

Regional correlations between MRI-Derived muscle cross-sectional area and ultrasound-derived muscle thickness of the Vastus Lateralis

WATANYA JAIDEE¹, CHANTHAM SUNMAHAKHUN², SORNSUPHA LIMCHAREON³, TEETAWAT JEARSIRIKUL⁴, SUTASINEE KONGPROMSUK⁵, WIRAT SONCHAN⁶, RATANYOO LONGRAK^{7*}
^{1,2,3,4,5} Faculty of Medicine, Burapha University, Chon Buri, THAILAND
^{6,7} Faculty of Sport Science, Burapha University, Chon Buri, THAILAND

Published online: December 30, 2024

Accepted for publication: December 15, 2024

DOI:10.7752/jpes.2024.12313

Abstract:

Problem statement and purpose: Magnetic resonance imaging (MRI) has been regarded as the gold standard for quantifying vastus lateralis (VL) muscle size; however, its substantial cost has restricted its accessibility in resource-limited environments. Ultrasonography (US) has emerged as an affordable alternative. However, the relationship between regional VL muscle size measurements obtained via MRI and US remains uncertain. Consequently, this study aimed to investigate the correlations between the vastus lateralis cross-sectional area (VLCSA) derived from MRI and the vastus lateralis muscle thickness (VLMT) derived from US across three regions: proximal, middle, and distal. **Methods:** Eighteen healthy, physically active undergraduate students (age = 21.1 ± 0.5 years; height = 174.1 ± 5.3 cm; body weight = 68.8 ± 11.3 kg) underwent both US and MRI measurements of the VL muscle on the same day in a randomized order. Images of VLCSA and VLMT were acquired at the proximal, middle, and distal regions of the muscle. One-way ANOVA was used to compare VLCSA and VLMT among these regions. Pearson's correlation coefficient analyses were performed to examine the relationships between VLCSA and VLMT at each corresponding region and the sum of the three regions. **Results:** Statistical analyses revealed significant differences among regions for both VLCSA ($F_{[2,51]} = 24.616$, $p = 0.000$) and VLMT ($F_{[2,51]} = 7.786$, $p = 0.001$). Notably, a strong and significant correlation between VLCSA and VLMT was observed only in the middle region ($r = 0.72$, $p = 0.001$), while weaker and non-significant correlations were found at the proximal ($r = 0.35$) and distal regions ($r = 0.45$). However, when the VLMT and VLCSA values from all three regions were summed, a moderate and significant correlation was observed ($r = 0.54$, $p = 0.02$). **Conclusion:** Our findings suggest that prioritizing the middle region for US measurement of VLMT is advisable because this region exhibits a stronger correlation with MRI results. Furthermore, we recommend that practitioners assess VLMT across multiple regions rather than relying on a single, randomly selected region. By summing the measurements from multiple regions, a more reliable estimation of VLCSA can be obtained compared to using a single region alone.

Keywords: Measurement, Muscle morphology, Imaging technique, Quadriceps assessment, Diagnostic imaging

Introduction

Muscle mass is widely recognized as a crucial factor in physical performance, rehabilitation, and overall health (Wolfe, 2006). Understanding muscle size is particularly relevant in contexts such as aging, disease, and athletic training, where muscle hypertrophy or atrophy significantly impacts functionality and quality of life (Mankowski et al., 2015). Measuring muscle cross-sectional area (CSA) is a well-established and reliable method for quantifying changes in muscle size, with applications in both clinical and research settings (Longrak et al., 2024). Magnetic resonance imaging (MRI) is regarded as the gold standard for measuring muscle CSA owing to its high accuracy and ability to provide detailed insights into muscle morphology (Tothill & Stewart, 2002). For instance, the quadriceps muscle, particularly the vastus lateralis (VL), has been extensively studied owing to its critical role in lower-limb function, including locomotion, balance, and strength (Ahtiainen et al., 2010; Sterczala, et al., 2020).

Investigations into the VL frequently focus on regional muscle size variations. Researchers can identify patterns of regional atrophy or hypertrophy by evaluating CSA across proximal, middle, and distal regions, which have implications for rehabilitation procedures, targeted training, and understanding of muscle adaptation (Franchi et al., 2022). While MRI offers advantages, its high cost, limited availability, and time-consuming nature make it impractical for routine or widespread use (Nakatani et al., 2016). The high cost of MRI often restricts its use to well-funded research projects or specialized clinical settings, limiting its broader application in rehabilitation and sports science research. Moreover, the time required for image acquisition and analysis can be burdensome, particularly when assessing large cohorts or performing longitudinal studies (Engelke et al., 2023).

