Unique muscularity in cyclists’ thigh and trunk: A cross-sectional and longitudinal study

R. Ema¹², T. Wakahara¹, T. Yanaka¹, H. Kanehisa³, Y. Kawakami⁴

¹Graduate School of Sport Sciences, Waseda University, Saitama, Japan, ²Research Fellow of Japan Society for the Promotion of Science, Tokyo, Japan, ³Graduate School of Engineering and Science, Shibaura Institute of Technology, Saitama, Japan, ⁴Faculty of Health and Sports Science, Doshisha University, Kyoto, Japan, ⁵Department of Sports and Life Science, National Institute of Fitness and Sports in Kanoya, Kagoshima, Japan, ⁶Faculty of Sport Sciences, Waseda University, Saitama, Japan

Corresponding author: Yasuo Kawakami, PhD, Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan. Tel: +81 4 2947 6784, Fax: +81 4 2947 6784, E-mail: ykawa@waseda.jp

Accepted for publication 20 May 2015

This study examined the influence of regular training in competitive cycling on individual muscle volume of the thigh and psoas major cross-sectionally and longitudinally. T1-weighted magnetic resonance (MR) images of the trunk and right thigh were obtained from eight experienced varsity male cyclists (experience: >4 years) and 10 untrained men (experiment 1), and from 12 (10 males, two females) varsity cyclists before and after competitive cycling training for 6 months (experiment 2). From the MR images, the volumes of each of the quadriceps femoris and hamstrings, total adductors, gracilis, sartorius, and psoas major were determined. The volumes of the monoarticular thigh muscles, semitendinosus, and psoas major muscles were significantly greater in the experienced cyclists than in the untrained men (experiment 1), and increased significantly after the competitive training for 6 months (experiment 2). In contrast, the volumes of the other biarticular thigh muscles were similar among the experienced cyclists and untrained men (experiment 1), and did not change by competitive cycling training (experiment 2). The results indicate that competitive cycling training induces muscle-specific hypertrophy of the synergistic muscles, especially between the monoarticular and biarticular muscles, leading to quantitative profiles of the musculature in experienced cyclists.

Sport athletes often demonstrate event-related, unique muscular profiles that are possibly related to their competitive and training activities (Kanehisa et al., 1998; Ema et al., 2014). For instance, experienced oarsmen possess much greater muscle volume of the quadriceps femoris compared with untrained men (Ema et al., 2014), which would be due to the repetitive multi-joint leg extensions (simultaneous extensions of knee and hip joints) in rowing. Cycling also involves similar motions, and the anatomical cross-sectional area (ACSA) of the quadriceps femoris is associated with pedaling performance of competitive cyclists (Rønnestad et al., 2010). Thus, it is expected that competitive cyclists will develop the musculature of the quadriceps femoris similarly to oarsmen, thereby confirming the importance of increasing the quadriceps femoris size by training. However, no consensus has been reached regarding the cycling-specific musculature of the quadriceps femoris. Some found greater ACSA of the quadriceps femoris in experienced cyclists compared with untrained subjects or an increase in ACSA or volume after cycling training for 6–12 weeks (Linossier et al., 1997; Hug et al., 2006; McPhee et al., 2010; Harber et al., 2012), but others did not (Izquierdo et al., 2004; Rønnestad et al., 2010; Farup et al., 2012).

The above inconsistency may be related to nonuniform hypertrophy of the thigh muscles along their length (Narici et al., 1989, 1996; Ema et al., 2013; Franchi et al., 2014) because ACSA at one region does not accurately represent the entire muscle volume (Roman et al., 1993). Also, cross-sectional and longitudinal observations cannot perfectly eliminate the possibility of inherited muscular profiles in cyclists and time course differences in hypertrophic response among muscles that can be a function of training period, respectively. A combination of cross-sectional and longitudinal approaches can overcome above limitations, and this approach is useful for cyclists and coaches to identify the muscles that should be targeted during daily training activities.

