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ORIGINAL ARTICLE

Effects of squat training with different depths on lower limb muscle volumes

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Abstract

Purpose The purpose of this study was to compare the effects of squat training with different depths on lower limb muscle volumes.

Methods Seventeen males were randomly assigned to a full squat training group (FST, $n = 8$) or half squat training group (HST, $n = 9$). They completed 10 weeks (2 days per week) of squat training. The muscle volumes (by magnetic resonance imaging) of the knee extensor, hamstring, adductor, and gluteus maximus muscles and the one repetition maximum (1RM) of full and half squats were measured before and after training.

Results The relative increase in 1RM of full squat was significantly greater in FST (31.8 ± 14.9%) than in HST (11.3 ± 8.6%) ($p = 0.003$), whereas there was no difference in the relative increase in 1RM of half squat between FST (24.2 ± 7.1%) and HST (32.0 ± 12.1%) ($p = 0.132$). The volumes of knee extensor muscles significantly increased by 4.9 ± 2.6% in FST ($p < 0.001$) and 4.6 ± 3.1% in HST ($p = 0.003$), whereas that of rectus femoris and hamstring muscles did not change in either group. The volumes of adductor and gluteus maximus muscles significantly increased in FST (6.2 ± 2.6% and 6.7 ± 3.5%) and HST (2.7 ± 3.1% and 2.2 ± 2.6%). In addition, relative increases in adductor ($p = 0.026$) and gluteus maximus ($p = 0.008$) muscle volumes were significantly greater in FST than in HST.

Conclusion The results suggest that full squat training is more effective for developing the lower limb muscles excluding the rectus femoris and hamstring muscles.

Keywords Knee extensor · Hamstring · Adductor · Gluteus maximus · Magnetic resonance imaging

Abbreviations

ANOVA	Analysis of variance
BFl	Biceps femoris long head muscle
BFs	Biceps femoris short head muscle
EF	Effect size
FST	Full squat training
HST	Half squat training
SD	Standard deviation
SM	Semimembranosus muscle
ST	Semitendinosus muscle
1RM	One repetition maximum
RF	Rectus femoris muscle
VI	Vastus intermedius muscle
VL	Vastus lateralis muscle
VM	Vastus medialis muscle

Introduction

Squat training is one of the most common exercises for increasing the strength and power of the lower limbs. According to cross-sectional studies (Ikebukuro et al. 2011; Kanehisa et al. 1998), the knee extensor muscles of weightlifters, who performed squat training, were more specifically developed. Previous studies demonstrated that squat exercises with different depths altered kinetic, kinematic, and muscle activities of the lower limbs (e.g., Bryanton et al. 2012; Caterisano et al. 2002). Previous researchers examined the effects of shallow and deep squat training on strength and jump performance (e.g., Weiss et al. 2000).

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Furthermore, Bloomquist et al. (2013) and McMahon et al. (2014) reported that squat training with a deep knee bend (120° knee flexion for Bloomquist et al. 2013, 90° knee flexion for McMahon et al. 2014) resulted in greater increases in the cross-sectional areas of knee extensor muscles than that with a shallow knee bend (60° knee flexion for Bloomquist et al. 2013, 50° knee flexion for McMahon et al. 2014). In these studies, however, muscle cross-sectional areas, but not muscle volumes, were evaluated using limited slices from magnetic resonance imaging and ultrasonography. Since the muscle volume represents an important factor influencing the force-generating capacity (Fukunaga et al. 2001), squat training induced-changes in muscle volumes of the lower limbs should be investigated in more detail.

Previous studies that examined the effects of squat depth on activation levels of the hamstring muscles (Caterisano et al. 2002; Contreras et al. 2016; Gorsuch et al. 2013) showed no significant differences in the electromyographic activities of the hamstring muscles between deep and shallow knee bend squat exercises. Moreover, changes in the signal intensity and transverse relaxation time of magnetic resonance images of the hamstring muscles were negligible following squat exercises (Ploutz-Snyder et al. 1995; Sugisaki et al. 2014). Bloomquist et al. (2013) reported that the cross-sectional areas of the hamstring muscles did not significantly change after 12 weeks of full and shallow squat training, whereas that of knee extensor muscles increased as mentioned earlier. These findings indicate that the muscle volumes of the hamstring muscles do not increase after squat training regardless of squat depth.

The strength and power generation capabilities of hip extension are essential factors affecting performance in various sports (e.g., Fukashiro and Komi 1987; Watanabe et al. 2000). Anatomically, the gluteus maximus muscle contributes to hip extension. Some researchers suggested that the adductor muscles function in hip extension and flexion as well as hip adduction (Simonsen et al. 1985; Wiemann and Tidow 1995). Wiemann and Tidow (1995) reported that the adductor muscles were markedly activated during the forward and backward swing of the femur on sprinting. Regarding the effects of squat depth on activation of the gluteus maximus and adductor muscles, Caterisano et al. (2002) demonstrated that the electromyographic activity of the gluteus maximus muscle increased with greater squat depths. Sugisaki et al. (2014) also showed using the transverse relaxation time of magnetic resonance imaging that the activation levels of adductor muscles were equal to those of knee extensor muscles during squat exercises. To the best of our knowledge, the influence of squat training on the sizes of the gluteus maximus and adductor muscles has not been investigated. Based on these findings, it is considered that the volumes of the gluteus maximus and adductor muscles increase after squat training and that squat training with a deep knee bend (i.e., full squat) results in greater increases in the sizes of these muscles than that with a shallow knee bend (i.e., half squat).

