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Vastus Lateralis and Vastus Intermedius as Predictors of Quadriceps Femoris Muscle Hypertrophy after Strength Training

Polyxeni Spiliopoulou [1], Spyridon Methenitis [1,*], Nikolaos Zaras [2], Angeliki-Nikoletta Stasinaki [1], Maria Krekoukia [1], Stavroula Tsitkanou [3] and Gerasimos Terzis [1]

[1] Sports Performance Laboratory, School of Physical Education and Sport Science, National and Kapodistrian University of Athens, 172 37 Athens, Greece
[2] Human Performance Laboratory, Department of Life and Health Sciences, University of Nicosia, Nicosia 24005, Cyprus
[3] Cachexia Research Laboratory, Exercise Science Research Center, Department of Health, Human Performance and Recreation, University of Arkansas, Fayetteville, AR 72701, USA
* Correspondence: smetheni@phed.uoa.gr

Abstract: The aim of the present study was to investigate which of the four musle heads of the quadriceps femoris is the best surrogate of quadriceps hypertrophy, following resistance training, evaluated by ultrasonography. Forty three physical education students (age: 22.1 ± 3.1 years, height: 175.2 ± 9.3 cm, mass: 75.3 ± 8.0 kg, BMI: 22.8 ± 2.8 kg·m^{-2}) participated in the study. Participants followed an 8-week resistance training program in order to enhance quandriceps muscle hypertrophy. Before and after the training period muscle ultrasonography was used to evaluate: total quandriceps (T), vastus lateralis (VL), vastus intermidius (VI), vastus medialis (VM) and rectus femoris (RF) cross sectional area (CSA). Total quadriceps' as well as VL, VI and VM, CSAs were significantly increased after training (changes ranged between 10.9 ± 9.9% and 18.6 ± 10.8%; $p < 0.05$). No significant changes were found for RF CSA after training ($p > 0.05$). Agreement analyses revealed high values for VL and VI (e.g., ICC = 0.879–0.915; $p = 0.000$), and low values for VM and RF (e.g., ICC = 0.132–0.526; $p = 0.000$). These results suggest that training-induced changes in muscle hypertrophy in VL and VI measured via muscle ultrasonography may be significantly predict the whole quadriceps hypertrophy in response to lower body resistance training. Consequently, VL and VI may considered as valid surrogates of whole quadriceps muscle hypertrophy.

Keywords: quadriceps; muscle hypertrophy; ultrasonography; cross sectional area; resistance training

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1. Introduction

Quadriceps femoris consists of four muscle heads: Vastus Lateralis (VL), Rectus Femoris (RF), Vastus Medialis (VM) and Vastus Intermedious (VI). VL is a surface head positioned at the external side of the thigh. RF is placed in the middle of the front side of the thigh, while VM is located at the anterior side. VI is placed at the interior compartment of the thigh as it is located under the three surface heads and above femur [1]. Each head has unique architectural properties such as volume, physiological cross-sectional area (PCSA; the largest cross-sectional area point of a pennate muscle, perpendicular to its muscle fibers), muscle thickness, muscle length, fascicle length, and fascicle pennation angle [2]. Due to its' position, VL is the most studied head of the quadriceps and it has been used as a surrogate for the whole quadriceps muscle for the evaluation of muscle size, electromyographic activity, and metabolic properties and muscle fiber composition, either for clinical or athletic purposes [3–11].

