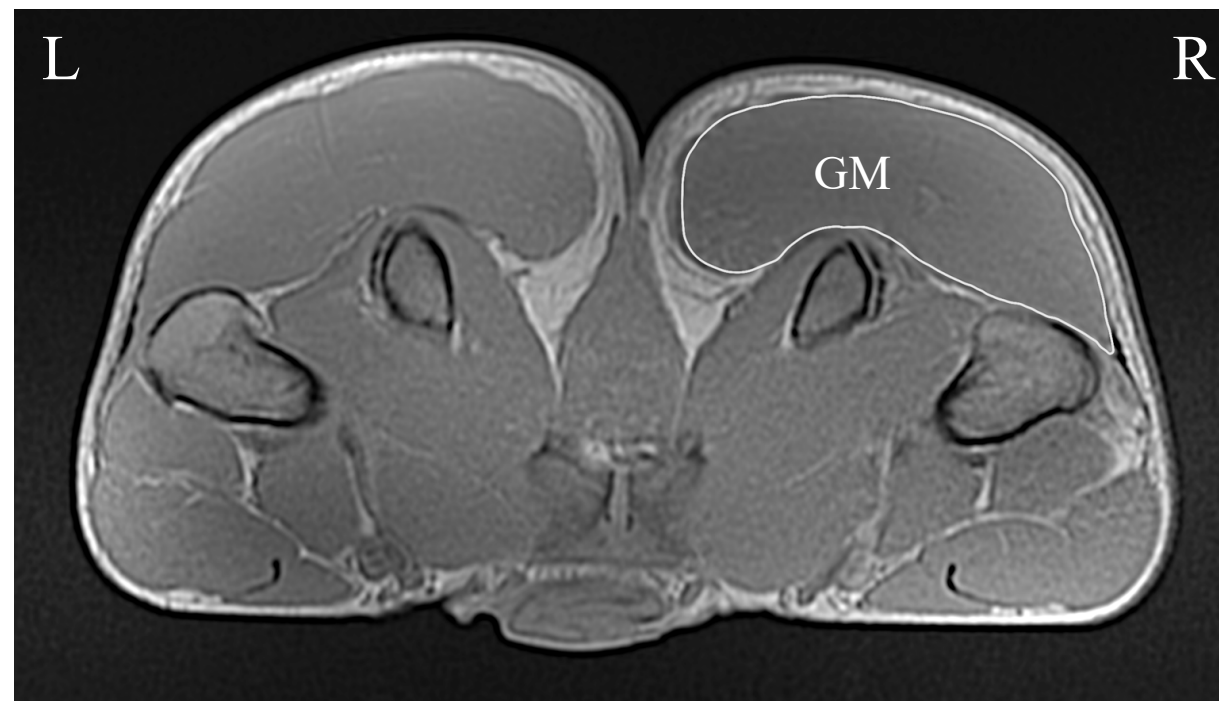
Reflective markers



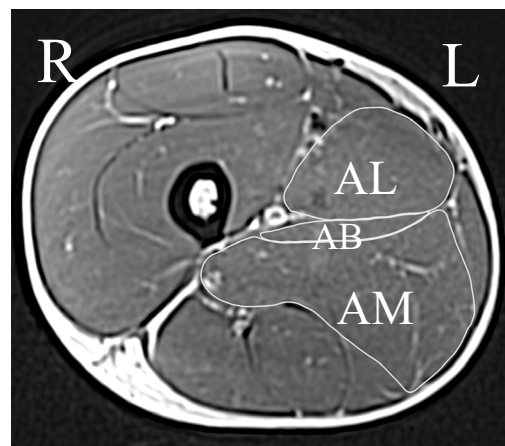
A



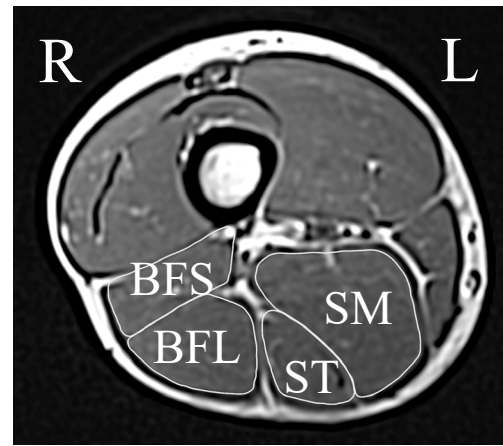
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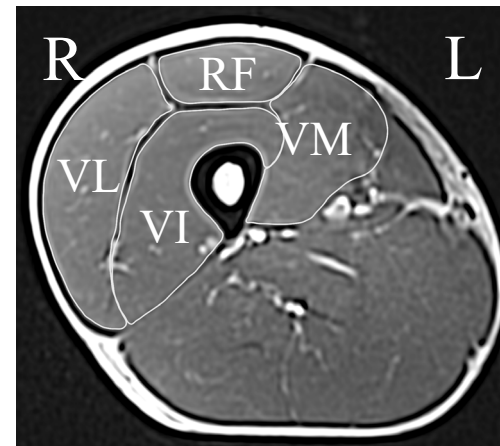
C



D



E



F