In the present study, we aimed to investigate the effects of squat training with different depths on muscle volumes of the lower limbs. We hypothesized that relative increases in the muscle volumes of the knee extensor, gluteus maximus, and adductor muscles are greater with full squat training than with half squat training, while the muscle volumes of hamstring muscles do not change after full and half squat training.

Methods

Subjects

Twenty healthy males volunteered for the present study. Subjects were assigned to a full squat training group (FST, $n=10$) or half squat training group (HST, $n=10$) by matching average baseline physical characteristics and the one repetition maximum (1RM) of full and half squats between the two groups. During the training intervention (10 weeks), three subjects ($n=2$ in FST, $n=1$ in HST) dropped out due to injury or illness ($n=2$) and a loss of interest ($n=1$). Therefore, data are presented for 17 subjects: $n=8$ in FST and $n=9$ in HST. The physical characteristics of both groups are shown in Table 1. Subjects were physically active, but had not participated in any organized program involving regular exercise for at least 1 year before testing. In the present study, we used untrained subjects since the obtained results would be affected by the effects of training experiences before the experiment if trained subjects were used. In addition, subjects were instructed to maintain their normal diet and avoid taking any supplements during the experimental period. They were fully informed of the procedures to be utilized as well as the purpose of the study. Written informed consent was obtained from all subjects. This study was approved by the Ethics Committee for Human

Table 1 Age, physical characteristics, and 1RM before training in both groups mean (sd)

	Full squat training group ($n=8$)	Half squat training group ($n=9$)
Age (years)	20.7 (0.4)	20.9 (0.8)
Height (cm)	173.6 (4.1)	172.3 (5.8)
Body mass (kg)	63.2 (6.6)	64.1 (6.1)
1RM of full squat (kg)	78.8 (14.6)	82.8 (15.2)
1RM of half squat (kg)	95.0 (16.0)	96.7 (15.0)

1RM one repetition maximum

Experiments, Department of Life Science (Sports Sciences), The University of Tokyo.

RM of full and half squats

Subjects completed two familiarization sessions to receive instructions on the proper squat technique for the full and half squat exercises. Regarding the full squat exercise, subjects performed a full range of motion squat (from complete knee extension to approximately 140° knee flexion) and then immediately returned to the extended knee position. In the half squat exercise, subjects performed a half range of motion squat (from complete knee extension to approximately 90° knee flexion) and then immediately returned to the extended knee. After a standardized warm-up (e.g., stretching of the major muscle groups), subjects performed 2 sets of 5 repetitions at approximately 50% and 70% of their estimated 1RM for each squat depth with a 2-min rest between sets. The load was then progressively increased until subjects were unable to lift the load with a correct squat form. An average of five to six trials was required to complete the 1RM test. The order of the measurements of 1RM for both exercises (full and half squats) was randomized to avoid any systematic effects. After 1RM was evaluated for a given condition, a 15-min rest was allowed before 1RM assessment of the alternative exercise.

Muscle volume

A series of cross-sectional images of the lower limb muscles on the right side were obtained using magnetic resonance imaging (FLEXART MRT-50GP, Toshiba Medical Systems, Tokyo, Japan). Before the measurement, subjects lay supine on the bed for 20–30 min to allow for body fluid shift stabilization (Berg et al. 1993). T1-weighted spin-echo imaging in the axial plane was performed with the following variables: TR 580 ms, TE 20 ms, matrix 256 × 192, field of view 250 mm, slice thickness 10 mm, and interslice gap 0 mm. Each subject lay supine in the body coil with the knee kept at 0° (full extension). Transverse scans were performed from the spina iliaca anterior superior to extremitas distal of the tibia. The muscles investigated were as follows: knee extensor muscles: rectus femoris (RF), vastus lateralis (VL), vastus intermedius (VI), and vastus medialis (VM), hamstring muscles: biceps femoris short head (BFs), biceps femoris long head (BFl), semitendinosus (ST), and semimembranosus (SM), and adductor muscles: adductor magnus, adductor longus, and adductor brevis. In addition, each subject lay prone in the body coil with the knee kept at 0° to obtain a series of cross-sectional images of the gluteus maximus muscle. Transverse scans were performed from the iliac crest to gluteal tuberosity. Typical examples of magnetic resonance images of the mid portions of the thigh and buttock are shown in Fig. 1. The number of axial images obtained for each subject was the same before and after training and was 39.5 ± 2.3 for the knee extensor muscles: 37.2 ± 2.4 for the hamstring muscles, 29.4 ± 3.1 for the adductor muscles, and 28.5 ± 1.5 for the gluteus maximus muscle. Images obtained with magnetic resonance imaging were transferred to a computer and analyzed using Osirix DICOM image analysis software (Pixmeo, Geneva, Switzerland). In the present study, we did not analyze the cross-sectional area of each synergistic muscle for the adductor muscles since it was difficult to identify the interfaces between the synergistic muscles. Muscle volumes were obtained by multiplying the anatomical cross-sectional area of each image by the thickness (10 mm).

