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Article

Vastus Lateralis Cross-Sectional Area Is Associated with Squat Strength and Power in Young Female Acrobatic Gymnasts

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Featured Application

Combining ultrasound-derived assessment of vastus lateralis cross-sectional area at the mid-thigh (35–50% of femur length) with force–velocity profiling may provide a practical framework for guiding and monitoring hypertrophy-focused strength training to enhance squat force–power performance in young elite acrobatic gymnasts.

Abstract

Muscle size and architecture contribution to force and power production in young female acrobatic gymnasts (ACRO) remains unclear. This study examined the associations between quadriceps muscle size and architecture and strength–power performance in young elite female ACRO. Twenty athletes (12–18 years) underwent ultrasound assessment of rectus femoris (RF) and vastus lateralis (VL) cross-sectional area (CSA), muscle VL volume, VL fascicle length, and VL pennation angle. Performance testing included one-repetition maximum (1RM) squat and hang power clean (HHPC), squat power (Pmax), and countermovement jump (CMJ). In adjusted (Tanner stage and height) linear regression models, VL CSA at 35% ($\beta = 2.38$ kg per cm^2 , 95% CI 0.24–4.51; $p = 0.031$) and 50% femur length ($\beta = 2.31$ kg per cm^2 , 95% CI 0.60–4.01; $p = 0.011$) were associated with 1RM squat ($R^2 = 0.46$). Similarly, VL CSA at 35% ($\beta = 45.75$ W per cm^2 , 95% CI 21.74–69.77; $p < 0.001$) and 50% ($\beta = 38.43$ W per cm^2 , 95% CI 17.93–58.94; $p < 0.001$) were associated with Pmax ($R^2 = 0.50$). No associations were observed for CMJ, HHPC or RF. Mid-thigh VL size appears to be an independent predictor of squat strength and power in ACRO.

Keywords: muscle morphology; neuromuscular performance; ultrasonography; force–velocity profiling; adolescent athletes; resistance training; lower-limb power; elite

1. Introduction

In sport performance contexts, athletes’ morphological and neuromuscular characteristics are shaped by both sport-specific demands and training exposure, and these features may partly explain inter-individual differences in strength and power capacities [1–3]. Acrobatic gymnastics is an early-

specialization discipline that has grown substantially among young female athletes and combines highly technical choreographic elements with demanding strength-based tasks performed individually and in pairs or groups [1,4]. Within this sport, athletes typically adopt distinct roles. “Bases”, who are generally taller and heavier than “tops”, must generate high levels of lower-limb force and maintain stability to support partner loading during static pyramids and transitional phases, whereas “tops” rely relatively more on low body mass and flexibility [1]. Consequently, lower-limb force and power are central determinants of performance, particularly for bases who repeatedly execute forceful actions under time constraints and partner-induced loads [5,6].

Strength and power are not only determined by neural factors and training status but are also strongly influenced by skeletal muscle morphology and architecture. Muscle cross-sectional area (CSA) is a primary determinant of maximal force-generating capacity, while architectural features such as fascicle length and pennation angle modulate force transmission and contraction velocity, thereby contributing to power output and force-velocity behavior [7]. These muscle parameters can be assessed non-invasively and reliably using ultrasonography [8], enabling sport-specific profiling, and potentially informing individualized training prescriptions [7]. In parallel, the force-velocity (F-V) relationship provides an integrative description of an athlete’s mechanical capacities across the spectrum from high-force/low-velocity to low-force/high-velocity actions, and it has been widely used to characterize performance profiles in multi-joint tasks such as squatting and jumping [9,10]. In gymnastics sports, the ability to produce high force rapidly is critical for both explosive actions (e.g., take-offs) and quasi-isometric/static elements requiring high joint moments and postural control [6,11].

Despite the relevance of muscle architecture and mechanical profiling in youth athletes, evidence remains limited in young female acrobatic gymnasts, and especially in bases, who face unique loading patterns (partner support, sustained static holds, and repeated transitions). Previous studies have examined anthropometric profiles across acrobatic gymnastics categories [1] and neuromuscular training effects on muscle architecture and stretch-shortening cycle function in trained female young gymnasts [11]. However, it is still unclear whether quadriceps femoris architecture is independently associated with strength and power outcomes once biological maturation and body size are considered. This gap is practically relevant because identifying the morphological correlates of performance may help practitioners optimize strength and power development while accounting for maturation-related changes in adolescence [7].

Therefore, this study aimed to examine the associations between quadriceps muscle size and architecture, focusing on rectus femoris (RF) and vastus lateralis (VL) CSA, muscle volume, VL fascicle length, and VL pennation angle, and strength and power performance outcomes (one-repetition maximum (1RM) in the back squat (SQ) and hang power clean from the mid-thigh position (HHPC), squat power, and countermovement jump height (CMJ)) in young elite female acrobatic gymnasts performing the base role. Additionally, we evaluated whether these associations remained after adjustment for pubertal maturation (Tanner stage) and height. We hypothesized that vastus lateralis muscle morphology would be positively associated with squat strength and power, and that these relationships would persist after controlling for maturation and height.

2. Materials and Methods

2.1. Participants

Twenty young elite female acrobatic gymnasts (12–18 years) performing the base role voluntarily participated in this cross-sectional study. Athletes were recruited from a single high-level acrobatic gymnastics club (Acrobatik, Comunidad Valenciana, Spain) and were actively training (~4 sessions·week⁻¹, 90–120 min·session⁻¹). All participants had at least one year of experience with structured resistance training and were familiar with the exercises and testing procedures. Inclusion criteria were: (i) current participation in acrobatic gymnastics as a base athlete; (ii) competitive level (national or international); and (iii) ability to perform maximal-effort testing. Exclusion criteria were: (i) performing the top role; (ii) current musculoskeletal injury or recent injury limiting maximal

performance; and (iii) any medical condition or contraindication to intense exercise. Participants and their legal guardians received written and verbal information about study procedures, potential risks, and benefits, and provided written informed consent prior to testing. Athletes were instructed to avoid strenuous exercise for 48 h before each testing session and to attend the training facility in a rested state. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Technical University of Madrid (approval code: 2022-038).