The power generation capacity at the knee and hip joints substantially contributes to pedaling power development (Elmer et al., 2011), and the hamstrings and adductors as well as quadriceps femoris are highly activated during pedaling motions (Richardson et al., 1998; Endo et al., 2007). Therefore, the hamstrings and adductors can also be sizably developed in cyclists. To our knowledge, only one study has ever examined the quantitative profiles of hamstrings and adductors for cyclists (Hug et al., 2006). Hug et al. (2006) showed greater...
Muscle-specific adaptation to cycling

Experiment 1: cross-sectional approach

Subjects

Eight varsity male cyclists (20.3 ± 1.4 years, 173.3 ± 6.0 cm, 64.2 ± 6.6 kg; mean ± SD) and 10 untrained men (21.3 ± 1.5 years, 171.6 ± 3.5 cm, 65.2 ± 5.5 kg) participated in this study. All cyclists had participated in both track and road races. The cyclists had experienced competitive cycling for more than 4 years (7.0 ± 3.1 years), and had practiced cycling training for 21 ± 6 h per week at least for the past year. They had not conducted any resistance training besides regular cycling training. Their records of 200 m and 1000 m time trials in the latest season were 11.5 ± 0.2 s and 69.6 ± 1.4 s, respectively. Peak power determined by Wingate anaerobic test using a mechanically braked cycle ergometer (POWERMAX-V2, Combi, Tokyo, Japan) in the latest season was 1125 ± 141 W. Each had won a prize or participated in national college competitive meets in Japan. Four of the cyclists had participated in international competitive meets. The untrained men were sedentary or recreationally active, but none had conducted conventional sport activities or resistance training for at least 2 years. The above information was collected using a questionnaire. Prior to the experiment, the subjects were informed of the purpose and risks of the study and provided written informed consent. The studies including experiment 2 were approved by the Ethics Committee on Human Research of Waseda University.

MR imaging and data analysis

T1-weighted MR images of the whole right thigh (echo time: 10 ms, repetition time: 520 ms, matrix: 256 × 192, field of view: 240 mm, slice thickness: 10 mm, gap: 0 mm) and trunk (echo time: 15.6 ms, repetition time: 860 ms, matrix: 256 × 192, field of view: 450 mm, slice thickness: 10 mm, gap: 0 mm) were obtained using an MR scanner (Signa EXCITE 1.5T, GE Medical Systems, Waukesha, WI, USA). The subjects lay supine with their legs fully extended and muscles relaxed in the magnet bore. Taking into consideration fluid shifts of the lower extremity, the trunk images were obtained first (this procedure took 15–20 min) after a few minutes’ rest in the supine position, and then thigh images were acquired. All the subjects were instructed to refrain from drinking alcohol and from performing intensive exercise on the day before MR imaging. The ACSAs from the origin to insertion of each muscle of the quadriceps femoris (VL; vastus medialis, VM; vastus intermedius, VI; and rectus femoris, RF), hamstrings (biceps femoris long head, BF_long; BF_short; semitendinosus, ST; and semimembranosus, SM), adductors (adductor magnus, adductor longus, adductor brevis, and pectineus), Gr, Sar, and PM were measured (Fig. 1) using ImageJ software (National Institute of Health, Bethesda, MD, USA). It was difficult to separate individual muscles of the adductors along the thigh, and thus we report the data of the total adductors (ADD_total). Care was taken to exclude visible adipose and connective tissue incursions. Each image was digitized twice, and the mean of the two values was used for further analysis. The coefficient of variation (CV) of the two measurements by a tester was 0.9 ± 0.7%. The intraclass correlation coefficient (ICC) of the two measurements was 1.000. Moreover, the inter-tester (two testers) reproducibility of ACSA measurements was evaluated for each muscle (n = 6; at 50% of thigh length). The CV was 2.8 ± 2.0% and the ICC was 0.997, respectively. The ACSA at 30% (proximal), 50% (middle), and 70% (distal) of muscle length of each muscle was determined from the mean of the three nearest slices, respectively (Ema et al., 2014). The muscle volume of each muscle was determined by summing ACSA times the slice thickness (1.0 cm). In addition, the percentage of each muscle volume to the total quadriceps femoris or hamstrings was calculated.