The repeatability of muscle volume measurements was investigated on two separate days with six young males in a preliminary study. No significant differences were observed between the test and retest values for muscle volumes. Test–retest correlation coefficients and coefficients of variance were 0.92 and 2.2% for the knee extensor muscles, 0.86 and 3.2% for the hamstring muscles, 0.94 and 2.4% for the adductor muscles, and 0.97 and 1.6% for the gluteus maximus muscle.

Squat training

Both groups completed 10 weeks (2 days per week) of squat training. FST performed full squat exercise (see above) and HST performed half squat exercise (see above). The safety bar was raised or lowered in the squat rack for each subject to provide a visual gage of the depth required. For both groups, subjects were instructed that stance width was almost the same as shoulder width. The barbell was positioned across their shoulders on the trapezius. All subjects were allowed to use a lifting belt during squat training. All training sessions were monitored and supervised to ensure correct squat depth and form by at least one experienced investigator. In order to become accustomed to training and acquire a correct form, subjects performed 3 sets of 60% 1RM × 10 repetitions in the first week, 3 sets of 70% 1RM × 8 repetitions in the second week, and 3 sets of 80% 1RM × 8 repetitions in the third week. In the present study, we adopted the moderate-to-high intensity protocol (8RM) that was thought to provide enough mechanical and metabolic stress on the muscles (Ratamess et al. 2009). 8RM usually corresponded to approximately 80% of 1RM (e.g., Mayhew et al. 2008 JSCR). However, we expected the muscle strength of subjects to increase in the fourth week, since subjects trained using lighter loads until the third week. Therefore, 90% of 1RM was used in the first session of the fourth week. In the first session of the fourth week, the training protocol was 3 sets of 90% 1RM × 8 repetitions. If subjects were able to perform 3 sets