2.2. Experimental Approach to the Problem

The present study was a cross-sectional, observational, non-controlled design aimed at examining the associations between quadriceps muscle morphology and strength–power performance in young elite female acrobatic gymnasts (ACRO) performing the base role. Two testing sessions were carried out, separated by 48–72 h, by the same evaluators during the competitive season (July 2024) at the athletes' regular training facilities (Club Acrobatic, Comunidad Valenciana, Spain). On the first testing session, biological maturation, anthropometry, body composition, ultrasound-derived muscle architecture, and CMJ performance were assessed. On the second session, participants performed an incremental squat loading protocol to determine the individual force–velocity (F–V) relationship, followed by one-repetition maximum (1RM) testing in the squat and hang power clean exercises. All testing sessions were conducted in the morning to minimize circadian variability.

2.3. Procedures

2.3.1. Biological Maturation

Biological maturation was assessed using self-reported pubertal development according to the Tanner scale (stages I–V) [12]. Participants completed a standardized questionnaire based on schematic drawings representing breast and pubic hair development, selecting the stage that best matched their status. Tanner stage was used as an indicator of pubertal maturation and was considered both as a continuous covariate in the adjusted regression models and as a categorical variable for descriptive comparisons. For between-group analyses, athletes were classified as pre/mid-pubertal (Tanner stages 1–3) or post-pubertal (Tanner stages 4–5) [13]. This stratification was applied due to muscle mass and performance differences depending on maturational status.

2.3.2. Anthropometry and Body Composition

Height was measured using a calibrated stadiometer (± 0.1 cm) (Seca, Hamburg, Germany), with participants barefoot and positioned according to standardized procedures previously reported [14]. Body composition was assessed by a segmental bioelectrical impedance analyzer (Tanita BC-601 Segment, Tanita Corp., Tokyo, Japan). All participants followed a standardized protocol (e.g., removal of metal accessories, voiding immediately beforehand, and in absence of menstruation) to minimize measurement variability. The variables obtained included body fat percentage (%), fat mass (kg), fat mass index (FMI; $\text{kg}\cdot\text{m}^{-2}$), muscle mass (% and kg), and muscle mass index (MMI; $\text{kg}\cdot\text{m}^{-2}$). Body mass index (BMI) was calculated as body mass divided by height squared ($\text{kg}\cdot\text{m}^{-2}$). FMI and MMI were calculated as fat mass and muscle mass divided by height squared, respectively. All measurements were performed in the morning under standardized conditions [14,15].

2.3.3. Muscle Architecture Assessment

Muscle size and architecture of the RF and VL were assessed using B-mode ultrasonography (MyLab 25, Esaote Biomedica, Genoa, Italy) equipped with a 5-cm, 7.5–12 MHz linear-array probe. All scans were performed by the same experienced technician (>200 h) to minimize inter-operator variability. Participants were positioned supine with the lower limbs relaxed and fully extended. Femur length was measured as the distance between the greater trochanter (0% of the distance) and the inferior border of the lateral epicondyle of the femur using a flexible anthropometric tape.

Transverse panoramic ultrasound images were obtained at 35%, 50%, and 65% of femur length. These thigh lengths were found to be valid and highly repeatable to measure quadriceps femoris [16]. Anatomical landmarks were identified and marked prior to scanning to ensure consistent probe placement across sites. Minimal probe pressure and a generous amount of water-soluble gel were used to avoid muscle compression. Representative transverse ultrasound images of RF and VL at each measurement site are shown in Figure 1. RF (1) and VL (2) were manually delineated using image analysis software to determine muscle CSA. CSA was quantified from transverse images using Fiji software (ImageJ, National Institutes of Health, USA). Two independent measurements were obtained for each site. The coefficient of variation (CV) between measurements was calculated as $(\text{standard deviation (SD)} / \text{mean}) \times 100$. If the CV exceeded 5%, a third measurement was performed and the final CSA value was calculated as the average of the three-measurements [16]; otherwise, the mean of the two measurements was retained. VL fascicle length and VL pennation angle were assessed from longitudinal images at 50% of femur length using SMA software (LISiN-Politecnico di Torino, Italy). When the entire fascicle was not visible within the image frame, linear extrapolation was applied according to established procedures [17]. VL muscle volume was estimated from the VL CSA obtained at 35%, 50% and 65% of the femur length and insertion points of the VL muscle in the femur (5 and 80% of the femur length) [18]. Calculations were performed using OriginPro software (OriginLab Corporation, USA).