Inactivity, aging, chronic diseases and systematic training (mostly resistance training), induce several well-known changes on quadriceps femoris size and morphology. These changes can be evaluated by several different methods, either invasive (muscle biopsies) or non-invasive (magnetic resonance imaging, ultrasonography, etc.). More specifically, the ultrasonography technique is a non-invasive, easy to use, valid and reliable method to evaluate quadriceps muscle cross-sectional areas (CSA), volumes and architecture characteristics [12–17]. Thus, muscle ultrasonography has attracted the interest of many clinical and sports scientists, for the evaluation of quadriceps muscle CSA and architecture characteristics, both in cross-sectional and longitudinal studies. For example, the ultrasonography technique has effectively been used for the evaluation of training-induced changes in the whole quadriceps femoris CSA [16,18–20]. Nevertheless, the majority of the researchers seem to evaluate only one muscle head of quadriceps femoris per time, mostly the VL's CSA and/or architecture characteristics before and after different training programs, for the determination of quadriceps femoris' training-induced muscle hypertrophy [21–29]. The decision for the evaluation only of VL for the training-induced hypertrophy is mainly based on reports, indicating that VL may be a good surrogate for the entire quadriceps muscle size, metabolic properties and muscle fiber composition as previously presented in cross-sectional studies [8,11,30,31]. However, after systematic resistance training, the training-induced hypertrophy in the four muscle heads of quadriceps femoris is inhomogeneous, with significant differences between the four heads of quadriceps femoris, but also within the regions of each muscle head separately [19,32]. Thus, considering the inhomogeneous training-induced hypertrophy between the four muscle heads of quadriceps femoris [19,32], it is questionable if the evaluation of only VL's CSA through ultrasonography could provide representative, reliable and valid information about the training-induced hypertrophy of the whole quadriceps femoris. The identification of which of the four muscle heads of quadriceps femoris is/are a good surrogate/s of quadriceps hypertrophy, is of high scientific and practical importance, especially in long-termed training studies, with many participants, where the evaluation and the analysis of the whole quadriceps femoris CSA is time-consuming. Therefore, the purpose of the present study was to investigate which of the four musle heads of quadriceps femoris is the best surrogate of quadriceps hypertrophy, following resistance training, evaluated by ultrasonography.

2. Materials and Methods

2.1. Expiremental Design

Participants were recruited via advertisements at the local university. Paricipants visited the laboratory on two occasions during T1 and T2. During the first day, anthropometric characteristics and the quadriceps femoris size, VL, RF, VM, VI and Total quadriceps (T) CSAs were evaluated through ultrasonography. During the second day, maximum strength in leg press and half squats were evaluated. The same order of measurements was performed during T2.

2.2. Subjects

All participants (N = 43) were physical education students (age: 22.1 $\pm$ 3.1 years, body height: 175.2 $\pm$ 9.3 cm, body mass: 75.3 $\pm$ 8.0 kg, BMI: 22.8 $\pm$ 2.8 kg$\cdot$m^{-2}). Prior to the entry in the study, participants were informed about the experimental procedure and gave their written consent to participate as volunteers before entering in the research procedure. Inclusion criteria were: (a) absence of systematic exercise training at least during the study period, (b) body mass stability before entry, (c) absence of restraining orthopedic/neuromuscular maladies, (d) age range between 18 and 35 years, and (e) absence of drug abuse or medications, which are known to affect the neuromuscular system. All procedures were in accordance with the 1975 Declaration of Helsinki as revised in 2000 and were approved by the Institutional Ethics Committee of the School of Physical Education and Sport Science of the National and Kapodistrian University of Athens.

2.3. Training Intervention

Analytical description of the training protocol has been previously reported [18,33]. Training was performed during the morning hours in a abient temperature of 24 °C in an indoor gym. In short, after a 5-min cycling at 50–75 Watt and some dynamic stretching exercises, participants performed the inclined leg press (45° angle) first and the half-squats (knee angle 90°) on a Smith machine second, 2 times per week for 8 weeks. In each training session, participants performed 4 sets of 6-RM, in both exercises. Rest between sets was 3 min and between the exercises 5 min. The external load during the first 2 weeks was set at 80% of 1-RM, and increased to 85% of 1-RM from the third week onwards. Thereafter, the loads were increased by 2.0–2.5% in every training session until the last week of training intervention [23,34,35].

2.4. Evaluation of 1-RM Strength

Maximal strength in incline leg press and half-squat was assessed on the same 45° incline leg press and Smith machine, that were used in the training program. Before testing procedures, 10 min of cycling at low intensity, dynamic stretching exercises and 2 sets × 10 repetitions in unloaded machines were preceded. Then, efforts with incremental load were followed until participants were unable to lift a heavier load, as previously described [18,20,23,25,29]. Knee angle in the lowest position of half-squats was set to 90°. An elastic antenna was placed on an adjusted stool by the side of the athletes so that when the pelvis touched the antenna athlete begun the upward movement [28]. Rest between efforts were 3 min. At least two of the researchers were present to evaluate the technique and vocally encourage participants during the trials, by a standardized procedure. The ICC for the leg press and the half-squat were 0.982 (95%CI: 0.940–0.990) and 0.990 (95%CI: 0.96–0.99), respectively.