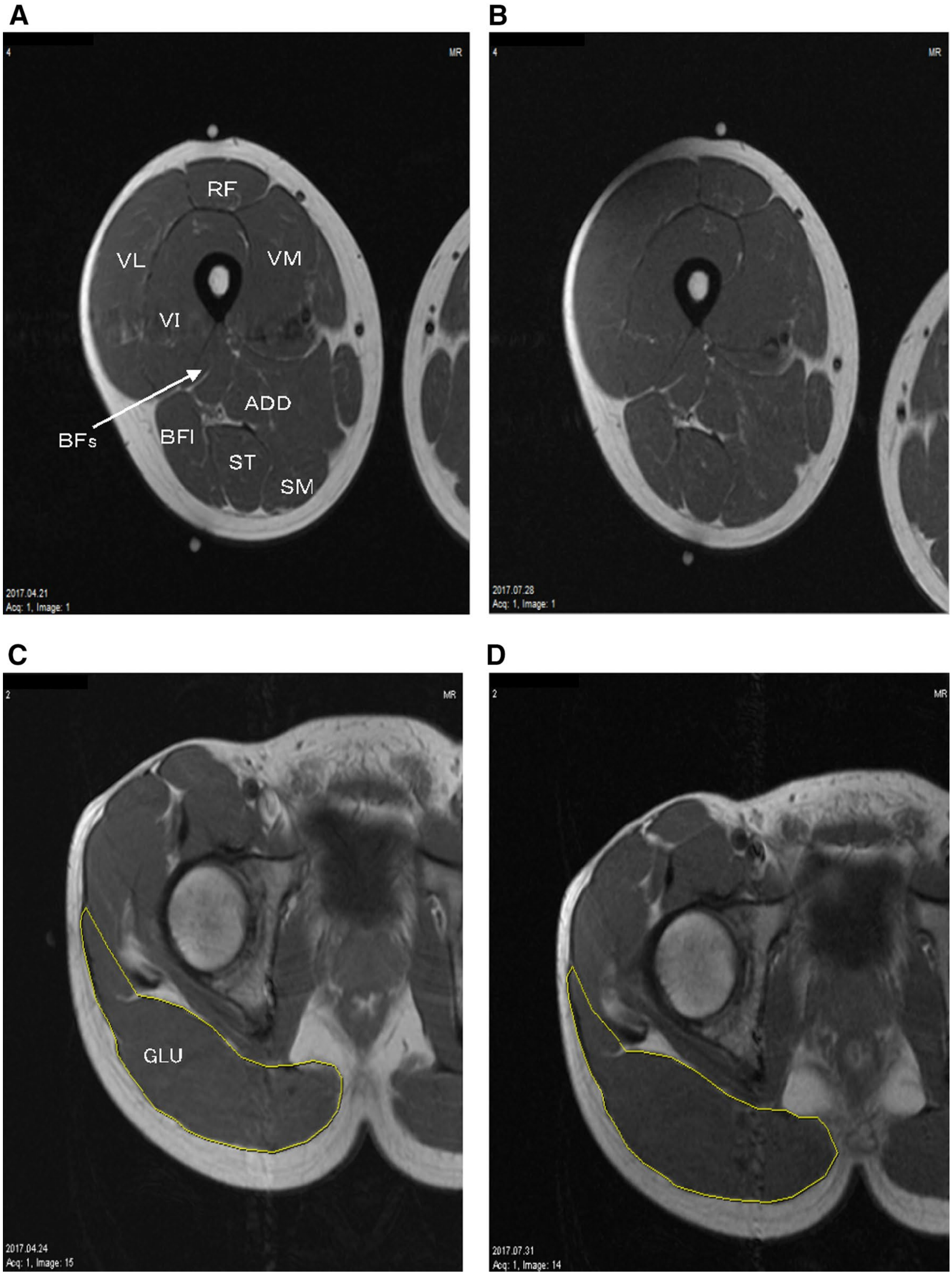

Fig. 1 Typical magnetic resonance images showing transverse sections of the mid-thigh (**a** before training, **b** after training) and mid-buttock (**c** before training, **d** after training). *RF* rectus femoris, *VL* vastus lateralis, *VI* vastus intermedius, *VM* vastus medialis, *BFs* biceps femoris short head, *BFl* biceps femoris long head, *ST* semitendinosus, *SM* semimembranosus, *ADD* adductor muscles, *GLU* gluteus maximus muscle

of 8 repetitions per set, the training load was increased by 5 kg for the next training session. The training volume was calculated from the load × repetition × movement distance of the barbell. Regarding the movement distance of the barbell, subjects were filmed with a digital video camera (MV-GS250, Panasonic, Tokyo, Japan) at a sampling frequency of 30 Hz during the first session of the fourth and seventh weeks. The movement distance of the barbell during squat training was measured using open-source image analysis software (ImageJ, NIH, Bethesda, MD).

Statistical analysis

Descriptive data included mean ± SD. A two-way analysis of variance (ANOVA) {2 (groups) × 2 (test times)} with repeated measures was used to analyze data. The F ratio for the main effects and interactions was considered to be significant at $p < 0.05$. Significant differences among means at $p < 0.05$ were detected by a post hoc test using the Bonferroni procedure. Percent changes from the baseline were also compared between groups using an unpaired t test. The effect size (ES) was calculated for all dependent variables between before and after training using Cohen's d formula: $ES = (M_{after} - M_{before})/SD_{pooled}$, where M_{after} is the mean variable after training, M_{before} is the mean variable before training, and SD_{pooled} is the pooled SD of the measured variables of before and after training. Power calculations (statistical power) were performed using G*power computer software. Statistical power of > 0.8 was obtained for the main significant changes, e.g., muscle volume.

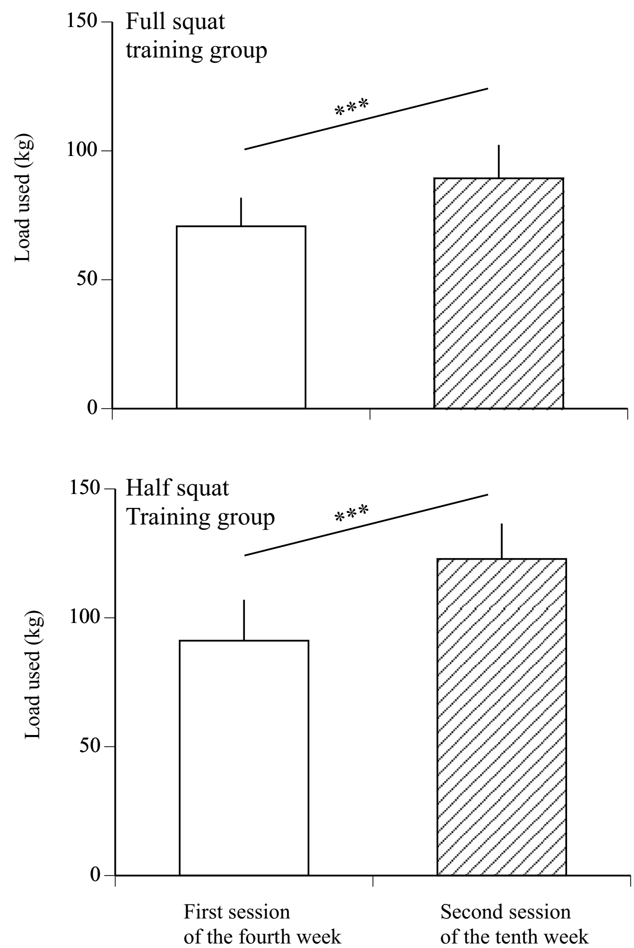

Fig. 2 The load used during the first session of the fourth week (open) and the second session of the tenth week (oblique) in full squat training (upper) and half squat training (lower) groups. *Significantly different between the two sessions (***$p < 0.001$)

