Original Article

doi: 10.16926/par.2026.14.02

The effect of squat-based strength training on the morphology of the vastus medialis muscle

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Authors' Contribution: A – Study Design, B – Data Collection, C – Statistical Analysis, D – Manuscript Preparation, E – Funds Collection

Abstract: This study aimed to examine the effects of a six-week strength-training program consisting of barbell and isometric squats on suprapatellar thigh circumference and vastus medialis obliquus (VMO) thickness in both lower limbs. Thirty participants (aged 18–24 years) were recruited for the study. Over six weeks (12 sessions), 17 participants completed a lower-limb strength-training protocol centered on squats; seven performed barbell squats, whereas ten performed isometric squats. The remaining 13 participants served as controls. The suprapatellar thigh circumference and ultrasound-derived VMO thickness were measured bilaterally at baseline and after the intervention. Ultrasonography was performed in three positions: supine, standing, and half-squat. The six-week lower-limb strength-training intervention in the experimental group produced a statistically significant bilateral increase in suprapatellar thigh circumference ($p < 0.001$). VMO thickness also increased significantly in the supine (right leg, $p < 0.05$; left leg, $p < 0.01$) and half-squat (right leg, $p < 0.001$; left leg, $p < 0.01$) positions. The mode of squatting (barbell vs. isometric) did not differentially influence the VMO morphology.

Keywords: strength training, thigh circumference, thickness, vastus medialis obliquus, ultrasonography

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Recevied: 05.07.2025; Accepted: 2.09.2025; Published online: 7.01.2026

Citation: Lachcik J, Helbin J, Saulicz E, Krzysztofik M. The effect of squat-based strength training on the morphology of the vastus medialis muscle. Phys Act Rev 2026; 14(1): 14-25. doi: 10.16926/par.2026.14.02

INTRODUCTION

Proper functioning of the knee joint largely depends on the harmonious cooperation of the thigh muscles in the form of synergy, syntony, and synchrony. Within the quadriceps femoris, a special role is indicated in the medial head mechanism. The head is often treated as a separate muscle unit referred to as the vastus medialis (VM) [1]. Anatomically, the vastus medialis muscle consists of a longitudinal part (vastus medialis longus [VML]) and an oblique part [2,3] (vastus medialis obliquus [VMO]), which perform different functions and are mainly responsible for generating the force needed to extend the knee, while the VMO stabilizes the patella [1]. The stability and proper movement of the patella in the patellofemoral joint, i.e. the so-called "tracking", are largely maintained by the dynamic balance between the VMO, rectus femoris (RF) and vastus lateralis (VL) [4–6]. Preferential strengthening of the VMO has been proposed to restore the previously described muscle imbalance and enhance dynamic medial stabilization of the patella [7]. VMO contains a higher percentage of fast-twitch fibers than the VL [8]. Consequently, VMO fibers exhibit low oxidative capacity but high force-generating potential [9]. Owing to this predominance of fast-twitch fibers, the VMO is particularly susceptible to strength training-induced hypertrophy [10]. In contrast, the VM has shorter muscle fibers that experience greater tensile stress and more frequent microtrauma during contraction. The VM also transmits force along a different vector than the VL, a distinction that may further increase its hypertrophic potential relative to the VL [11,12]. Appropriately targeted lower-limb resistance training can therefore induce VMO hypertrophy and restore dynamic balance among muscles that control patellar tracking.