2.5. Muscle Ultrasonography

Quadriceps CSA was assessed through B-mode ultrasonography (Product model Z5, Shenzhen Mindray Bio-Medical Electronics Co., Ltd., Shenzhen, China) with a 10 MHz linear array probe (38 mm width), always by the same investigator—co-author. After participants entered our laboratory, they were placed in supine position for 15 min before the measurement. Ultrasound images were occurred at the non-dominant leg of each participant. Firstly, it was found and marked the point at 40% (proximal to the knee) of these two places: (a) center of the patella, (b) medial aspect of the anterior superior iliac spine. This point was choosen because of the largest cross-sectional area along thigh [16]. Then, a perpendicular guide line along thigh was drawn with an indelible marker, so that the probe was moved transversely across the thigh. Full presentation of quadriceps was achieved with a panoramic picture method, the extended-field-of-view (EFOV) mode [9,16–18,20,29,33]. In each image, it was pictured the CSA of the four heads of quadriceps. Images were input in an image analysis software (Motic Images Plus, 2.0, Hong Kong), where CSA of each head (VL, RF, VM, VI) was measured. Total CSA of quadriceps femoris was the sum of the four heads CSA. Two images were taken and analyzed for each participant and mean values of them were used for statistical analysis. The ICC for CSA of VL, RF, VI, VM and T were 0.962 (95%CI: 0.835–0.991), 0.949 (95%CI: 0.725–0.989), 0.956 (95%CI: 0.814–0.99), 0.872 (95%CI: 0.479–0.971) and 0.974 (95%CI: 0.892–0.994), respectively.

2.6. Statistical Analysis

Shapiro-Wilks test was used to assess the normality of our data. No violations of normality in distribution was found ($p > 0.05$). All data are presented as mean and standard deviation (± SD). For the agreement analyses of the pre to post, training percentage changes (%) of VL, RF, VI, VM and T CSAs values were used. The decision of using the percentage changes and not the absolute values of the CSAs originates from the aim of the study which was to identify which of the four heads of quadriceps femoris is the best surrogate of quadriceps resistance training-induced hypertrophy (e.g., change in muscle size). Students' t-tests were used for the determination of the differences between pre and post-training absolute values of VL, RF, VI, VM and T CSAs separately. One-way analysis of variance (ANOVA) was used for the determination of differences between the percentage changes in VL, RF, VI, VM and T CSAs after training. Additionally, Bland & Altman 95% limits of agreements (LOA), standard error of the limits (SEL = $\sqrt{3 \cdot Standard\ Deviation\ of\ Difference^2 \cdot n^{-1}}$) and 95% confidence interval for the limits of agreement (CILOA = 95% LOA $\pm$ $(1.96 \cdot SEL)$ were also calculated [36–42]. Values of means of the differences near to zero, as well as low values/ranges at LOAs and SELs are thought to be indicators of the absolute agreement of the measurements [36–42] Statistical analysis was performed with SPSS Statistics Ver. 20 (IBM Corporation, Armonk, NY, USA). Statistical significance was accepted at $p \leq 0.05$ for all tests.

3. Results

Leg press (pre: 258.6 $\pm$ 53.7 kg, post: 355.9 $\pm$ 57.1 kg) and half-squat (pre: 149.5 $\pm$ 28.7 kg, post: 191.8 $\pm$ 25.4 kg) 1-RM were significantly increased after training ($p < 0.001$). The T CSA was significantly increased after the training intervention (pre: 63.4 $\pm$ 12.8 cm^2; post: 72.4 $\pm$ 18.1 cm^2; $p < 0.001$). Considering the four heads of quadriceps, significant increases were observed for CSAs of VL (pre: 18.3 $\pm$ 3.6 cm^2; post: 22.3 $\pm$ 5.4 cm^2; $p < 0.001$), VM (pre: 11.1 $\pm$ 3.5 cm^2; post: 12.1 $\pm$ 3.8 cm^2; $p = 0.037$) and VI (pre: 23.7 $\pm$ 5.1 cm^2; post: 27.8 $\pm$ 6.0 cm^2; $p < 0.001$). No significant changes were observed between pre- and post-training values for RF CSAs ($p = 0.485$). Significant deferences were observed between the percentage changes in RF CSA and that of VM, VM, VI and T ($p < 0.05$; Figure 1).