Results

No significant differences in age, physical characteristics, or 1RM before training were found between FST and HST (Table 1), although three subjects dropped out as described earlier. From the first session of the fourth week to the end of the training session (except for the first 3 weeks when lighter training loads were used in order to become accustomed to training and acquire a correct form), the load used significantly increased by 26.6 ± 8.0% in FST ($p < 0.001$, ES = 1.73) and 29.2 ± 11.5% in HST ($p < 0.001$, ES = 2.21) (Fig. 2). As mentioned earlier, the movement distance of the barbell during squat training was measured in the first session of the fourth and seventh weeks. No significant differences in the movement distances of the barbell during full squat for FST and half squat for HST were found between the fourth and seventh weeks. The movement distance of the barbell during squat training was 87.9 ± 2.1 cm in FST and 53.8 ± 1.8 cm in HST. There was no significant difference in the total training volume (calculated from the fourth to last week) between FST (186.4 ± 34.0 kg rep m) and HST (198.4 ± 19.9 kg rep m) ($p = 0.388$, ES = 0.45).

In both groups, the 1RM of full and half squats significantly increased after training (Fig. 3). The relative increase in 1RM of the full squat was significantly greater in FST (31.8 ± 14.9%) than in HST (11.3 ± 8.6%) ($p = 0.003$, ES = 1.74), whereas there was no difference in the relative increase in 1RM of half squat between FST (24.2 ± 7.1%) and HST (32.0 ± 12.1%) ($p = 0.132$, ES = 0.81).

The volumes of knee extensor muscles significantly increased by 4.9 ± 2.6% in FST ($p < 0.001$, ES = 0.34) and 4.6 ± 3.1% in HST ($p = 0.003$, ES = 0.43) (Fig. 4a). No significant differences were observed in relative increases in the volumes of knee extensor muscles between the two groups ($p = 0.812$, ES = 0.11). Similarly, there were no significant differences in relative increases in the muscle volumes of VL, VI, and VM between the two groups ($p = 0.497$–0.892, ES = 0.02–0.34; Table 2). However, the

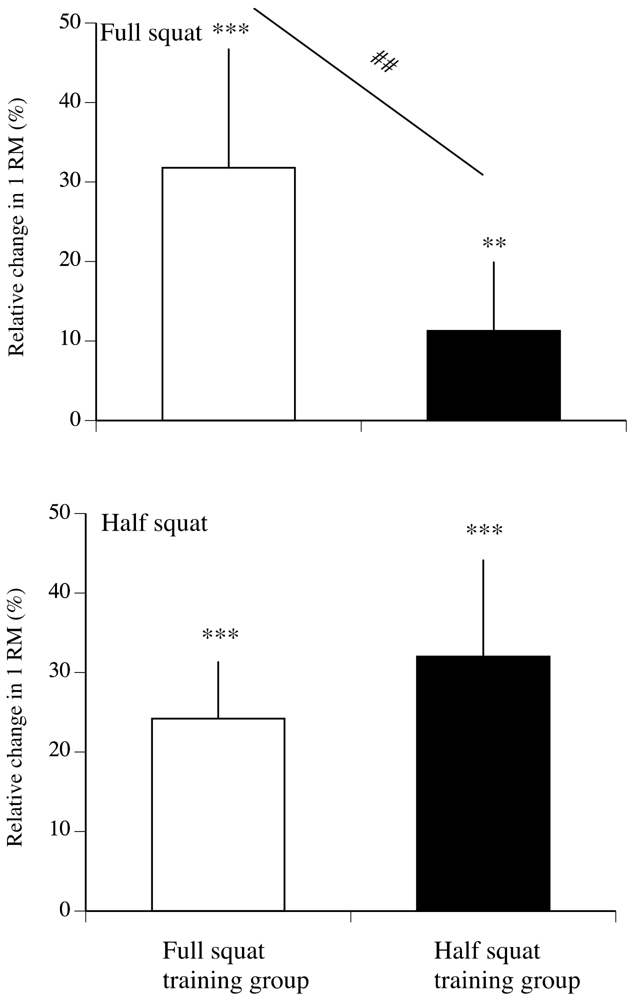

Fig. 3 Relative changes in one repetition maximum in full (upper) and half (lower) squat exercises for full squat training (open) and half squat training (closed) groups. *Significantly different from before (**$p < 0.01$, ***$p < 0.001$). #Significantly different between the two groups (##$p < 0.01$)

muscle volume of RF did not significantly change after training in FST ($p = 0.608$, ES = 0.08) or HST ($p = 0.233$, ES = 0.10). The volumes of each constituent of all hamstring muscles did not significantly change after training in either group ($p = 0.129$–0.911, ES = 0.01–0.07) (Table 3, Fig. 4b).