Experiment 2: longitudinal approach

Subjects

Twelve varsity cyclists (10 males and two females; 20.0 ± 1.2 years, 170.2 ± 8.0 cm, 62.6 ± 8.3 kg) and 10 untrained males...
(21.5 ± 1.7 years, 173.1 ± 5.6 cm, 65.6 ± 5.0 kg) participated in this study. The untrained males were served as control subjects. Four male cyclists had also participated in experiment 1 before the beginning of experiment 2. All cyclists had participated in both track and road races. Their competitive experience was 4.1 ± 2.9 years (range: 0.1–10.7 years) at the beginning of the experiment (three cyclists were ≤2 years, four cyclists were ≤4 years, and the remainder were >4 years). The first and second measurements were made at the early and late stages of a season, respectively. During the last 3 months before the first measurement, competitive training was conducted both on the road (∼150 km per training) and by using a bicycle roller (∼60 min per training) indoors. During the observation period, the cyclists practiced cycling training mainly on the road for 15 ± 5 h per week and the training distance was 280 ± 125 km per week. In daily training sessions, the cyclists recorded the bicycle speed using their own speed meter. According to the records, the top speed in a training session was about 30–35 km/h. However, their training course included urban areas with some traffic signals, meaning that the cyclists could not continue cycling without interruptions. Thus, their average speed during the training session should be lower than the above speed. During the last 3–4 weeks before the second measurement, most of the cyclists reduced their training volume. Some conducted a similar training regime with a slightly shorter training distance, others adopted pedaling training using a bicycle roller instead of the training on the road. Information on the content of training programs was collected by using a questionnaire to which the cyclists responded by referring to their training diary. Among the cyclists, three had conducted resistance training (squat at an intensity of 70% of one repetition maximum) twice per week during the observation periods. The training modality was a multi-joint leg extension, and the training frequency was lower than that of cycling training. We confirmed similar hypertrophic adaptation of the three to the remaining cyclists, and therefore, all data were pooled. The untrained control subjects were requested to continue their usual lifestyle and not to perform intensive exercises. Some of them had taken part in various recreational physical activities such as jogging or ball games once or twice a week and others had walked or cycled when commuting. Prior to the experiment, the subjects were informed of the purpose and risks of the study and provided written informed consent.

MR imaging
The same measurement as experiment 1 was carried out before and after the observation period of 6 months. To investigate the regional differences in hypertrophy, ACSAs at 30% (proximal), 50% (middle), and 70% (distal) along the length of each muscle were determined from the means of the three nearest slices, respectively. In addition, the muscle volume was determined for each muscle.

Multi-joint leg extension power
Voluntary multi-joint bilateral leg extension peak power was measured with a leg extension machine (Anaeropress 3500, Combi, Tokyo, Japan), in a similar manner to the previous study (Kawakami et al., 1993). The load of multi-joint leg extension was set according to subjects’ body mass. The subjects sat on the bench of the machine with the pelvis and the feet secured to the bench and the plate, respectively, by nonelastic straps. After several
warm-up trials, the subjects were asked to extend their legs (knee and hip joints) as fast as possible with maximal effort. The multi-joint leg extension power was measured five times. The mean of the highest and second highest values in the trials was used for further analysis. The CV and ICC of the two values were 2.9 ± 2.7% and 0.967, respectively.

Statistical analysis

Descriptive data are presented as means ± SDs. All the analyses were performed with statistical software (IBM SPSS Statistics 22, IBM, Armonk, NY, USA). In experiment 1, an independent t-test was conducted to examine statistical differences in age, height, and body mass between the experienced cyclists and untrained men. Analysis of the muscle volume was performed by two-way analysis of variance (ANOVA) with one within-group factor (VL, VM, VI, RF, PM, BF long, BF short, ST, SM, ADD total, Gr, Sar) and one between-group factor (experienced cyclists, untrained men). A two-way ANOVA was used to determine the significance of effects of group and regions (proximal, middle, distal) on ACSA for each muscle. A two-way ANOVA was conducted to test the difference in percentage of individual muscle volume to the total synergists (quadriceps femoris or hamstrings).

In experiment 2, a paired t-test was used to test the significance of the difference in body mass and multi-joint leg extension power in percentage of individual muscle volume to the total synergists (quadriceps femoris or hamstrings).

Results

Experiment 1

Physical characteristics

There were no significant differences between the experienced cyclists and untrained men in age, height or body mass.

ACSA

The ACSA distributions along the thigh or trunk are illustrated in Fig. 2. The two-way ANOVA showed a significant main effect of group for VL ($P = 0.006$, partial $\eta^2 = 0.391$), VM ($P = 0.031$, partial $\eta^2 = 0.260$), VI ($P = 0.024$, partial $\eta^2 = 0.280$), BF short ($P = 0.035$, partial $\eta^2 = 0.248$), ST ($P = 0.016$, partial $\eta^2 = 0.310$), ADD total ($P = 0.049$, partial $\eta^2 = 0.221$), and PM ($P = 0.008$, partial $\eta^2 = 0.361$) with no significant interaction of group × region. The ACSAs of the above muscles were significantly greater in the experienced cyclists than in the untrained men. On the other hand, there was no significant main effect of group or interaction of group × region for RF, BF long, SM, Gr, or Sar.