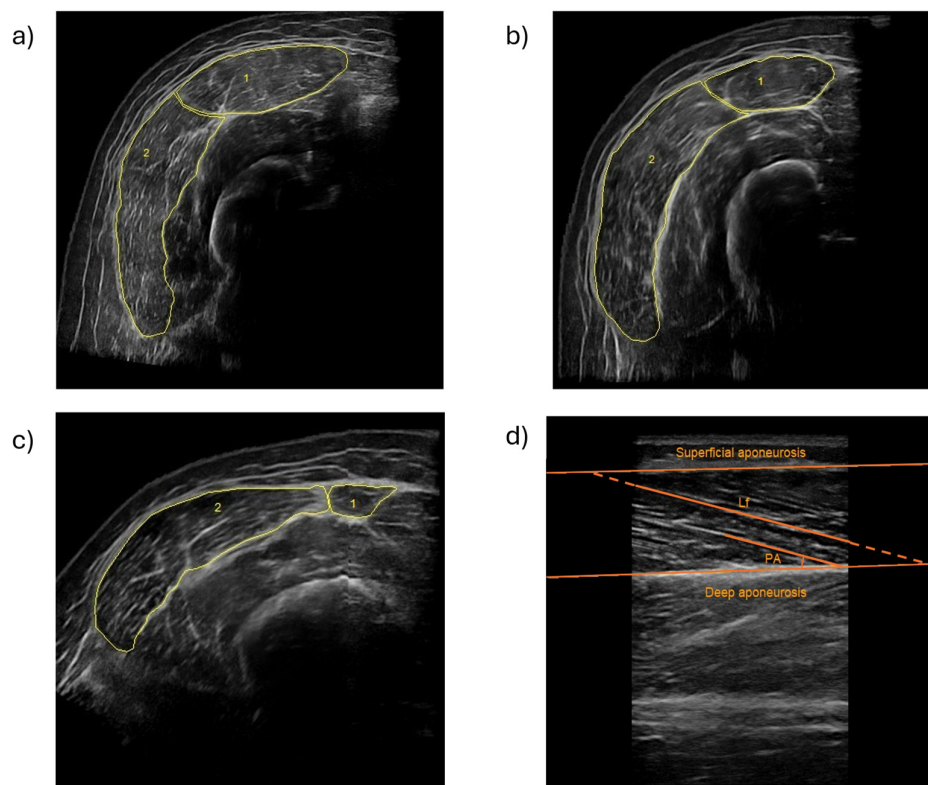


Figure 1. Representative B-mode ultrasound images of quadriceps cross-sectional area (CSA) at different femur lengths. Transverse panoramic scans obtained at (a) 35%, (b) 50%, and (c) 65% of femur length (measured from the greater trochanter to the lateral epicondyle). The rectus femoris (RF) is indicated as (1) and the vastus lateralis as (2). Yellow outlines represent manually traced muscle boundaries used for CSA calculation. Fascicle length; Vastus lateralis pennation angle (PA) and Vastus Lateralis fascicle length (Lf) are presented in (d).

2.3.4. Countermovement Jump

Vertical jump performance was assessed using the CMJ test performed on dual force plates (Hawkin Dynamics Inc., Westbrook, ME, USA; sampling frequency = 1000 Hz), in accordance with previously described procedures [19]. Participants stepped onto the force plates and stood upright, motionless, for at least 1 s to allow body weight determination prior to movement onset. All jumps were performed with hands placed on the hips (arms akimbo) to minimize upper-limb contribution. Athletes were instructed to jump “as fast and as high as possible” while maintaining full lower-limb extension during flight and avoiding knee tucking. Each participant performed three maximal CMJ trials, separated by ~60 s of passive recovery. A minimum of three technically valid trials was required. If a trial was deemed invalid (e.g., arm swing, excessive countermovement strategy deviation, or knee flexion during flight), an additional attempt was allowed. Vertical ground reaction force (vGRF) data were low-pass filtered using a 50 Hz cut-off frequency and analyzed using proprietary software (Hawkin Dynamics Inc.). Jump height was calculated from take-off velocity using the impulse–momentum method [19].

2.3.5. Force-Velocity Profiling

The individual F–V relationship was assessed during the concentric phase of the free-weight parallel back squat using a linear position transducer (ADR device, Toledo, Spain)[20]. Following a standardized warm-up, participants performed an incremental loading protocol consisting of progressively increasing external loads, starting with a light load (~20 kg) and increasing in 5–10 kg increments until mean concentric velocity fell below ~0.60 m·s⁻¹ [9]. Two repetitions were performed at each load with maximal intended concentric velocity. Mean propulsive velocity (MPV) was recorded for each repetition, and the highest velocity value per load was retained for analysis. If a repetition deviated by >0.05 m·s⁻¹ from the expected individual linear regression, an additional repetition was performed to ensure data consistency. A linear F–V equation was fitted over F–V data comprised between 45% and 100% of theoretical maximal force (F_0)[9]. From this relationship, theoretical maximal unloaded velocity (V_0), and maximal mechanical power (P_{max}) were calculated. Optimal force (F_{opt}) and optimal velocity (V_{opt}) were calculated as the coordinates corresponding to maximal power output [9].

2.3.6. Maximal Dynamic Strength

After completion of the incremental F–V protocol, maximal dynamic strength was assessed through SQ and HHPC 1RM. Both exercises were selected due to their high mechanical and neuromuscular relevance for the base role in acrobatic gymnastics, which requires high levels of lower-limb force production and explosive strength during propulsions and receptions. All strength assessments were performed under the supervision of experienced strength and conditioning professionals and following established youth resistance training guidelines [21]. For the SQ 1RM, load was progressively increased until failure, defined as the inability to complete a repetition through the predefined range of motion (~90° knee flexion) while maintaining correct technique. Rest intervals of 2–3 min were provided between attempts. The highest successfully lifted load was recorded as the 1RM. For the HHPC, participants initiated the lift from the mid-thigh hang position and performed an explosive triple extension followed by bar reception in a partial front rack position. Load was progressively increased until technical failure occurred. The 1RM HHPC corresponded to the maximal successfully lifted load.

2.4. Statistical Analysis

Statistical analyses were performed using SPSS Statistics (version 28, IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots. Homogeneity of variances between maturational groups was evaluated using Levene’s test. Descriptive statistics are presented as mean ± SD. Between-group differences according to

maturational status (pre/mid-pubertal: Tanner stages 1–3; post-pubertal: Tanner stages 4–5) were examined using independent-samples t-tests. Effect sizes for group comparisons were calculated using Cohen’s d and interpreted as small (0.2), moderate (0.5), and large (0.8) [22]. To examine the associations between muscle morphological variables (RF and VL CSA at 35%, 50%, and 65% of femur length; VL muscle volume; VL fascicle length; VL pennation angle) and performance outcomes (1RM SQ, squat Pmax, CMJmax, and 1RM HHP), separate multiple linear regression analyses were performed. Three models were constructed for each outcome: Model 1 was unadjusted; Model 2 was adjusted for pubertal maturation (Tanner scale); and Model 3 was additionally adjusted for Tanner stage and height. Assumptions of linear regression (linearity, normality of residuals, homoscedasticity, and absence of multicollinearity) were verified. Adjustment for tanner scale was conducted due to differences between groups in different maturational status. Multicollinearity was assessed using variance inflation factor (VIF), with $VIF < 3$ considered acceptable. Standardised β coefficients, unstandardised β coefficients with 95% confidence intervals (CI), adjusted R^2 values, and p-values were reported. Statistical significance was set at $p < 0.05$. Values between 0.05 and 0.10 were interpreted as statistical trends.