Squats are among the most widely used exercises for strengthening and activating the lower limb muscles, and gains in muscle strength constitute a key factor in injury prevention [13,14]. Moreover, squats elicit substantial activation of the VM while maintaining joint safety through co-contraction of the surrounding musculature, which dynamically stabilizes the knee [15,16]. Additionally, variations in squat technique or load placement can alter muscle recruitment patterns [17]. The multi-joint movement pattern of the squat challenges the neuromuscular system, as coordinated action of the hip and knee joints is required to perform the movement [18]. An additional factor that complicates exercise is the type of work (concentric, isometric, eccentric) of muscles running through more than one joint, which increases the complexity of the exercise compared to exercises performed in an open kinematic chain [18]. One of the most popular forms of squat exercise used in strength training is the barbell squat, which is commonly used to increase the strength of the lower limb muscles and their hypertrophy [19]. Many training programs incorporate either dynamic or isometric squats [20,21]. Because isometric contractions develop joint-angle–specific force, whereas dynamic barbell squats distribute loading across the range of motion with phase-dependent recruitment, these modalities are expected to differ in their neuromuscular and morphological effects; nonetheless, they are often combined in practice[17,22,23]. The review by Oranchuk et al. [22] shows that there are different neuromuscular properties between two types of isometric contractions: "pushing isometric muscle action" type (i.e. exerting force on a stationary object) and "holding isometric muscle action" (maintaining the position of the joint against an external force). The significant advantages of isometric training include generating greater force in the trained joint angle compared with classical strength training, immediate analgesic effect of this type of contraction, and precise control of force in the painless range of motion, which may be particularly useful in rehabilitation [22,24].

Despite the widespread use of squats in both athletic conditioning and rehabilitation, conclusive data comparing the efficacy of isometric and dynamic squat modalities in producing muscle-specific adaptations in the VMO are still lacking. Accordingly, additional research is required to furnish practitioners with evidence-based guidance on selecting the most effective training method for inducing selective VMO hypertrophy. Such knowledge could help optimize training and rehabilitation protocols, particularly for injury prevention and the management of patellofemoral pain syndrome.

Ultrasonography is well suited for this purpose because it enables the real-time assessment of muscle morphology in multiple joint positions. In this setting, an ultrasonographically detected increase in muscle thickness signifies concentric contraction, whereas a decrease indicates eccentric contraction. In summary, to date, no study has directly compared dynamic barbell and isometric squat training on VMO morphology using ultrasonography across functional positions (supine, standing, half-squat).

The aim of the present study was to evaluate changes in suprapatellar thigh circumference and VMO thickness, measured ultrasonographically in supine, standing, and half-squat positions, before and after a six-week training program consisting of either dynamic or isometric barbell squats.

MATERIAL AND METHODS

Design

The study was authorized by the Bioethics Committee for Scientific Studies at the Jerzy Kukuczka Academy of Physical Education in Katowice (No. 02/2023). All study procedures were performed according to the Helsinki Declaration of Human Rights of 1975, amended in 1983. All participants gave their consent to participate after being informed of the study objectives and procedures. The research was completely voluntary and completely anonymous at the stage of collecting and processing the results.

Participants

The study involved a group of 33 female and male students of physical education, coaching, and physiotherapy at the Jerzy Kukuczka Academy of Physical Education in Katowice (Poland), aged 18–24 years. The subjects were divided into two groups: experimental and control. The inclusion criteria for both groups were good general health, no injuries or musculoskeletal injuries in the preceding 12 months, no medical contraindications to moderately intensive physical exercise, and written informed consent to participate in the study. First, subjects were recruited from the experimental group. For this purpose, information about the planned experiment was posted on the Jerzy Kukuczka Academy of Physical Education campus. Of the 25 participants who declared their willingness to participate in the study, 20 met the inclusion criteria. The participants in the control group were recruited in a similar manner. Of the people who declared their willingness to participate in the study, 13 met the inclusion criteria. In the experimental group, three people were unable to participate in all planned training sessions due to unforeseen health reasons (a cold) and were therefore not included in the final analysis. In the control group, all participants who participated in the initial measurement completed the final measurement. Finally, the results of 17 and 13 participants from the experimental and control groups, respectively, were included in the statistical analysis. The characteristics of the participants from both groups and the inter-group comparisons are presented in Table 3.

Randomization

Randomization consisted of participants drawing cards bearing the name of the group. Participants who drew the name "barbell squat" were assigned to experimental group A. Participants who drew a card with the name "isometric squat" were assigned to Experimental Group B. Random allocation of participants to groups was carried out by a person who neither took part in the study nor conducted the strength-training.