Muscle volume

Descriptive data of each muscle’s volume are shown in Fig. 3. The two-way ANOVA indicated a significant main effect of group ($P = 0.001$, partial $\eta^2 = 0.510$) with a significant interaction of group × muscle ($P < 0.001$, partial $\eta^2 = 0.354$). The volumes of VL ($P = 0.001$, $r = 0.759$), VM ($P = 0.002$, $r = 0.675$), VI ($P = 0.006$, $r = 0.618$), PM ($P < 0.001$, $r = 0.746$), BF short ($P = 0.029$, $r = 0.499$), ST ($P = 0.021$, $r = 0.613$), and ADD total ($P = 0.001$, $r = 0.714$) were significantly greater in the experienced cyclists than in the untrained men. In contrast, the muscle volumes of RF, BF long, SM, Gr, and Sar did not differ significantly between the two groups. These results were consistent even when each muscle volume was normalized by body mass.

Relative muscle volume

The percentages of the volume of each muscle relative to that of the total quadriceps femoris or hamstrings are presented in Fig. 4. The two-way ANOVA showed a significant interaction of group × muscle ($P = 0.001$, partial $\eta^2 = 0.301$) for the quadriceps femoris, but no main effects or interaction were observed in the hamstrings. The percentage of RF volume was significantly lower in the experienced cyclists ($12.0 ± 1.1\%$) than in the untrained men ($15.4 ± 1.5\%; P < 0.001$, $r = 0.798$). The percentage of VL volume was significantly higher in the experienced cyclists ($33.9 ± 1.6\%$) than in the untrained men ($31.5 ± 2.1\%; P = 0.018$, $r = 0.552$). The corresponding values for VM and VI did not differ significantly between the two groups.

Experiment 2

Body mass and multi-joint leg extension power

Paired t-tests indicated no changes in body mass (cyclists: before, 62.6 ± 8.3 kg, after, 61.8 ± 8.8 kg; controls: before, 65.6 ± 5.0 kg, after, 65.4 ± 5.7 kg) or multi-joint leg extension power (cyclists: before, 1477 ± 399 W, after, 1522 ± 408 W; controls: before, 2040 ± 357 W, after, 1985 ± 298 W) for both groups.

ACSA

In the control group, no main effect of time or interaction of time × region was observed in any muscles. In VL and VM of the cyclists, there was a significant main effect of time (VL, $P = 0.01$, partial $\eta^2 = 0.467$; VM, $P = 0.002$, partial $\eta^2 = 0.583$) with a significant interaction of
time \times \text{region} \quad (\text{VL}, \quad P = 0.002, \quad \text{partial } \eta^2 = 0.715; \quad \text{VM}, \quad P = 0.048, \quad \text{partial } \eta^2 = 0.241). \quad \text{The ACSAs of the two muscles in the middle (VL, } \quad P = 0.013, \quad r = 0.663; \quad \text{VM, } \quad P = 0.029, \quad r = 0.605) \quad \text{and distal (VL, } \quad P < 0.001, \quad r = 0.877; \quad \text{VM, } \quad P = 0.001, \quad r = 0.790) \quad \text{regions increased significantly, whereas those in the proximal region did not (Fig. 5). For VI, a main effect of time} \quad (P = 0.018, \quad \text{partial } \eta^2 = 0.410) \quad \text{with no significant interaction of}
time × region was observed. For RF, there was no main effect of time or interaction of time × region. Regarding the relative changes in ACSA, one-way ANOVA showed a main effect of region in VL (P < 0.001, partial η² = 0.562) but not in VM, VI, or RF. Relative change in ACSA of VL was significantly greater in the distal (P = 0.006, r = 0.715) and middle (P = 0.001, r = 0.804) regions than in the proximal region (Fig. 5).

For PM of the cyclists, the two-way ANOVA showed a significant main effect of time (P = 0.007, partial η² = 0.498) with no significant interaction of time × region. The relative changes in ACSA in the three regions did not differ significantly.