The volumes of the adductor muscles significantly increased by 6.2 ± 2.6% in FST ($p < 0.001$, ES = 0.55) and 2.7 ± 3.1% in HST ($p = 0.030$, ES = 0.33) (Fig. 4c). Similarly, the volume of the gluteus maximus muscle significantly increased by 6.7 ± 3.5% in FST ($p < 0.001$, ES = 0.35) and 2.2 ± 2.6% in HST ($p = 0.041$, ES = 0.14) (Fig. 4d). Relative increases in adductor and gluteus maximus muscle volumes were significantly greater in FST than in HST ($p = 0.026$, ES = 1.23 for the adductor muscles, $p = 0.008$, ES = 1.50 for the gluteus maximus muscle).

Discussion

The main results of the present study were that (1) 10 weeks of full and half squat training increased the volumes of the vasti muscles, but not rectus femoris or hamstring muscles, and (2) relative increases in the volumes of the adductor and gluteus maximus muscles were greater with full squat training than half squat training.

In the present study, the muscle volumes of the knee extensor muscles (except for the RF) equally increased after 10 weeks of squat training regardless of the squat depth. Previous studies reported no significant differences in the electromyographic activities of the knee extensor muscles among partial, half, and full squat exercises (Caterisano et al. 2002; Contreras et al. 2016; da Silva et al. 2017). The present results for the knee extensor muscles (except for the RF) were consistent with these findings. According to the findings of previous studies investigating the chronic effect of squat training on knee extensor muscle sizes (Bloomquist et al. 2013; McMahon et al. 2014), relative increases in the cross-sectional areas of the knee extensor muscles were significantly greater for squat training with a deep depth than that with a shallow depth. In these studies, however, the range of motion at the knee joint (50°–60°) for a shallow squat was less than that in HST of the present study (90°). In addition, the number of muscles and slices analyzed were limited in these studies. In any case, we considered our results on changes in the sizes of the vasti muscles to be accurate because we evaluated muscle volumes from all slices of magnetic resonance imaging from the origin to insertion of the muscles. Therefore, we may reasonably conclude that full squat training was equal to half squat training in regard to changes in the sizes of vasti muscles if the relative load was equal between full and half squat training.

Among the knee extensor muscles, only the size of RF did not change in FST and HST. Previous findings obtained using the transverse relaxation time from magnetic resonance images revealed that the activation level of the rectus femoris muscle was relatively lower than that of other vasti muscles (Ploutz-Snyder et al. 1995; Sugisaki et al. 2014). According to cross-sectional studies (Ema et al. 2014; Ikebukuro et al. 2011), the rectus femoris muscle for rowers and weightlifters, who frequently perform squat exercises without active hip flexion, was relatively smaller than that of untrained individuals. Accordingly, the present results on RF are consistent with these findings.

Regarding the hamstring muscles, FST and HST did not increase muscle sizes. Previous studies showed that the activation levels of the hamstring muscles measured by electromyography and magnetic resonance imaging were lower during squat exercises regardless of the squat depth