Circumference measurements and ultrasound assessments of vastus medialis thickness were performed by investigators experienced in such procedures (JL and ES), who were blinded to group allocation. The same investigators performed the final tests and remained unaware of each participant's group affiliation (experimental groups A or B, or the control group). The results were recorded directly from the ultrasound monitor onto specially designed data sheets by a person who did not perform ultrasound measurements.

Research methodology

Before the study began, the subjective sense of the level of habitual physical activity was assessed. For this purpose, the Baecke questionnaire was used [25].

In each subject, thigh circumference was measured twice, one week before the start of the training intervention and one week after its completion, at a distance of 6 cm from the base of the patella [26]. Measurements were performed on both the lower limbs in a relaxed supine position. At the same time, the VMO thickness was measured in both lower limbs. The thickness of this muscle was assessed using an ultrasound system (SonoScape, E2) with a 4-16 MHz linear transducer. Before the measurement, the location where the ultrasound probe was applied was precisely determined by marking a point located 2 cm above the base of the patella [27] during isometric tension of the thigh muscles. Half of the VMO width was determined at the level of the previously marked point above the patella and this location was marked with a line. In subsequent measurements, the ultrasound probe was applied perpendicular to the long axis of the limb, such that the marked location was located halfway along the applied probe. Ultrasound measurements of VMO thickness were performed on both lower limbs in a relaxed supine position, in a relaxed standing position with feet hip-width apart, and in half squats. Each measurement in all positions and on both limbs was repeated three times, and the average value of these three measurements was used for further statistical analyses [28]. In order to maintain randomness in the order of measurements, they were performed in such a way that if the measurement was started from, for example, the right lower limb, then in the next examined person the first measurement was performed on the left lower limb [29]. This research procedure was performed by members of the research team (JL and ES) who had the appropriate qualifications to perform ultrasound examinations and many years of experience in ultrasound assessment of muscles.

Methodology of the strength training

During the 6-week training program, 12 sessions were conducted. There was a 2-day break between subsequent training sessions. Each training session, lasting 90 min, began with a 15-min warm-up. The warm-up consisted of subjects riding a stationary bike for 5 min and performing a series of preliminary squats. The actual training phase lasted 65 min. During the first training session, the correct technique for performing a barbell squat (experimental group A) and an isometric squat (experimental group B) was demonstrated. After finding the right individual rhythm and range of the squat, training in Experimental Group A consisted of performing a barbell squat on the back. In experimental group B, strength training of the lower limb muscles was performed using an isometric squat in which the participants assumed a squat position (90° of knee flexion) and pressed against a stationary barbell to move it. Participants were randomly allocated to two subgroups. Group A performed dynamic barbell back squats only, and Group B performed isometric squats at 90° knee flexion only, according to the schedule (Table 1).

Table 1. Load progression in the dynamic and isometric squat in experimental groups A and B

Exercise	week 1	week 2	week 3	week 4	week 5	week 6
Experimental Group A	4x8 70%1RM[1] 2/0/1/1[2]	4x8 75%1RM[1] 2/0/1/1[2]	4x6 80%1RM[1] 2/0/1/1[2]	4x4 82.5%1RM[1] 2/0/1/1[2]	4x5 82.5%1RM[1] 2/0/1/1[2]	4x5 85%1RM[1] 2/0/1/1[2]
Experimental Group B	4x(3x3”) 80%MVIC[3]	4x(3x3”) 90%MVIC[3]	4x(4x3”) 95%MVIC[3]	4x(4x3”) 100%MVIC[3]	4x(5x3”) 100%MVIC[3]	4x(5x4”) 100%MVIC[3]

[1] One repetition maximum (1RM), [2] Tempo of movement eccentric/isometric/concentric/isometric, [3] Maximum voluntary isometric contraction

Table 2. Structure of the lower limb resistance training program used in both experimental groups.