3. Results

Twenty female acrobatic gymnasts (base role) aged 12 to 18 years (14.1 ± 1.7 years) participated in the study. Descriptive characteristics for the overall sample and stratified by maturational status are presented in Table 1. Post-pubertal athletes presented significantly greater body mass ($p = 0.003$; $d = 1.53$), BMI ($p = 0.006$; $d = 1.33$), fat mass ($p = 0.028$; $d = 1.21$), FMI ($p = 0.031$; $d = 1.09$), and absolute muscle mass ($p = 0.032$; $d = 1.12$) compared with pre/mid-pubertal athletes. Relative muscle percentage was higher in the pre/mid-pubertal group ($p = 0.006$; $d = 1.41$). Despite these differences in body composition, no significant between-group differences were observed in quadriceps CSA, muscle volume, VL fascicle length, or VL pennation angle (all $p > 0.20$; d values < 0.60). Regarding mechanical performance, post-pubertal athletes demonstrated greater theoretical maximal force (F_0 ; $p = 0.006$; $d = 1.28$), optimal force (F_{opt} ; $p = 0.004$; $d = 1.31$), 1RM SQ ($p = 0.037$; $d = 0.99$), and squat Pmax ($p = 0.039$; $d = 0.96$). In contrast, CMJ height ($p = 0.351$; $d = 0.25$) and 1RM HHP ($p = 0.259$; $d = 0.56$) did not significantly differ between groups.

Table 1. Participant characteristics stratified by maturational status.

Variable	Overall n = 20	Pre/mid-pubertal (Tanner 1–3) n = 12	Post-pubertal (Tanner 4–5) n = 8
Anthropometry			
Age (years)	14.1 ± 1.7	13.2 ± 1.4**	15.4 ± 1.5**
Tanner scale (points)	3.35 ± 0.75	2.83 ± 0.39***	4.13 ± 0.35***
Height (cm)	157.5 ± 4.2	156.5 ± 4.3	158.9 ± 3.9
Weight (kg)	51.9 ± 6.3	48.6 ± 3.7**	56.7 ± 6.4**
BMI (kg/m²)	20.9 ± 2.3	19.9 ± 1.5**	22.6 ± 2.4**
Body composition			
Fat (%)	20.6 ± 5.5	18.6 ± 4.6*	23.6 ± 5.8*
Fat mass (kg)	11.0 ± 4.1	9.2 ± 2.6*	13.7 ± 4.7*
Fat Mass Index (kg/m²)	4.4 ± 1.6	3.7 ± 1.1*	5.4 ± 1.8*
Muscle (%)	76.2 ± 5.6	78.6 ± 3.4**	72.1 ± 5.8**
Muscle mass (kg)	39.3 ± 2.4	38.2 ± 2.1*	40.6 ± 2.3*
Muscle Mass Index (kg/m²)	15.8 ± 0.9	15.6 ± 0.8	16.1 ± 0.9
Muscle Morphology			
RF 35% CSA (cm²)	9.58 ± 1.93	9.53 ± 2.01	9.66 ± 1.93
RF 50% CSA (cm²)	6.05 ± 1.32	6.35 ± 1.19	5.59 ± 1.45
RF 65% CSA (cm²)	2.08 ± 0.90	2.20 ± 0.69	1.90 ± 1.18
VL 35% CSA (cm²)	16.70 ± 2.32	16.11 ± 1.78	17.59 ± 2.84

VL 50% CSA (cm ²)	17.31 ± 2.74	16.96 ± 2.92	17.84 ± 2.53
VL 65% CSA (cm ²)	11.43 ± 2.27	11.45 ± 2.24	11.40 ± 2.46
VL Volume (cm ³)	258.49 ± 35.87	250.56 ± 32.98	270.39 ± 38.91
VL Fascicle length (cm)	7.25 ± 0.80	7.43 ± 0.73	6.98 ± 0.86
VL Pennation angle (°)	15.65 ± 1.56	15.54 ± 1.59	15.80 ± 1.62
Performance			
F ₀ SQ (N)	1520 ± 186	1437 ± 129**	1648 ± 192**
V ₀ SQ (m·s ⁻¹)	1.88 ± 0.44	1.84 ± 0.44	1.95 ± 0.45
F _{opt} SQ (N)	745 ± 116	693 ± 99**	824 ± 96**
V _{opt} SQ (m·s ⁻¹)	—	0.92 ± 0.22	0.98 ± 0.23
1RM SQ (kg)	86.6 ± 12.5	82.1 ± 11.3*	93.4 ± 11.6*
P _{max} SQ (W)	711 ± 156	653 ± 135*	797 ± 152*
CMJ _{max} (m)	0.30 ± 0.04	0.29 ± 0.04	0.30 ± 0.04
1RM HHPC (kg)	34.86 ± 5.52	33.64 ± 5.29	36.79 ± 5.72

Continuous variables are presented as mean ± standard deviation (SD). BMI, Body Mass Index; RF, Rectus Femoris; CSA, Cross-Sectional Area; VL, Vastus Lateralis; F₀, maximum isometric force; V₀, maximum unloaded velocity; F_{opt}, optimal force; V_{opt}, optimal velocity, SQ, squat; 1 RM, one maximum repetition; P_{max}, maximum muscle power; CMJ_{max}, maximum countermovement jump height; HHPC, High Hang Power Clean; SD, Standard Deviation. Significance levels: *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001.