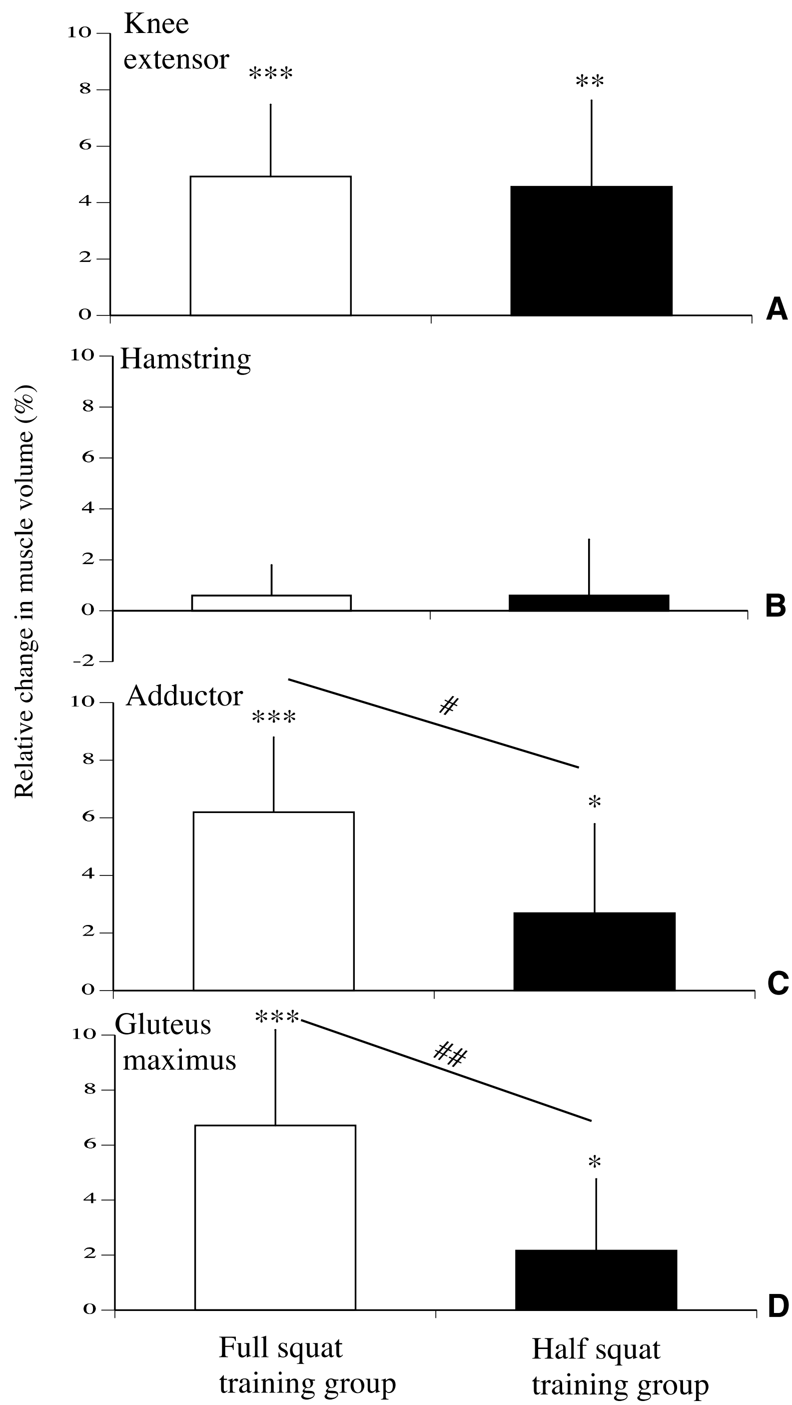

Fig. 4 Relative changes in knee extensor, hamstring, adductor, and gluteus maximus muscle volumes in full squat training (open) and half squat training (closed) groups. *Significantly different from before (*$p<0.05$, **$p<0.01$, ***$p<0.001$). #Significantly different between the two groups (#$p<0.05$, ##$p<0.01$)

Table 2 Muscle volume of each constituent of knee extensor muscles before and after training mean (sd)

	Full squat training group ($n=8$)		Half squat training group ($n=9$)	
	Before	After	Before	After
Rectus femoris muscle (cm^2)	291.8 (46.5)	290.9 (39.7)	286.2 (31.7)	287.3 (38.8)
Vastus lateralis muscle (cm^2)	639.0 (95.9)	682.7 (93.1)***	653.9 (71.5)	694.1 (83.3)**
Vastus intermedius muscle (cm^2)	556.3 (99.0)	576.0 (94.3)**	499.8 (63.7)	523.8 (63.0)**
Vastus medialis muscle (cm^2)	480.2 (72.5)	512.5 (72.5)***	457.5 (56.0)	488.1 (63.1)***

*Significantly different from before (**$p<0.01$, ***$p<0.001$)

Table 3 Muscle volume of each constituent of hamstring muscles before and after training mean (sd)

	Full squat training group ($n=8$)		Half squat training group ($n=9$)	
	Before	After	Before	After
Biceps femoris short head muscle (cm^2)	106.2 (20.2)	106.1 (20.3)	104.6 (22.2)	105.4 (22.2)
Biceps femoris long head muscle (cm^2)	194.0 (29.4)	195.2 (27.7)	192.3 (31.9)	193.4 (27.3)
Semitendinosus muscle (cm^2)	179.7 (26.9)	182.1 (24.7)	187.5 (39.4)	186.5 (36.1)
Semimembranosus muscle (cm^2)	237.7 (36.9)	238.2 (39.9)	214.9 (31.2)	217.0 (27.8)

(Caterisano et al. 2002; Contreras et al. 2016; Gorsuch et al. 2013). As a reason for the weaker activation of the hamstring muscles during squat exercises, Sugisaki et al. (2014) indicated that there was no change in the lengths of the hamstring muscles, and, thus, these muscles contract almost isometrically. Other researchers also indicated that squat training did not provide a sufficient training stimulus for the hamstring muscles (Ebben 2009; Wright et al. 1999). Bloomquist et al. (2013) showed that the cross-sectional area of the hamstring muscles did not change after 12 weeks of full and shallow squat training. Taking these previous findings into account together with the present results on the hamstring muscles, squat training regardless of depth was insufficient to induce hypertrophy of the hamstring muscles.