Exercise	sets	reps	tempo	exercise intensity	rest
Squat variation	4	According to the Tab. 1	According to the Tab. 1	According to the plan	3’
Romanian deadlift	4	8	2/0/1/1[2]	RPE[1] 7-8	2’
Rear foot elevated split squat	3	10 each side	2/0/1/1[2]	RPE[1] 8-9	2’
Machine lying leg curl	3	10	2/0/1/1[2]	RPE[1] 8-9	2’
Standing calf raise	3	10	2/0/1/1[2]	RPE[1] 8-9	2’

[1]Rating of Perceived Exertion, [2] Tempo of movement eccentric/isometric/concentric/isometric

Statistical analysis

To assess the homogeneity of the groups for quantitative characteristics, the t-test for independent samples and the U-Mann-Whitney Test (in the case of deviation of the distribution of the studied characteristics from the normal distribution) were used, as well as the Chi2 test for comparisons of qualitative characteristics. The normality of data distribution was checked using Shapiro–Wilk tests. The assessment of the effects of strength training was made using the analysis of variance (ANOVA) for repeated measures with between subjects factor being group (experimental vs. control) and within subjects factor being study (“baseline” vs. “final”). Additionally, the effect of the main exercise variant was analyzed (barbell squat—Experimental Group A; isometric squat—Experimental Group B). When statistical significance for the main effect was achieved, pairwise comparisons were performed using the post-hoc Tukey test. Significance for statistical tests was set a priori at $p < 0.05$.

RESULTS

The comparison of both groups (Table 3) did not show any statistically significant differences in basic demographic data (sex) and biometric data (age, body mass and height, BMI) between the subjects participating in the strength-training program and the subjects from the control group. The level of habitual physical activity was similar between groups. Therefore, it can be stated that both groups were homogeneous in this respect. This allowed us to ignore the influence of sex, body mass, height, and possible overweight and obesity on the circumference of the thighs above the knee and the thickness of the VMO. Additionally, comparisons between the experimental groups (A and B) did not reveal any significant differences in age (p=0.409), body mass (p=0.923), height (p=0.889), and BMI (p=0.815). Both experimental groups were homogeneous with respect to sex (p =0.761) and habitual physical activity (p =0.982).

The mean values of above-knee thigh circumference for both (experimental and control) and the ANOVA test results are presented in Table 4. Analogous results for both experimental groups (A and B) are presented in Table 6. Post hoc analysis showed that there were no statistically significant differences between the lower limbs. Significant intergroup differences were observed at the final examination. In both the lower limbs, larger circumferences were recorded in the experimental group (p<0.01 in the right limb (p<0.001 in the left limb). In the experimental group, there was a therapy effect, in which the increase in circumference by an average of 2.35 cm in the right limb and by 2.59 cm in the left limb proved to be statistically significant (p<0.001 in the post hoc test). In the control group, no significant differences were observed between the 1st and 2nd measurement (p=0.802 – right lower limb, p=0.535 – left lower limb). Comparisons of analogous circumference measurements between subjects from both experimental groups (A and B) (Table 6) in post hoc analysis showed significant intragroup differences between initial and final measurements for both the right and left lower limbs (group A: p<0.001 for right leg and p<0.01 and accordingly for group B: p<0.01 for both lower limbs). In both studies (initial and final) no intergroup differences were observed.