Regarding the hamstrings of the cyclists, a main effect of time (P = 0.019, partial η² = 0.407) with no significant interaction of time × region was observed in BF_short. For the other three muscles, no significant main effect of time (BF_long, P = 0.193, partial η² = 0.149; ST, P = 0.089, partial η² = 0.240; SM, P = 0.600, partial η² = 0.020) or interaction of time × region was observed. The relative changes in ACSA were not significantly different among the three regions in any muscles.

For ADD_total, a main effect of time (P = 0.038, partial η² = 0.336) with no significant interaction of

time × region was found. There were no significant differences in the changes of ACSA in the three regions. There was no main effect of time or interaction of time × region in Gr or Sar. No significant differences in the relative changes in ACSA in the three regions were seen in any muscles.

Muscle volume

In the control group, no main effect of time or interaction of time × muscle was observed. In the cyclists, the two-way ANOVA demonstrated significant main effects of time (P = 0.002, partial η² = 0.594) and muscle (P < 0.001, partial η² = 0.955) with a significant interaction of the two factors (P = 0.007, partial η² = 0.443). The volumes of VL (P < 0.001, r = 0.869), VM (P < 0.001, r = 0.849), VI (P = 0.002, r = 0.779), PM
Relative changes in anatomical cross-sectional area (ACSA) of the vastus lateralis (VL, upper) and vastus medialis (VM, lower) at 30% (proximal), 50% (middle), and 70% (distal) of each muscle length. *Indicates a significant change as a result of regular training in competitive cycling for 6 months. #Denotes a significant difference between the regions.

(P < 0.001, r = 0.867), BF_short (P = 0.006, r = 0.716), ST (P = 0.011, r = 0.675), and ADD_total (P = 0.025, r = 0.616) increased significantly (Fig. 6). In contrast, the volumes of RF, BF_long, SM, Gr, and Sar did not change significantly. One-way ANOVA revealed a significant main effect of muscle for the relative change in muscle volume for the knee extensors (P < 0.001, partial \( \eta^2 = 0.647 \)), knee flexors (P < 0.001, partial \( \eta^2 = 0.409 \)), hip extensors (P < 0.001, partial \( \eta^2 = 0.500 \)), and hip flexors (P < 0.001, partial \( \eta^2 = 0.721 \)). The relative changes in the muscle volume of BF_short were significantly higher than those of BF_long (P = 0.009, r = 0.803) and SM (P = 0.01, r = 0.794), and that of ST was significantly higher than that of BF_long (P = 0.023, r = 0.765). For the hip extensors, the relative changes in the muscle volume of ST (vs BF_long, P = 0.014, r = 0.765; vs SM, P = 0.031, r = 0.724) and ADD_total (vs BF_long, P = 0.025, r = 0.735; vs SM, P = 0.035, r = 0.717) were significantly higher than those of BF_long and SM. The relative change in PM volume was significantly higher than those of RF (P < 0.001, r = 0.833) and Sar (P = 0.001, r = 0.854).

**Relationship between variables**

The relationships between the extent of increases in muscle volume of each muscle or total synergists and (a) the years of competitive experience or (b) muscle volume before training did not reach statistical significance in any muscles or synergists, although a tendency toward a negative correlation was observed in VI (r = -0.544, P = 0.067) and total quadriceps femoris (r = -0.508, P = 0.091) with the years of competitive experience.

**Discussion**

To the best of our knowledge, this is the first study to examine both cross-sectionally and longitudinally the quantitative profiles of the individual muscle volumes of the quadriceps femoris, hamstrings, ADD_total, Gr, Sar, and PM in competitive cyclists. It was demonstrated that (a) the volumes of VL, VM, VI, PM, BF_short, ST, and ADD_total were greater in the experienced cyclists than in the untrained men, but those of RF, BF_long, SM, Gr, and Sar were similar between the two groups, and (b) after competitive cycling training for 6 months the increases were observed in the volumes of VL, VM, VI, PM, BF_short, ST, and ADD_total, but were not observed for RF, BF_long, SM, Gr, or Sar. The results of the longitudinal study (experiment 2) substantiated those of the cross-sectional study (experiment 1). These findings suggest that the unique muscularity in experienced cyclists is due to their regular training in competitive cycling rather than being inherited, and that the longitudinal results are due to the specificity of cycling-induced hypertrophy, rather than the time course difference in hypertrophic response among muscles. Moreover, regardless of muscle group, all monoarticular but not biarticular thigh muscles were hypertrophied, except for ST. This may be linked to the different roles of these muscles during pedaling (van Ingen Schenau et al., 1992).