To date, little attention has been given to alterations in the size of the gluteus maximus muscle after resistance training, whereas the strength and power generation capabilities of hip extension are important for performance in various sports (e.g., Fukashiro and Komi 1987; Watanabe et al. 2000). To the best of our knowledge, this is the first study to demonstrate changes in the volume of the gluteus maximus muscle after squat training. According to previous findings on gluteus maximus muscle activity during squat exercises (Caterisano et al. 2002; Contreras et al. 2016; da Silva et al. 2017), the effects of the squat depth on gluteus maximus muscle activity were conflicting, although the reasons for the discrepancies were unknown. For example, Caterisano et al. (2002) showed that the electromyographic activity of the gluteus maximus muscle was higher during full squat exercises than partial squat exercises, whereas da Silva et al. (2017) reported the opposite finding. The present result agreed with the finding of Caterisano et al. (2002). From the relationship between the moment arm length and joint angle, the gluteus maximus muscle is able to exert higher hip extension torque in a more flexed position of the hip joint (Dostal et al. 1986). Furthermore, McCaw and Melrose (1999) and Paoli et al. (2009) reported that the electromyographic activity of the gluteus maximus muscle increased with wider stances during squat exercises. In the present study, however, this point did not affect the result on changes in the size of the gluteus maximus muscle, since all subjects were instructed that stance width during squat training was almost the same as shoulder width for FST and HST.

Similar to the gluteus maximus muscle, training-induced change in the adductor muscles has not been investigated, whereas the adductor muscles occupy approximately 25% of the muscle volume in the thigh (Akima et al. 2007). In the present study, the relative increase in the volume of the adductor muscles was significantly greater in FST than in HST (Fig. 4c). Previous studies demonstrated that the transverse relaxation times on magnetic resonance imaging of the vasti muscles and adductor muscles significantly increased after repeated parallel squat exercises (Ploutz-Snyder et al. 1995; Sugisaki et al. 2014). Anatomically, the adductor muscles contribute to extension and flexion as well as adduction of the hip joint (Pressel and Lengsfeld 1998). Furthermore, Dostal et al. (1986) reported that the adductor muscles contribute to hip extension when the hip joint is flexed. Therefore, the adductor muscles may function as hip joint extensors when the hip and knee joints flex deeply during full squat exercise, and this resulted in marked hypertrophy of adductor muscles after 10 weeks of full squat training. The results obtained for the gluteus maximus and adductor muscles indicate that full squat training will enhance performance during sprinting and jumping compared with half squat training.

There were several limitations of this study. First, the duration of muscle contractions during full squat exercise was longer than that during half squat exercise, although there was no significant difference in total work during training (load × repetition × moving distance) between FST and HST. This may be related to the present results on training-induced changes in the gluteus maximus and adductor muscles. Schott et al. (1995) showed that relative increases in the muscle strength and cross-sectional area were greater with a longer isometric contraction (30 s) than a shorter one (3 s). Practically, it was difficult to be equally the duration of muscle contractions during the full and half squat exercises. Second, the mechanical work during squat training was estimated from the load used, repetitions, and movement of the barbell. At present, however, it is difficult to directly measure "exerted muscle force" during exercises, except for measurements using the buckle technique and optic fibers (e.g., Komi et al. 1987). Third, we did not instruct about the angle of external rotation with the hip joint (i.e., direction of the toe) during squat training. This may be related to differences in the recruitment pattern of working muscles during squat training. Fourth, we did not analyze the cross-sectional area of each synergistic muscle for the adductor muscles because it was difficult to identify interfaces among the adductor magnus, adductor longus, and adductor brevis muscles. Watanabe et al. (2009) demonstrated that the adductor magnus muscle generated extension torque at the hip joint during pedaling, whereas the adductor longus muscle generated flexion torque at the hip joint. Therefore, there may be differences in training-induced changes in muscle volumes among the three muscles of the adductor muscles. Fifth, the present study was performed with a small sample size. In the present study, we calculated ES for relevant variables and statistical power of > 0.8 was obtained for the main significant changes, e.g., muscle volume. Therefore, we considered that this point did not affect the main results of this study.

Conclusion

The results suggested that the volumes of the vasti muscles increased equally after 10 weeks of full and half squat training, whereas those of rectus femoris and hamstring muscles did not. Furthermore, relative increases in the volumes of the adductor and gluteus maximus muscles were greater with full squat training than half squat training. Based on the results obtained for the gluteus maximus and adductor muscles, full squat training will enhance performance during sprinting and jumping compared with half squat training, since the capability of hip extension is important for performance in various sports (Fukashiro and Komi 1987; Watanabe et al. 2000). Taking the safety of subjects into account together with the present results, full squat training may be suitable for equally developing the lower limb muscles, except for the rectus femoris and hamstring muscles.

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Author contributions All authors approved to submit this manuscript. The contributions of all authors were as follows: KK: conception of this study, acquisition of data, drafting the manuscript; TI: acquisition of data, analysis data; HY: drafting figures and tables, conception of this study.

Compliance with ethical standards

Conflict of interest I have no conflict of interest with this work.

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