The mean values of the VMO thickness measurements in both studies (initial and final) and in the analyzed reference systems (resting supine position, free-standing position, and half-squat) for the experimental and control groups are presented in Table 5. Post hoc analysis showed a significant increase in VMO thickness in both lower limbs in the experimental group (p<0.05, right side; p<0.001, left side), which resulted in the emergence of a statistically significant difference between the experimental and control groups (post hoc test: p<0.01, right side; p<0.001, left side). In the standing position, analysis of variance for repeated measurements did not show significant intra- and intergroup differentiation in either study. However, the effect of strength training was clearly visible in the functional test, which was performed in the half-squat position. In the post hoc analysis, it was shown that the significant effect of measurement and interaction between measurement and group was associated with a statistically significant increase in VMO thickness on both the right and left sides (thickness increase by 3.25 mm on the right side, p<0.001 and by 3.7 mm on the left side, p<0.001). As a result, between the groups (experimental and control) in the final examination, a statistically significant greater thickness of the analyzed muscles was noted in the experimental group on the right side by 3.11 mm (p<0.001) and on the left side by 2.41 mm (p<0.05). Analysis of the results obtained in both experimental groups (A and B; Table 7) showed a similar effect on changes in VMO thickness in both lower limbs. In the supine position, only the left side was confirmed in the post hoc analysis (p<0.01 in both groups). In the standing position, no significant effect of the applied methods on shaping VMO strength and mass was observed. This effect was noted in the thicknesses of the vastus medialis obliquus measured in the half-squat position on both sides of the body in the group of people performing isometric squats (thickness increase of 3.46 mm on the right side, p<0.05 and 4.23 mm on the left side, p<0.01). The statistical significance of the analogous increases in VMO thickness of 2.93 mm on the right side and 2.96 mm on the left side in the half-squat position, recorded in people performing barbell squats, was not confirmed statistically. No significant intergroup differences were observed in either the initial or final study.

Table 3. Demographic data of the participants in the Experimental and Control Group

Variable	Experimental Group (n=17)	Control Group (n=13)	Statistic
Women (%) Men (%)	3 (17.65) 14 (82.35)	3 (23.08) 10 (76.92)	χ^2=0.135[1] p=0.713
Age ± SD [years] Range	20.7 ±1.8 18-24	21.6 ±1.7 19-24	t=-1.562[2] p=0.130
Weight ± SD [kg] Range	80.6 ±9.1 62-96.3	76.9 ±11.5 60-103	t=0.988[2] p=0.331
Height ± SD [cm] Range	179.3 ±6.5 167-190	177.8 ±8.9 164-197	t=0.542[2] p=0.592
BMI ± SD [kg/m^2] Range	25.04 ±2.1 21.5-28.23	24.25 ±2.3 19.84-27-14	t=0.989[2] p=0.330
IHPA ± SD [pkt] Range	10.2 ±0.8 8.5-11.5	9.9 ±1.3 6.88-12.0	U=0.356[3] p=0.722

IHPA - Index of habitual physical activity, [1] Chi^2 test, [2] t test for independent samples, [3] U-Mann-Whitney test

Table 4. The results of measurements circumference of the thigh above the knee in the Experimental and Control Group

C	Experimental Group		Control Group		ANOVA		
	Initial M mean±SD 95% CI	Final M mean±SD 95% CI	Initial M mean±SD 95% CI	Final M mean±SD 95% CI	Main effect: Group	Main effect: M	Interaction
on the right side	44.65 ±3.3 42.96-46.34	47.0 ±3.2 45.35-48.65	45.04 ±3.2 43.11-46.96	45.46 ±4.2 42.93-47.99	F=0.216 p=0.646	F=20.043 p<0.001*	F=9.687 p=0.004*
on the left side	44.44 ±2.8 43.0-45.88	47.03 ±2.6 45.69-48.37	44.5 ±2.8 42.81-46.19	45.12 ±3.2 43.2-47.04	F=0.864 p=0.361	F=28.341 p<0.001*	F=10.748 p=0.002*

C - Circumference, Initial M - initial measurement, Final M - final measurement, M – Measurement,
* statistically significant

Table 5. The results of thickness of m. vastus medialis obliquus in the Experimental and Control Group