3.1. Associations of Muscle Size and Architecture with Performance Outcomes

Linear regression analyses were performed to examine the associations of muscle size and architecture with strength–power performance outcomes (Tables 2–5). For 1RM SQ performance (Table 2), VL CSA at 35% of femur length was positively associated with maximal strength in unadjusted analyses ($\beta = 2.91 \text{ kg}\cdot\text{cm}^{-2}$, 95% CI 0.66 to 5.16; $p = 0.014$; adjusted $R^2 = 0.25$). After adjustment for maturational status and height, VL CSA at both 35% ($\beta = 2.38 \text{ kg}\cdot\text{cm}^{-2}$, 95% CI 0.24 to 4.51; $p = 0.031$) and 50% of femur length ($\beta = 2.31 \text{ kg}\cdot\text{cm}^{-2}$, 95% CI 0.60 to 4.01; $p = 0.011$) remained independently associated with 1RM SQ performance, explaining up to 46% of the variance. No significant associations were observed for RF CSA, muscle volume, VL fascicle length, or VL pennation angle.

Table 2. Associations between quadriceps muscle morphology and one-repetition maximum (1RM) squat performance.

Predictors	Standardized- β	Adjusted R^2	β (95% CI)	p
Model 1				
RF CSA 35%	0.170	-0.025	1.100 (-2.060, 4.260)	0.474
RF CSA 50%	0.024	-0.055	0.225 (-4.456, 4.906)	0.921
RF CSA 65%	-0.118	-0.041	-1.638 (-8.482, 5.206)	0.621
VL CSA 35%	0.539	0.251	2.910 (0.660, 5.160)	0.014*
VL CSA 50%	0.438	0.147	1.998 (-0.033, 4.030)	0.053
VL CSA 65%	-0.006	-0.056	-0.033 (-2.762, 2.696)	0.980
VL Volume	0.343	0.069	0.120 (-0.042, 0.282)	0.138
VL Fascicle Length	0.050	-0.053	0.398 (-3.561, 4.356)	0.835
VL Pennation angle	-0.215	-0.007	-3.377 (-10.957, 4.202)	0.362
Model 2				
RF CSA 35%	0.148	0.100	0.960 (-2.017, 3.937)	0.505
RF CSA 50%	0.108	0.089	1.025 (-3.428, 5.479)	0.633
RF CSA 65%	-0.095	0.086	-1.327 (-7.777, 5.122)	0.670

VL CSA 35%	0.460	0.295	2.483 (0.205, 4.762)	0.034*
VL CSA 50%	<i>0.386</i>	<i>0.239</i>	<i>1.760 (-0.188, 3.707)</i>	<i>0.074</i>
VL CSA 65%	-0.030	0.077	-0.166 (-2.733, 2.402)	0.893
VL Volume	0.237	0.133	0.083 (-0.083, 0.248)	0.307
VL Fascicle Length	0.091	0.085	0.731 (-2.992, 4.454)	0.684
VL Pennation angle	-0.091	0.084	-1.427 (-9.094, 6.241)	0.700
Model 3				
RF CSA 35%	0.268	0.254	1.738 (-1.094, 4.570)	0.212
RF CSA 50%	0.153	0.202	1.448 (-2.767, 5.664)	0.477
RF CSA 65%	-0.102	0.188	-1.415 (-7.525, 4.696)	0.630
VL CSA 35%	0.440	0.388	2.376 (0.239, 4.513)	0.031*
VL CSA 50%	0.505	0.455	2.306 (0.598, 4.014)	0.011*
VL CSA 65%	0.160	0.200	0.882 (-1.789, 3.553)	0.494
VL Volume	<i>0.368</i>	<i>0.310</i>	<i>0.128 (-0.026, 0.282)</i>	<i>0.096</i>
VL Fascicle Length	0.074	0.182	0.591 (-2.951, 4.133)	0.728
VL Pennation angle	0.100	0.184	1.565 (-6.557, 9.687)	0.688

Model 1 represents unadjusted analyses. Model 2 is adjusted for pubertal maturation (Tanner stage). Model 3 is additionally adjusted for Tanner stage and height. Standardised β coefficients, unstandardised β coefficients with 95% confidence intervals (CI), adjusted R^2 values, and p-values are reported. RF, rectus femoris; CSA, cross-sectional area; VL, vastus lateralis; Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Statistical trends ($0.05 \leq p < 0.10$) are presented in italics. Stronger associations were observed for SQ Pmax (Table 3). In model 1 (unadjusted), VL CSA at 35% ($\beta = 49.55 \text{ W}\cdot\text{cm}^{-2}$, 95% CI 26.93 to 72.17; $p < 0.001$; adjusted $R^2 = 0.52$) and 50% ($\beta = 38.43 \text{ W}\cdot\text{cm}^{-2}$, 95% CI 17.58 to 59.27; $p < 0.001$; adjusted $R^2 = 0.42$) were significantly associated with Pmax. These relationships persisted after adjustment for maturational status and height, with VL CSA at 35% ($\beta = 45.75 \text{ W}\cdot\text{cm}^{-2}$, 95% CI 21.74 to 69.77; $p < 0.001$) and 50% ($\beta = 38.43 \text{ W}\cdot\text{cm}^{-2}$, 95% CI 17.93 to 58.94; $p < 0.001$) independently predicting SQ Pmax (adjusted $R^2 \approx 0.50$). VL muscle volume was also positively associated with Pmax across models ($p \leq 0.003$), although variance explained was lower compared with site-specific CSA. No significant associations were identified for RF morphology or architectural variables.

Table 3. Associations between quadriceps muscle morphology and maximal power squat performance.