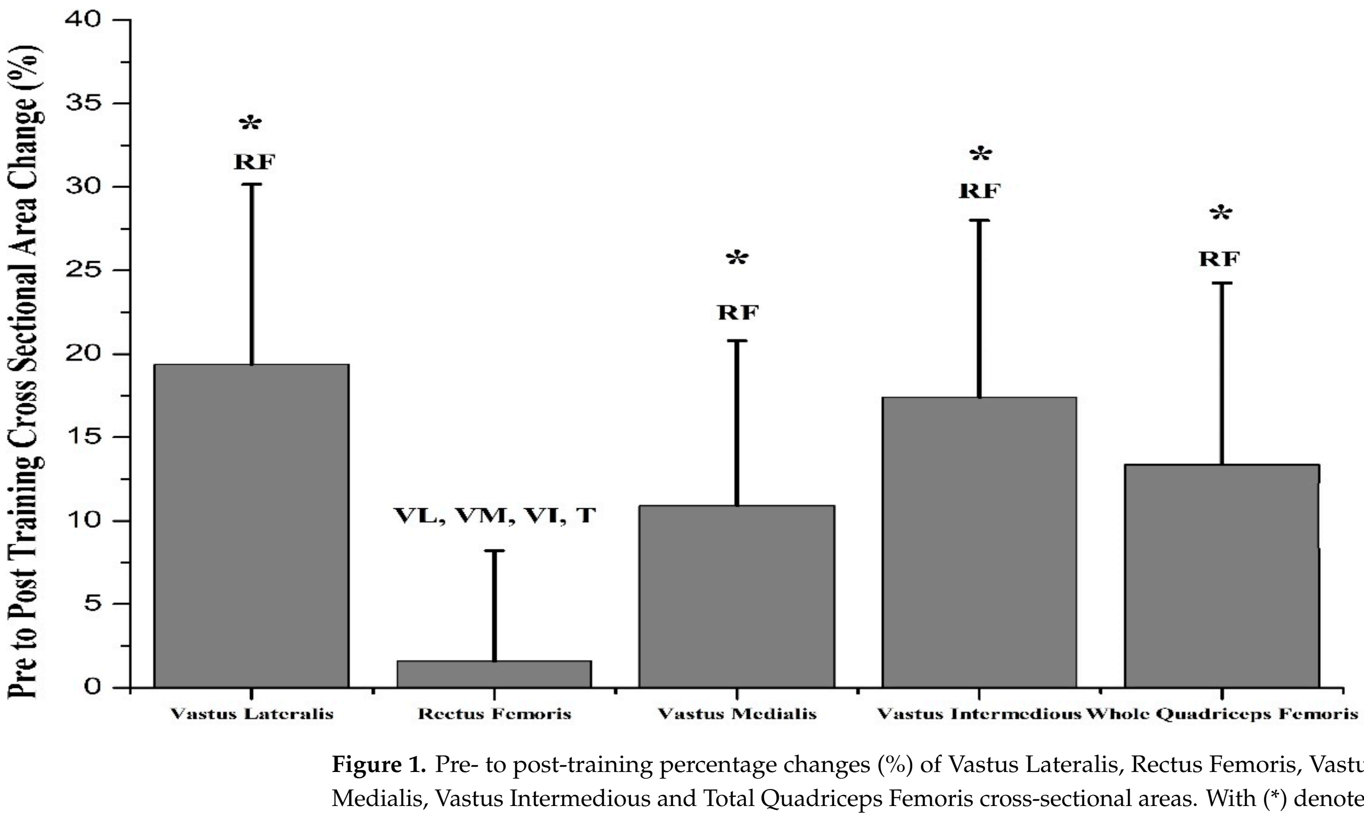

Figure 1. Pre- to post-training percentage changes (%) of Vastus Lateralis, Rectus Femoris, Vastus Medialis, Vastus Intermedious and Total Quadriceps Femoris cross-sectional areas. With (*) denoted the significant differences between pre and post-training cross-sectional areas absolute values for each muscle separately as well as for the Total Quadriceps Femoris ($p < 0.05$). Small letters denote statistically significant differences between the marked groups (where VL = Vastus Lateralis, RF = Rectus Femoris, VM = Vastus Medialis, VI = Vastus Intermedious, T = Total Quadriceps Femoris).

Table 1 present the results of the absolute agreement analyses between the training-induced changes (%) of CSA of T versus those of VL, RF, VM and VI. Representing graphs of Pearson correlations coefficients and Bland-Altman 95% limits of agreements plots for each comparison are presented in Figure 2. In short, only VL and VI CSAs percentage changes were highly related to those of T, predicting 0.83% and 0.76% the variations of quadriceps CSA training-induced changes. In addition, these correlations were accompanied by low values of means of the differences while small range of LOA and SEL values were observed, indicating a high agreement between these variables [36,37] (Table 1 and Figure 2). According to these results, the training-induced changes in VL and VI CSAs seem to be the best surrogates of T quadriceps CSA training-induced hypertrophy, at least when muscle hypertrophy is evaluated at the specific point used in the present study.