BP	Experimental Group		Control Group		ANOVA		
	Initial M mean±SD 95% CI	Final M mean±SD 95% CI	Initial M mean±SD 95% CI	Final M mean±SD 95% CI	Main effect: Group	Main effect: M	Interaction
Supine position right side	30.87 ±3.5 29.08-32.67	33.21 ±3.7 31.3-35.11	30.09 ±6.4 26.22-33.96	30.29 ±6.7 26.21-34.37	F=1.073 p=0.309	F=4.757 p=0.038*	F=3.373 p=0.077
Supine position left side	30.36 ±4.1 28.27-32.45	33.9 ±2.9 32.41-35.4	31.12 ±6.3 27.34-34.88	30.42 ±6.4 26.57-34.26	F=0.605 p=0.443	F=11.021 p=0.002*	F=24.424 p<0.001*
Standing right side	33.99 ±4.2 31.84-36.14	35.16 ±3.1 33.55-36.77	31.62 ±5.1 28.52-34.72	31.74 ±5.5 28.43-35.05	F=3.317 p=0.079	F=2.491 p=0.126	F=1.638 p=0.211
Standing – left side	34.1 ±4.4 31.9-36.35	34.8 ±3.3 33.13-36.48	32.57 ±5.3 29.4-35.74	32.73 ±5.1 29.69-35.78	F=1.270 p=0.269	F=1.298 p=0.264	F=0.496 p=0.487
Squat right side	33.01 ±3.1 31.44-34.59	36.26 ±2.5 34.97-37.54	32.58 ±5.5 29.24-35.91	33.11 ±6.1 29.45-36.78	F=1.366 p=0.252	F=16.349 p<0.001*	F=8.368 p=0.007*
Squat left side	32.24 ±3.7 30.32-34.16	35.94 ±2.6 34.61-37.28	34.02 ±4.9 31.01-37.03	33.53 ±5.7 30.1-36.96	F=0.046 p=0.832	F=9.248 p=0.005*	F=15.784 p<0.001*

BP - Body position/activity , Initial M - initial measurement, Final M - final measurement, M - Measurement
* statistically significant

Table 6. The results of measurements circumference of the thigh above the knee in experimental groups: A (barbell squats) and B (isometric squats)

C	Experimental Group A (barbell squats)		Experimental Group B (isometric squats)		ANOVA		
	Initial M	Final M	Initial M	Final M	Main effect		Interaction
	mean±SD 95% CI	mean±SD 95% CI	mean±SD 95% CI	mean±SD 95% CI	Group	M	
on the right side	44.71 ±3.3 41.63-47.8	47.86 ±4.1 44.1-51.61	44.6 ±3.4 42.15-47.05	46.4 ±2.5 44.6-48.2	F=0.246 p=0.627	F=40.832 p<0.001*	F=3.014 p=0.103
on the left side	44.36 ±2.5 42.03-46.68	47.5 ±3.1 44.65-50.35	44.5 ±3.1 42.28-46.72	46.7 ±2.3 45.04-48.36	F=0.065 p=0.803	F=36.014 p<0.001*	F=1.122 p=0.306

C - Circumference, Initial M - initial measurement, Final M - final measurement, M – Measurement,
* statistically significant

Table 7. The results of thickness of m. vastus medialis obliquus in experimental groups: A (barbell squats) and B (isometric squats)