The current results that well-trained cyclists have large quadriceps femoris and that cycling training induces hypertrophy of the quadriceps femoris are consistent with previous studies (cross-sectional study in professional road cyclists, Hug et al., 2006; longitudinal study for 6–12 weeks in untrained individuals, Linossier et al., 2017).
et al., 1997; McPhee et al., 2010; Harber et al., 2012). However, some studies failed to find a significant difference in the quadriceps femoris size compared with controls (Izquierdo et al., 2004) or a significant change following cycling training (Rønnestad et al., 2010; Farup et al., 2012). Rønnestad et al. (2010) and Farup et al. (2012) evaluated ACSA of the total quadriceps femoris at the proximal regions where RF ACSA was comparatively large. The present findings indicated that competitive cycling training elicited uneven hypertrophy among the muscles and between regions within a muscle: there was preferential hypertrophy of the vasti, middle, and distal regions in VL and VM in particular but not in RF. Specificity of the hypertrophic responses among the muscles and among different regions may also have existed in those studies (Izquierdo et al., 2004; Rønnestad et al., 2010; Farup et al., 2012). Moreover, a previous study demonstrated that training volume rather than training intensity was important for muscle hypertrophy (Mitchell et al., 2012). The training volumes in the current cyclists are clearly large compared with those in many previous training intervention studies. In any case, the current approach (muscle volume evaluation) provides clearer evidence for the greater size of the quadriceps femoris in experienced cyclists compared with untrained controls, together with their hypertrophic response.

The quantitative profiles of the quadriceps in the cyclists are consistent with the previous finding in oarsmen (30% greater volume of the vasti but comparable RF volume to untrained controls, Ema et al. 2014). The current results strongly suggest that such muscle specificity can be generalized to athletes who mainly perform repetitive multi-joint leg extensions in their sport activities. A possible explanation for the lack of hypertrophy of RF is the lower activation of RF compared with the vasti during pedaling (Endo et al., 2007; Gondoh et al., 2009; Chin et al., 2011). Another possibility is poor trainability of RF, but this can be discarded because of the preferential hypertrophy of the muscle after single-joint knee extension training (Narici et al., 1996; Ema et al., 2013). Taken together, the difference in muscle activation between the vasti and RF during pedaling motions may account for the current results. These responses of RF should depend on the training modality (multi-joint leg extension vs single-joint knee extension).

To the best of our knowledge, this is the first study to show preferential hypertrophy of VL and VM in the distal region after cycling training. Some training

---

**Fig. 6.** Relative changes in muscle volume of each muscle of the quadriceps femoris, psoas major, sartorius, hamstrings, total adductors, and gracilis of cyclists (upper) and control subjects (lower). $^a$A significant change after the observation periods for 6 months; $^a$A significant difference between the muscles, and $^b$A significant difference between ST and SM when the one-way analysis of variance followed by Bonferroni correction was performed for hip extensors but not for knee flexors. VL, vastus lateralis; VM, vastus medialis; VI, vastus intermedius; RF, rectus femoris; PM, psoas major; Sar, sartorius; BF$_{short}$, biceps femoris short head; BF$_{long}$, biceps femoris long head; ST, semitendinosus; SM, semimembranosus; ADD$_{total}$, total adductors; Gr, gracilis.
Ema et al.

intervention (single-joint knee extension) studies also observed similar responses in VL (Narici et al., 1996; Ema et al., 2013), whereas others did not (Narici et al., 1989). Franchi et al. (2014) showed a different effect of contraction type (concentric or eccentric) during leg press training on the region-specific hypertrophy in VL. In their results, eccentric-only training elicited significant increases in ACSA of VL in the middle and distal regions. On the other hand, they failed to find a significant hypertrophy in the distal region following concentric-only (similar contraction type to that during pedaling motions) training, which is not in line with the current findings. Thus, it remains unclear whether or not the above results are specific to exercise modality and contraction type. The mechanisms for the regional differences are unclear, but might involve the differences in regional activation level during pedaling. It was reported that regional differences in hypertrophy along the muscle were associated with regional differences in muscle activation level (Wakahara et al., 2012). In addition, in an animal study, expression of mRNA of insulin-like growth factor-1 after compensatory overload was not uniform along the length (Yamaguchi et al., 2003), which can be related to the regional difference in the extent of hypertrophy. Considering these findings, it seems that a regional difference in the signaling process on protein synthesis resulting from a difference in muscle activation might be involved in the observed region-specific hypertrophy.