Table 1. Results of absolute agreement analyses between the training-induced changes (%) of cross-sectional area (CSA) of Total Quadriceps versus those of vastus lateralis, rectus femoris, vastus medialis and vastus intermedious (N = 43).

		Quadriceps vs. Vastus Lateralis	Quadriceps vs. Rectus Femoris	Quadriceps vs. Vastus Medialis	Quadriceps vs. Vastus Intermedious
	***p* Value of the Contrast**	0.706	0.009	1.000	1.000
	Grand Mean ± SD (%)	17.2 ± 12.4	7.7 ± 13.6	10.9 ± 15.7	15.6 ± 14.8
	Pearson's r product/*p*	0.915/<0.001	0.526/<0.001	0.132/<0.398	0.879/<0.001
	Adjusted R^2	0.833	0.259	−0.006	0.767
LOA	**$Mean_{Diff}$ ± SD_{Diff}**	−8.6 ± 13.3	12.4 ± 11.7	6.1 ± 20.5	−3.4 ± 8.3
LOA	**95% CI_{Diff}**	−12.7 to −4.5	8.7 to 16.1	−0.5 to 12.3	−6.0 to −0.9
LOA	**High 95% of LOA (95%CILOA)**	17.4 (16.4–18.5)	35.5 (34.5–36.4)	46.4 (44.7–48.1)	12.9 (12.3–13.6)
LOA	**Low 95% of LOA (95%CILOA)**	−34.7 (−35.7–−33.6)	−10.6 (−11.6–−9.7)	−34.2 (−35.9–−32.6)	−19.8 (−20.5–−19.2)
LOA	**LOA 95% Width**	52.2	46.2	80.7	32.8
LOA	**SEL**	0.533	0.474	0.829	0.337

LOA: Bland & Altman 95% limits of agreements; $Mean_{Diff}$: mean of the difference between measured and predicted values; SD_{Diff}: standard deviation of the difference between measured and predicted values; CI: confidence interval; CI_{Diff}: confidence interval of the difference between measured and predicted values; 95% CILOA: 95% confidence interval for the limits of agreement; SEL: standard error of limits, vs.: versus.