BP	Experimental Group A (barbell squats)		Experimental Group B (isometric squats)		ANOVA		
	Initial M	Final M	Initial M	Final M	Main effect		Interaction
	mean±SD 95% CI	mean±SD 95% CI	mean±SD 95% CI	mean±SD 95% CI	Group	M	
Supine position right side	30.61 ±4.1 26.46-34.75	33.21 ±5.0 28.57-37.85	31.06 ±2.9 29.01-33.11	33.2 ±2.8 31.22-35.18	F=0.020 p=0.889	F=6.055 p=0.026*	F=0.055 p=0.817
Supine position left side	30.46 ±4.1 26.72-34.2	34.58 ±3.1 31.72-37.43	30.29 ±4.3 27.23-33.35	33.43 ±2.8 31.39-35.47	F=0.158 p=0.697	F=27.642 p<0.001*	F=0.502 p=0.489
Standing right side	34.20 ±4.5 30.0-38.4	35.81 ±3.6 32.44-39.18	33.84 ±4.2 30.87-36.81	34.71 ±2.8 32.68-36.74	F=0.172 p=0.684	F=3.588 p=0.078	F=0.321 p=0.579
Standing left side	34.58 ±4.5 30.38-38.78	35.61 ±3.6 32.31-38.91	33.76 ±4.5 30.56-36.95	34.24 ±3.1 32.02-36.46	F=0.353 p=0.561	F=1.522 p=0.236	F=0.196 p=0.664
Squat right side	33.29 ±3.7 29.9-36.67	36.22 ±2.3 34.1-38.35	32.82 ±2.8 30.84-34.81	36.28 ±2.8 34.31-38.25	F=0.029 p=0.867	F=17.802 p<0.001*	F=0.119 p=0.735
Squat left side	33.4 ±3.7 29.99-36.81	36.36 ±1.7 34.76-37.95	31.42 ±3.7 28.76-34.09	35.65 ±3.1 33.42-37.89	F=0.971 p=0.340	F=19.066 p<0.001*	F=0.602 p=0.449

BP - Body position/activity , Initial M - initial measurement, Final M - final measurement, M - Measurement
* statistically significant

DISCUSSION

The present findings confirm that a six-week training intervention aimed at increasing lower limb strength and muscle mass, with squats as the primary exercise, induces significant morphological changes in the VMO. This aligns with the results of Khoshkhoo et al. [30], who reported a significant increase in the mean VMO pennation angle after a 6-week program. A literature review by Counts et al. [31] revealed substantial differences in reported rates of muscle hypertrophy. For the lower limbs, some studies found no significant changes in muscle size even after 5–12 weeks of strength training [32,33], whereas others recorded noticeable hypertrophy after only 3–4 weeks of resistance exercise [34–38]. The earliest macroscopic signs of muscle hypertrophy were observed after only 20 days (nine training sessions) in one study [12]. VMO thickness was measured using ultrasonography, a safe, non-invasive, effective, and accurate method for assessing VMO architecture [39,40], which is also less expensive and more accessible than other techniques used to evaluate muscle hypertrophy [41,42].

According to scientific reports, measurements intended to detect hypertrophy must account for the acute physiological processes elicited by resistance training that generate an inflammatory response [43]. These reactions temporarily increase muscle volume and distort hypertrophy measurements [44]. Therefore, all assessments were carried out one week before the intervention and one week after its completion. Both suprapatellar thigh circumference and ultrasonographically measured VMO thickness in the supine and half-squat positions increased significantly in the experimental group. Subgroup analysis showed a significant increase in the supine position on the left side in both subgroups, whereas right-side changes did not reach statistical significance. The absence of significant differences in the control group allowed us to attribute the observed increases in muscle thickness and thigh circumference solely to applied training stimuli.

Analysis of the images obtained at the three test positions revealed clear position-specific adaptations. In the relaxed standing position, no significant architectural changes were observed, possibly because this posture provides a less precise mapping of VMO activation and is more influenced by whole-body stabilizing mechanisms, which can mask local changes in a single muscle. In contrast, the relatively small knee flexion angle in the half-squat position produced the greatest increase in the muscle thickness, indicating that the VMO responds most strongly to loading within the trained joint angles, where it serves as a stabilizer of the knee joint [45]. Similar angle- and position-specific adaptations of neuromuscular patterns have also been demonstrated in studies on combat sports techniques, where kinematics and muscle activation strongly depend on the motor task and its execution conditions [46].