The present study demonstrated a muscle-specific hypertrophy of the hip flexors, namely, hypertrophy of PM but not of RF or Sar as a result of competitive cycling training, and greater PM in the experienced cyclists compared with the untrained men. Gondoh et al. (2009) observed substantial activation of PM and Sar with lower activation of RF compared with the vasti, although they did not compare the values among the three muscles. The current results partly support their finding. Theoretically, a hip flexion moment or angular impulse is needed to control the angular momentum of the thigh segment for smooth hip extension-flexion transition. In fact, previous kinetic analysis showed the largest hip flexor moment in the proximity of the bottom dead center during one cycle of pedaling motion (Bini & Diefenthaler, 2010). A previous study observed low activation of RF around the bottom dead center (Dorel et al., 2009), whereas no data are available regarding the relationship between the activation level and crank angle for Sar. Based on these points, it is reasonable to assume that PM rather than RF and Sar plays the major role as a hip flexor during pedaling motions. The reasons for the lack of response of Sar despite substantial activation during pedaling (Gondoh et al., 2009) are not clear at this moment. Other possible factors, such as poor hypertrophic responsiveness, interindividual variability in the adaptation to cycling training, and much smaller size compared with RF and PM (Fig. 3), might be involved in the current results.

Inter-muscle differences in hypertrophic response and quantitative characteristics in the experienced cyclists were also observed among the thigh knee flexors and among the thigh hip extensors. Regarding the knee flexors, the current results are partly in line with Akima et al. (1997), who showed significant hypertrophy of BF_long but not of the other four (BF_short, ST, SM, Sar) muscles as a result of cycling training. To our knowledge, no evidence is available on the activation level of each muscle of the hamstrings and Sar during pedaling motions. A previous kinetic and kinematic analysis pointed to the substantial contribution of knee flexor muscles during pedaling (Elmer et al., 2011). Muscle volume is greater in the hamstrings than in the gastrocnemius and Sar (Akima et al., 2007), suggesting that the hamstrings are the major contributors to knee flexion moment. Based on the functional roles of biarticular and monoarticular muscles (van Ingen Schenau et al., 1992), knee flexor moment contributing to pedal force can be mainly generated by the monoarticular BF_short during pedaling motions. However, the relative volume of BF_short to the total hamstrings was only 14.5% in the experienced cyclists (Fig. 4). Therefore, it is reasonable to assume that the other hamstring muscles are also activated to generate the pedal force rather than to control the direction of the pedal force. It was shown that activation level during knee flexion exercise was higher in ST than BF_long and SM (Ono et al., 2010). Hence, it is possible that BF_short and ST act as preferential knee flexion moment generators during pedaling, resulting in the increases in volume of these two muscles through competitive cycling training. With respect to hip extensor muscles, the activation level during hip extension exercises has been shown to be higher in BF_long and SM than in ST (Ono et al., 2011), implying that BF_long and SM act mainly as hip extensors rather than as knee flexors. The ADD_total acts as the hip extensor (Dostal et al., 1986) and is considerably activated during pedaling (Richardson et al., 1998; Endo et al., 2007; Gondoh et al., 2009). In the current results, ADD_total was hypertrophied and greater in the experienced cyclists than in the untrained controls. The volume of ADD_total was clearly greater than the sum of BF_long and SM (Fig. 3). Considering the previous and current results, it is likely that ADD_total, but not BF_long and SM, is the major contributor to the hip extension moment during pedaling.