Predictors	Standardized- β	Adjusted R^2	β (95% CI)	p
Model 1				
RF CSA 35%	0.145	-0.033	11.762 (-27.861, 51.385)	0.541
RF CSA 50%	-0.007	-0.056	-0.838 (-59.317, 57.642)	0.976
RF CSA 65%	-0.202	-0.012	-35.141 (-119.437, 49.154)	0.393
VL CSA 35%	0.735	0.515	49.552 (26.931, 72.173)	<0.001***
VL CSA 50%	0.674	0.424	38.425 (17.582, 59.268)	<0.001***
VL CSA 65%	0.267	0.020	18.393 (-14.453, 51.238)	0.255
VL Volume	0.684	0.439	2.977 (1.407, 4.548)	<0.001***
VL Fascicle Length	0.134	-0.037	13.370 (-35.688, 62.428)	0.574
VL Pennation angle	0.195	-0.016	38.101 (-56.981, 133.184)	0.411
Model 2				
RF CSA 35%	0.125	0.075	10.099 (-27.605, 47.802)	0.579
RF CSA 50%	0.072	0.063	8.531 (-47.864, 64.926)	0.754

RF CSA 65%	-0.181	0.094	-31.498 (-111.692, 48.696)	0.419
VL CSA 35%	0.678	0.533	45.675 (22.512, 68.838)	<0.001***
VL CSA 50%	0.630	0.492	35.906 (16.030, 55.782)	<0.001***
VL CSA 65%	0.245	0.124	16.877 (-14.349, 48.103)	0.270
VL Volume	0.621	0.448	2.703 (1.057, 4.350)	0.003**
VL Fascicle Length	0.174	0.091	17.412 (-28.940, 63.765)	0.439
VL Pennation angle	0.359	0.187	70.303 (-19.940, 160.546)	0.119
Model 3				
RF CSA 35%	0.140	0.020	11.333 (-29.206, 51.872)	0.562
RF CSA 50%	0.075	0.005	8.886 (-49.891, 67.663)	0.753
RF CSA 65%	-0.182	0.038	-31.558 (-114.607, 51.490)	0.432
VL CSA 35%	0.679	0.504	45.752 (21.735, 69.769)	<0.001**
VL CSA 50%	0.674	0.496	38.433 (17.929, 58.938)	<0.001**
VL CSA 65%	0.313	0.092	21.514 (-14.012, 57.040)	0.218
VL Volume	0.676	0.453	2.942 (1.232, 4.651)	0.002**
VL Fascicle Length	0.174	0.034	17.370 (-30.692, 65.431)	0.455
VL Pennation angle	0.458	0.178	89.649 (-12.157, 191.456)	<i>0.080</i>

Model 1 represents unadjusted analyses. Model 2 is adjusted for pubertal maturation (Tanner stage). Model 3 is additionally adjusted for Tanner stage and height. Standardized β coefficients, unstandardized β coefficients with 95% confidence intervals (CI), adjusted R^2 values, and p-values are reported. Abbreviations: RF, rectus femoris; CSA, cross-sectional area; VL, vastus lateralis; Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Statistical trends ($0.05 \leq p < 0.10$) are presented in italics.

In contrast, quadriceps morphological variables were not significantly associated with CMJ height in either unadjusted or adjusted models (all $p > 0.10$; Table 4). Similarly, for 1RM HHP (Table 5), VL CSA at 35% and 50% showed borderline associations in unadjusted analyses ($p = 0.060$ and $p = 0.051$, respectively), but these did not remain significant after adjustment for maturational status and height.

Table 4. Associations between quadriceps muscle morphology and maximal countermovement jump height.

Predictors	Standardised- β	Adjusted R^2	β (95% CI)	p
Model 1				
RF CSA 35%	0.008	-0.055	0.000 (-0.009, 0.010)	0.972
RF CSA 50%	-0.252	0.011	-0.007 (-0.021, 0.006)	0.284
RF CSA 65%	-0.348	0.072	-0.014 (-0.034, 0.005)	0.132
VL CSA 35%	0.142	-0.034	0.002 (-0.006, 0.010)	0.551
VL CSA 50%	-0.244	0.007	-0.003 (-0.010, 0.003)	0.300
VL CSA 65%	<i>-0.407</i>	<i>0.119</i>	<i>-0.007 (-0.014, 0.001)</i>	<i>0.075</i>
VL Volume	-0.146	-0.033	0.000 (-0.001, 0.000)	0.539
VL Fascicle Length	0.1236	-0.036	0.003 (-0.008, 0.015)	0.569
VL Pennation angle	-0.212	-0.008	-0.010 (-0.033, 0.013)	0.370
Model 2				
RF CSA 35%	0.010	-0.117	0.000 (-0.010, 0.010)	0.969
RF CSA 50%	-0.266	-0.041	-0.008 (-0.022, 0.007)	0.280

RF CSA 65%	-0.350	0.020	-0.015 (-0.035, 0.005)	0.142
VL CSA 35%	0.160	-0.091	0.003 (-0.006, 0.011)	0.529
VL CSA 50%	-0.246	-0.051	-0.003 (-0.010, 0.003)	0.316
VL CSA 65%	-0.407	0.068	-0.007 (-0.014, 0.001)	0.084
VL Volume	-0.154	-0.093	0.000 (-0.001, 0.000)	0.551
VL Fascicle Length	0.135	-0.097	0.003 (-0.009, 0.015)	0.584
VL Pennation angle	-0.244	-0.057	-0.011 (-0.036, 0.013)	0.340
Model 3				
RF CSA 35%	0.101	-0.065	0.002 (-0.008, 0.012)	0.688
RF CSA 50%	-0.234	-0.015	-0.007 (-0.021, 0.008)	0.339
RF CSA 65%	-0.356	0.073	-0.015 (-0.034, 0.005)	0.127
VL CSA 35%	0.143	-0.054	0.002 (-0.006, 0.011)	0.569
VL CSA 50%	-0.181	-0.041	-0.002 (-0.010, 0.005)	0.468
VL CSA 65%	-0.338	0.033	-0.006 (-0.014, 0.003)	0.197
VL Volume	-0.072	-0.072	0.000 (-0.001, 0.000)	0.785
VL Fascicle Length	0.120	-0.060	0.003 (-0.009, 0.015)	0.620
VL Pennation angle	-0.126	-0.063	-0.006 (-0.034, 0.022)	0.657

Model 1 represents unadjusted analyses. Model 2 is adjusted for pubertal maturation (Tanner stage). Model 3 is additionally adjusted for Tanner stage and height. Standardised β coefficients, unstandardised β coefficients with 95% confidence intervals (CI), adjusted R^2 values, and p-values are reported. RF, rectus femoris; CSA, cross-sectional area; VL, vastus lateralis; Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Statistical trends ($0.05 \leq p < 0.10$) are presented in italics.