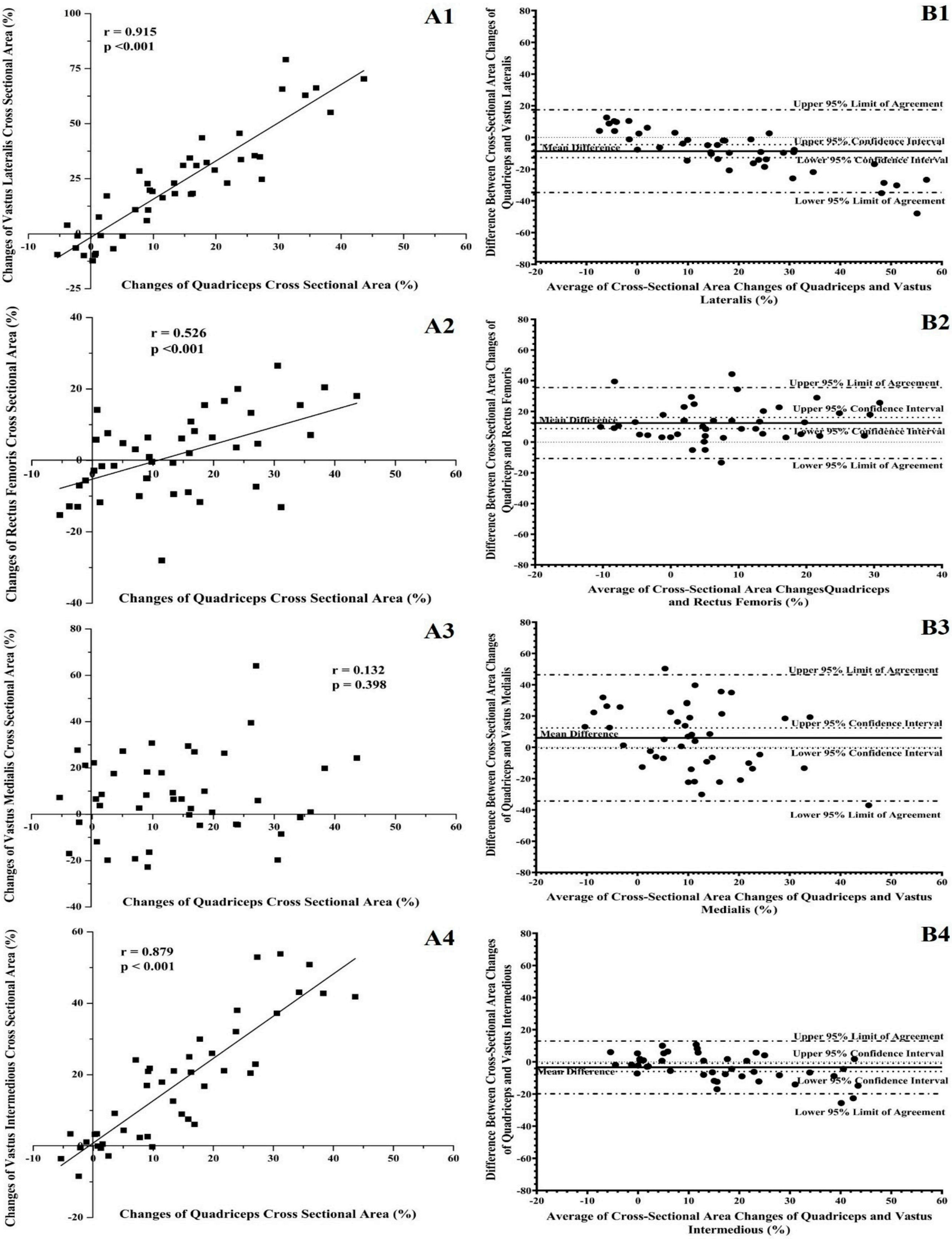

Figure 2. Correlation plots (**A**) and Bland-Altman 95% limits of agreements plots (**B**) for the comparisons between the training induced changes (%) of quadriceps femoris cross-sectional area, and those of Vastus Lateralis (**1**), Rectus Femoris (**2**), Vastus Medialis (**3**) and Vastus Intermedious (**4**).