Moreover, because of the similarity of the test position (half-squat) to the main exercise performed, neuromuscular adaptations may have occurred, leading to stronger VMO activation during measurements in this specific position [45]. This angle-specific response also underscores several caveats of isometric training. Although isometric squats are effective for angle-specific strength gains and may induce morphological adaptations, several limitations warrant consideration [22]. Their effects are largely joint-angle specific, which can restrict transfer across the full range of motion. Moreover, isometric efforts provide little eccentric loading, which is an established hypertrophic stimulus, and they do not reproduce the velocity- and coordination-dependent demands of dynamic multi-joint movements. The half-squat position requires significant engagement of the target muscle [47], which makes it a more sensitive test for detecting differences before and after rehabilitation and training interventions. A comparison of the two exercise variants showed that an isometric squat at 90° knee flexion, characterized by a prolonged time under tension, produced a greater increase in VMO thickness in the half-squat position than in the dynamic barbell squat. Longer exposure to tension imposes a greater mechanical load on the muscle, which translates into a more pronounced increase in thickness [13]. In contrast, the variable moment of force during the dynamic squat distributes the load across a larger number of structures, potentially limiting the selective adaptation of a single muscle. Although the absolute increases were similar in both subgroups, those observed in the dynamic barbell squat group did not reach statistical significance. This should not be taken as evidence of greater effectiveness of the isometric variation, as between-subgroup differences were not significant and power to detect small effects was limited due to the small sample sizes of the subgroups. A review by Soares et al. [48] showed that higher-intensity training protocols, ranging from 70–80 % of 1RM, produced better results for muscle-thickness gain. In our study, participants performed dynamic squats at 70–85 % 1RM, whereas isometric squats were carried out in line with guidelines for enhancing explosive strength [24]. This approach yielded a satisfactory increase in muscle thickness. From a practical standpoint, it is important that the observed gains were essentially symmetrical; although slightly greater increases were noted on the left side in both the supine and half-squat positions, these differences were not statistically significant. Accordingly, both squat variations can be used to promote symmetrical hypertrophy, which is an important factor in preventing knee joint dysfunction and lower limb muscle imbalances. The importance of common methodological frameworks in physical activity sciences has also been underlined in recent works that emphasize the need for consensus and standardization of research tools [49].

LIMITATION

This study has several limitations that should temper interpretation. The experimental subgroups were small and women were under-represented, which limits statistical power and the generalisability of the findings. All participants were healthy, physically active young adults; therefore, the results should not be directly extrapolated to populations with disease-related muscular deficits. The intervention lasted only six weeks with no post-intervention follow-up, so the durability and functional relevance of the observed changes remain uncertain. Both experimental subgroups completed an identical accessory programme alongside the assigned squat variation, which limits the ability to isolate the independent effect of squat modality on VMO morphology; accordingly, between-modality comparisons should be regarded as exploratory and underpowered. Previous physical activity was not objectively controlled beyond the Baecke questionnaire, so unmeasured training loads or lifestyle factors may have influenced adaptations. Ultrasonography quantified VMO thickness as a surrogate of muscle size; other architectural variables (e.g., fascicle length, pennation angle) and tendon or functional outcomes were not assessed. Taken together, these limitations support cautious interpretation and highlight the need for larger, sex-balanced trials with longer follow-up—including clinical cohorts with knee joint pathologies—and study designs that better isolate the squat component; given that this is among the first studies to track position-specific morphological adaptations, confirmatory research is warranted.

CONCLUSION

In healthy young adults, a 6-week squat-based program was associated with small-to-moderate increases in VMO thickness, most evident in the half-squat position. Subgroup differences between dynamic and isometric squats were not significant; therefore, any apparent advantage of the isometric variant should be considered tentative. From a practical standpoint, dynamic barbell squats should remain the primary option when the goal is strength and hypertrophy across the range of motion (ROM) and transfer to athletic tasks. Isometric squats at 90° knee flexion may be a pragmatic, joint-friendly alternative when pain, instability, or ROM limitations preclude dynamic loading, or when angle-specific force and joint control are prioritized; they require minimal equipment and may reduce peak knee shear forces [50]. Coaches may alternate or combine both modalities within a training cycle based on constraints and goals.

Funding Statement: This research received no external funding.

Acknowledgments: We sincerely thank all participants for their contributions to this study.

Conflicts of Interest: The authors declare no conflict of interest.

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