Table 5. Associations between quadriceps muscle morphology and one-repetition maximum in hang power clean from the mid-thigh position.

Predictors	Standardized- β	Adjusted R^2	β (95% CI)	p
Model 1				
RF CSA 35%	0.343	0.062	1.004 (-0.455, 2.463)	0.164
RF CSA 50%	-0.103	-0.051	-0.546 (-3.327, 2.235)	0.683
RF CSA 65%	-0.337	0.058	-2.190 (-5.438, 1.057)	0.172
VL CSA 35%	0.451	0.153	1.068 (-0.053, 2.188)	0.060
VL CSA 50%	0.466	0.169	0.934 (-0.005, 1.872)	0.051
VL CSA 65%	-0.013	-0.062	-0.035 (-1.427, 1.358)	0.959
VL Volume	0.310	0.040	0.048 (-0.030, 0.125)	0.210
VL Fascicle Length	0.282	0.022	1.031 (-0.829, 2.892)	0.257
VL Pennation angle	0.229	-0.007	1.958 (-2.447, 6.363)	0.360
Model 2				
RF CSA 35%	0.316	0.032	0.927 (-0.582, 2.435)	0.210
RF CSA 50%	-0.090	-0.069	-0.473 (-3.299, 2.353)	0.726
RF CSA 65%	-0.348	0.058	-2.265 (-5.533, 1.003)	0.160
VL CSA 35%	0.422	0.110	1.000 (-0.195, 2.194)	0.095
VL CSA 50%	0.440	0.132	0.881 (-0.103, 1.865)	0.076
VL CSA 65%	-0.056	-0.075	-0.146 (-1.580, 1.287)	0.831

VL Volume	0.265	-0.010	0.041 (-0.045, 0.127)	0.329
VL Fascicle Length	0.344	0.049	1.258 (-0.629, 3.144)	0.176
VL Pennation angle	0.297	0.016	2.540 (-1.965, 7.045)	0.248
Model 3				
RF CSA 35%	0.296	-0.009	0.868 (-0.695, 2.431)	0.254
RF CSA 50%	-0.051	-0.108	-0.270 (-3.233, 2.692)	0.848
RF CSA 65%	-0.321	0.007	-2.090 (-5.556, 1.376)	0.217
VL CSA 35%	<i>0.430</i>	<i>0.098</i>	<i>1.017 (-0.194, 2.228)</i>	<i>0.093</i>
VL CSA 50%	0.419	0.088	0.839 (-0.191, 1.869)	0.102
VL CSA 65%	-0.127	-0.094	-0.333 (-1.860, 1.194)	0.647
VL Volume	0.234	-0.056	0.036 (-0.054, 0.126)	0.408
VL Fascicle Length	0.321	0.006	1.176 (-0.789, 3.140)	0.220
VL Pennation angle	0.263	-0.037	2.249 (-2.589, 7.087)	0.336

Model 1 represents unadjusted analyses. Model 2 is adjusted for pubertal maturation (Tanner stage). Model 3 is additionally adjusted for Tanner stage and height. Standardized β coefficients, unstandardized β coefficients with 95% confidence intervals (CI), adjusted R^2 values, and p-values are reported. RF, rectus femoris; CSA, cross-sectional area; VL, vastus lateralis; Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Statistical trends ($0.05 \leq p < 0.10$) are presented in italics.

Overall, mid-thigh VL CSA (35–50% of femur length) emerged as the only morphological variable consistently associated with SQ-specific strength and power performance in this cohort.

4. Discussion

The main finding of this study is that mid-thigh VL CSA was consistently associated with SQ-specific strength and power performance in young elite female acrobatic gymnasts, independently of pubertal maturation and height. Specifically, VL CSA at 35–50% of femur length explained a substantial proportion of the variance in 1RM SQ and SQ Pmax, whereas RF variables were not associated with performance outcomes. This is physiologically plausible, since muscle CSA is closely related to force production capacity through its relationship with physiological CSA and the number of sarcomeres arranged in parallel [23]. In multi-joint lower-limb exercises such as the SQ, the VL is typically one of the primary contributors to knee extensor torque [24]. Task-specific activation patterns may therefore explain why VL, but not RF, morphology was associated with performance. The biarticular nature of the RF and its involvement in both hip flexion and knee extension may result in a different functional contribution during loaded squatting tasks, potentially reducing its direct association with maximal force and power production in this movement [24]. Moreover, because the RF simultaneously contributes to hip flexion, its net mechanical contribution to knee extension torque during squatting may be constrained by inter-joint coordination demands, further attenuating the relationship between its size and squat-specific performance [25].