4. Discussion

The purpose of the study was to investigate which of the four muscle heads of quadriceps femoris is the best surrogate of quadriceps resistance training-induced hypertrophy, evaluated by ultrasonography. The main finding of the present study was that training-induced changes in VL and VI CSAs, may be good surrogates of the whole quadriceps muscle hypertrophy following strength training, at least when the CSAs are evaluated with ultrasonography and at the 40% of the distance between the center of the patella and medial aspect of the anterior superior iliac spine, proximal to knee. According to the results of the present study, it could be suggested that when the evaluation of the whole quadriceps training-induced hypertrophy could not be performed, clinical and sports scientists may evaluate first the training-induced changes in VL's CSA, and if this evaluation is also not possible then to choose VI for the estimation of the whole quadriceps training-induced hypertrophy. Although VM CSA was significantly increased following training while RF CSA remained unchanged, these muscle heads are suggested to be avoided as predictors of the whole quadriceps hypertrophy. The results of the present study are in line with previous reports, especially with cross-sectional studies, indicating that VL is a good surrogate for the whole quadriceps muscle size, electromyographic activity, and force/power production [8,11,30,31]. However, according to the authors knowledge, this is the first study to present that the ultrasonographic evaluation of training-induced hypertrophy of VL and VI could be used for the representation of whole quadriceps muscle hypertrophy. The results of the present study are of high practical importance, especially for clinical and sports scientists who investigate the effect of resistance training on muscle mass and morphology.

A strong aspect of the present study was that it employes all of the needed statistical analyses as well as an absolute agreement analysis between the percentage training-induced changes in CSA of T versus those of VL, RF, VM and VI. Until now, the majority of the studies investigating which of the four heads of quadriceps is the best surrogate for T quadriceps used only the Pearson-r correlation coefficient and/or the ICC coefficient [8,11,30,31]. However, using Pearson-r correlation coefficient and/or the ICC coefficient could not provide sufficient evidence about the accuracy and reliability in such type of studies [36–42]. Thus, further statistical analysis was needed, such as SEM, CV, mean of the differences, Bland-Altman plots, LOA, SEL and RC, to provide readers and professionals details regarding the accuracy as well as the extent of the existing error between the mesaurements [36–42]. According to the results of these analyses, in the present study, all of the established criteria for high accuracy, reliability, repeatability and reproductivelity have been met for the ultrasonographic evaluation of VL's and VI's CSAs' training-induced increases, as potent surrogates of whole quadriceps muscle hypertrophy. Contrariwise, very low values were observed for VM and especially for RF. Specifically the training-induced change in RF hypertrophy were significantly different from those observed either in the other three heads of quadriceps, but mostly of the whole quadriceps hypertrophy. Significant inhomogeneous hypertrophy between the four heads of quadriceps has been previously reported, with significant hypertrophy to observed in whole quadriceps muscle, and specifically in VL, VI and VM, while no hypertrophy in RF was found after different types of multijoint lower body exercise [18,19], such as those adopted in the present study. However, the highest hypertrophy in RF compared to the other three quadriceps heads has been reported only after resistance training with leg extension [32,43–46]. Thus, it could be suggested that the results of the present study may be more accurate when lower-body multijoint exercises were adapted during the resistance training program. The results of the present study should be tested in future studies, adopting single-joint lower-body exercises.

The present study evaluated the CSA of the four muscle heads of quadriceps femoris at 40% of center of the patella and medial aspect of the anterior superior iliac spine, proximal to the knee. This point seems to have the largest cross sectional area along thigh [16]. However, it was recently revealed that anatomical CSA is different between different points across the thigh [47]. Unfortunately, only one point was evaluated in the present study and this data may not be representative for other points of quadriceps femoris. Only male participants were recruited in the study, thus more studies are needed for females. Lastly, the present findings cannot support other training protocols such as aerobic training.

5. Conclusions

In conclusion, VL and VI seems to be the best surrogates for the whole quadriceps resistance training-induced hypertrophy, when ultrasonography technique and multi-joint lower-body exercises are used. These results suggest that when ultrasonography is used to evaluate resistance training-induced hypertrophy, VL and VI could provide valid information about whole quadriceps muscle hypertrophy in response to lower-body multi-joint resistance training. This information can be applied in both exercise physiology and sport specific perceptions. Further research is needed in order to investigate possible similar tendencies in different points of the quadriceps and using different evaluating methods.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available after a reasonable request from the corresponding.

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

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