In the current study, there was no change in the multi-joint leg extension power of the cyclists, despite significant increases in the volumes of some knee and hip extensors. These results are partly in line with previous reports showing no change (Sale et al., 1992) or even a decrease (Akima et al., 1997) in strength after training with a significant increase in muscle size, when the strength was measured in a different task from the one used in the training. Pedaling motions are repetitive
multi-joint unilateral leg extensions, while we evaluated multi-joint bilateral leg extension power. It is known that the strength of maximal voluntary bilateral actions is less than that of the sum of the unilateral actions (bilateral deficit; Vandervoort et al., 1984). Trained cyclists showed a similar degree of bilateral deficit of multi-joint leg extension strength compared with untrained controls (Secher et al., 1988), suggesting that competitive cycling training does not improve the extent of the deficit. Moreover, Taniguchi (1997) showed that unilateral multi-joint leg extension training increased the extent of the bilateral deficit (3.9%). Therefore, the difference in the task (unilateral vs bilateral) may be related to the current results. It is also possible that the magnitudes of hypertrophy of the thigh muscle groups were not so high (−3.5% on average) as to increase the multi-joint bilateral leg extension power.

The major limitation of the current study was that the training intensity during competitive training was unclear in both experiments, and in experiment 2, training regimens during the observation period were not controlled among the subjects. In general, training intensity is a factor accounting for variance in the hypertrophic response to resistance exercise (Fry, 2004). Therefore, there is a possibility that the variability in the extent of hypertrophic changes might be attributed to the interindividual variations of training regimen. This does not explain the observed nonresponsiveness of biarticular muscles despite significant hypertrophy of the monoarticular muscles. Moreover, if the variability of training content has a substantial impact, the results of cross-sectional and longitudinal experiments would not have matched each other. On the other hand, if a distinctly different training regimen from that in the current study, e.g. very high-intensity training such as sprint cycle training is adopted, the muscles that did not show hypertrophic change in the experiment 2 might have increased in size. However, Akima et al. (1997) conducted sprint cycle training yet failed to find the significant hypertrophy of the biarticular muscles. This finding denies the above suggestion.

In conclusion, the current results indicate that regular training in competitive cycling induces muscle-specific hypertrophy of the synergistic muscles, leading to quantitative profiles of the quadriceps femoris, hamstrings, adductors, total adductors, and psoas major in experienced cyclists.

This unique musculature may be due to selective utilization of particular muscles during cycling, depending in part on the differences in the number of joints that the muscles cross.

**Perspectives**

Since the current study used both cross-sectional and longitudinal approaches, several limitations, which are separately inherent in the respective methods, could be eliminated. Therefore, the current results provide a robust conclusion regarding the musculature of the thigh and psoas major in cyclists, which is due to competitive cycling training. The present findings indicate the different quantitative adaptations between monoarticular and biarticular muscles in the thigh. Based on previous results in the functional roles of monoarticular and biarticular muscles (van Ingen Schenau et al., 1992), the present findings can lead to a new research direction into the association between functional roles of muscles during sport activities and event-specific musculature in athletes. Considering our previous finding (Ema et al., 2013), the specificity of hypertrophic responses of the monoarticular and biarticular thigh muscles would be exercise dependent. Also, cycling is accepted as a training modality for various athletes. When adopting cycling as an exercise aiming to increase thigh musculature, athletes and coaches should consider the specificity of cycling-induced hypertrophy in the thigh muscles. As a next step, we need to clarify the underlying mechanism(s) of the current findings, and to elucidate how the specificity of hypertrophic response can be associated with performance improvement.

**Key words:** Quadriceps femoris, hamstrings, adductors, psoas major, muscle volume, synergistic muscles, monoarticular muscle, biarticular muscle

**Acknowledgements**

This work was partly supported by a Grant-in-Aid for JSPS Fellows (no. 252723) and a Grant-in-Aid for Scientific Research (B, no. 24300209) from the Japan Society for the Promotion of Science. The authors gratefully acknowledge Dr. Shoji Konda and Dr. Masanori Sakaguchi for data acquisition.


Muscle-specific adaptation to cycling

Additional Supporting Information may be found in the online version of this article at the publisher’s web-site:

**Fig. S1.** The volume of each muscle of the quadriceps femoris, psoas major, sartorius, hamstrings, total adductors, and gracilis of cyclists (upper) and untrained control subjects (lower) before (black bar) and after (white bar) regular training in competitive cycling for 6 months. *Indicates a significant change. VL, vastus lateralis; VM, vastus medialis; VI, vastus intermedius; RF, rectus femoris; PM, psoas major; Sar, sartorius; BF\textsubscript{short}, biceps femoris short head; BF\textsubscript{long}, biceps femoris long head; ST, semitendinosus; SM, semimembranosus; ADD\textsubscript{total}, total adductors; Gr, gracilis.