Interestingly, the associations were stronger for SQ Pmax than for 1RM. This suggests that mid-thigh

muscle size at the mid-thigh may be particularly relevant for the F-V characteristics underpinning Pmax production [26]. Whereas 1RM primarily reflects maximal force output under near-zero velocity conditions, Pmax is derived from the individual F-V profile and represents the optimal balance between F and V (i.e., the product of F and V at the point of Pmax)[26]. Therefore, its stronger association with VL CSA indicates that muscle size may influence performance across a broader mechanical spectrum rather than solely under maximal loading conditions. Within the F-V framework, greater muscle CSA is associated with increased force-generating capacity (higher theoretical F_0). An upward shift in the F-V relationship due to increased F capacity may consequently

elevate power output at intermediate velocities, even if maximal velocity (V_0) remains unchanged [26]. In this context, larger VL CSA may enhance the ability to sustain higher force levels at moderate contraction velocities, thereby increasing the mechanical power produced during the concentric phase of the SQ. This interpretation is consistent with the observed stronger relationships between VL CSA and Pmax compared with 1RM. Moreover, Pmax may be more sensitive than 1RM to morphological differences because it reflects integrated mechanical performance across multiple loading conditions rather than performance at a single high-load point. From a sport-specific perspective, this may be particularly relevant for acrobatic gymnastics bases, who are required to generate substantial force rapidly during dynamic transitions and partner lifts, where both force magnitude and movement velocity are critical. Our findings are consistent with those reported by Cornejo-Daza et al. in young males [16], who observed significant associations between quadriceps morphology and F-V-derived power parameters, reinforcing the notion that muscle size contributes meaningfully to mechanical power output during multi-joint lower-limb tasks in youth athletes. The fact that these relationships remained significant after adjusting for Tanner stage and height suggests that they are not explained solely by maturational growth but may also reflect training-related neuromuscular adaptations in these athletes [7]. Although causal inference cannot be established due to the cross-sectional design, these findings are compatible with the possibility that inter-individual differences in training exposure and neuromuscular specialization contribute to squat force–power performance beyond biological maturation alone.

In contrast, quadriceps morphology was not significantly associated with CMJ performance or 1RM HHPC. CMJ performance is influenced by a wide range of mechanical and neuromuscular determinants beyond isolated muscle size, including intermuscular coordination, stretch–shortening cycle efficiency, tendon stiffness, and neuromuscular timing. Previous research has shown that differences in jumping ability are not solely explained by muscle size but also by variations in neuromechanical strategies and force application patterns [27]. Accordingly, CMJ performance likely reflects the integrated function of the entire lower-limb neuromuscular system rather than the size of a single muscle group [28]. Variability in coordination strategies or neuromuscular efficiency may therefore account for a larger proportion of performance variance than differences in quadriceps CSA alone.

A similar rationale may explain the absence of independent predictors for 1RM HHPC after adjustment. The HHPC is a technically complex, multi-joint movement characterized by coordinated triple extension and phase-specific kinetic demands [29]. Performance in this lift requires rapid force transmission through the kinetic chain, precise motor coordination, and high rates of force development. Consequently, whole-body mechanical integration and technical proficiency may play a more prominent role than the morphology of an individual muscle such as the VL. The borderline associations observed in unadjusted models further suggest that shared variance with maturation or overall body size may partially explain initial relationships, which were attenuated after statistical adjustment.

Several limitations should be acknowledged. First, the relatively small sample size may limit statistical power and increase the risk of type II error, particularly for multivariable models. However, this constraint reflects the inherent difficulty of recruiting homogeneous groups of elite acrobatic gymnasts performing the base role, a highly specialized and limited athletic population. Future studies including larger cohorts and longitudinal designs are warranted to confirm these findings and to further clarify the relationships between muscle architecture, F-V characteristics, and sport-specific performance. Longitudinal training studies would be particularly valuable to determine whether targeted increases in VL CSA translate into measurable improvements in SQ F-V parameters and competitive performance.

Despite these limitations, a notable strength of the present study is the low multicollinearity observed between predictors (variance inflation factor < 3), supporting the stability of the regression coefficients and reducing the likelihood that the observed associations were driven by shared variance among morphological variables. In addition, the combined assessment of ultrasound-

derived muscle morphology and F-V profiling provides a sport-specific and mechanically grounded characterization of performance determinants in this population.

Taken together, these findings indicate that mid-thigh VL CSA represents a meaningful structural correlation of SQ-specific F-P performance in young elite acrobatic gymnastics bases. While muscle size alone does not determine performance in complex whole-body tasks, its association with F-V-derived power highlights its relevance within mechanically constrained movements such as the SQ and may offer a useful framework for monitoring structural and mechanical adaptations during adolescent training.

5. Conclusions

Mid-thigh VL CSA was independently associated with SQ-specific strength and Pmax in young elite female acrobatic gymnasts performing the base role, even after adjustment for pubertal maturation and height. In contrast, RF CSA and the VL architectural parameters assessed were not significant predictors of SQ performance. In addition, CMJ or HHPC were not associated with muscle size and architecture.

These findings indicate that mid-thigh VL muscle size represents a key determinant of SQ mechanical capacity within this population. While muscle size alone does not fully determine performance in complex multi-joint tasks, its association with power highlights its importance in mechanically constrained movements such as the SQ. From a practical perspective, ultrasound-based assessment of mid-thigh VL CSA may provide a useful tool to monitor structural adaptations and inform strength development strategies during adolescence in elite acrobatic gymnastics bases. This information may be useful for trainers to design practical exercises for this muscle group.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy and ethical restrictions involving minor participants.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Term
ACRO	Acrobatic Gymnastics
BMI	Body Mass Index
CSA	Cross-Sectional Area
RF	Rectus Femoris
VL	Vastus Lateralis
HHPC	High Hang Power Clean
SQ	Squat
CMJ	Countermovement Jump
1RM	One-Repetition Maximum
Pmax	Maximal Mechanical Power
F–V	Force–Velocity
F ₀	Theoretical Maximal Force
V ₀	Theoretical Maximal Velocity
F _{opt}	Optimal Force
V _{opt}	Optimal Velocity
FMI	Fat Mass Index
MMI	Muscle Mass Index
SD	Standard Deviation
CI	Confidence Interval
VIF	Variance Inflation Factor
R ²	Coefficient of Determination
β	Standardized Regression Coefficient

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