These constraints also make it difficult to monitor muscle morphology changes dynamically during intervention periods, which is essential for assessing such changes in real-time or frequently.

Ultrasonography (US), on the other hand, has emerged as a more budget-friendly and accessible option for muscle imaging (Young et al., 2021). US allows for quick, non-invasive measurements of muscle thickness (MT) (Franchi, et al., 2018), unlike MRI, making it suitable for both sports research and clinical settings. Previous research has explored VL MT assessments using US (Zaroni et al., 2019, Young et al., 2021). While US may not provide the comprehensive anatomical detail of MRI, it is increasingly preferred for applications requiring frequent evaluations (Lacerda et al., 2020; Sukkho et al., 2024). Several studies have shown a significant positive correlation between VL MT measured by US and CSA measured by MRI, especially in the muscle's middle region (Giles et al., 2015; Franchi et al., 2022; Ruple et al., 2022). This correlation highlights US's potential as an alternative to MRI in certain cases, particularly for tracking muscle adaptations over time.

Despite this progress, a critical gap remains in understanding how these two imaging modalities compare across different regions of the VL. While previous research has established correlations in the middle region, limited data exist for the proximal and distal regions. Exploring these regions could provide a more comprehensive understanding of the relationship between MRI-derived CSA and US-derived MT, potentially enhancing the applicability of US for localized muscle assessments. Therefore, the primary objective of this study was to investigate the regional correlations between MRI-derived VL CSA and US-derived VL MT across three specific regions: proximal, middle, and distal.

Methods

Study design

This study used a cross-sectional design to investigate the correlations between MRI-derived VL cross-sectional area (VLCSA) and US-derived vastus lateralis muscle thickness (VLMT) across three distinct regions. Participants underwent a single session of both MRI and US assessments on the same day, with the order of assessments randomized. VLCSA measurements were obtained using a 1.5-T MRI scanner at proximal, middle, and distal regions, while VLMT measurements were acquired via B-mode US in corresponding regions. Eligible participants were young, healthy, and active undergraduates between the ages of 18 and 22 with no prior experience in resistance training. However, they were actively engaged in sports and had no current reported injuries. The study adhered to the principles of the Declaration of Helsinki, and written informed consent was acquired from each participant. Ethical approval for the study was granted by the Institutional Review Board of Burapha University.

Participants

This study served as the first experiment of a broader research project investigating the impacts of resistance training programs on regional VL hypertrophy. The sample size was determined using G*Power software version 3.1.9.7, with an effect size of 0.75, an alpha level of 0.05, and a power of 0.80, referencing parameters from a previously published study that explored the effects of resistance training on muscle hypertrophy (Zaroni et al., 2019). The study recruited 20 healthy, active male undergraduates between the ages of 20 and 22 from the Faculty of Sport Science at Burapha University. These participants were not regularly engaged in strength training but actively participated in sports such as volleyball, cycling, running, football, and basketball.

Magnetic resonance imaging (MRI) measurement

The VLCSA of each participant was assessed using a 1.5-T MRI scanner (Vantage Elan, Canon, USA). All MRI procedures were performed by a registered clinical radiologist. Participants were positioned supine on the scanner bed with their knees extended. The imaging protocol included standard axial and coronal T1-weighted and T2-weighted fat-saturated sequences to ensure optimal visualization of the quadriceps muscles. VLCSA measurements were obtained at three different regions along the femur: the proximal region at 30%, the middle region at 50%, and the distal region at 70% of the femur length. The femur length was measured from the greater trochanter to the lateral epicondyle. This measurement approach was adopted from a previous study (Lacerda et al., 2020). Sample VLCSA images are presented in Figure 1a.

Ultrasonography (US) measurement

For the VLMT measurements, a B-mode US instrument (LOGIQ E10 Series, GE Healthcare, USA) was used on the same day as the MRI, with the order of measurements randomized. Consistent with the MRI protocol, identical measurement points along the femur were used to ensure consistency. Participants were marked with a skin marker at the 30% (proximal region), 50% (middle region), and 70% (distal region) locations of the femur length, aligning with the MRI protocol (Lacerda et al., 2020). US was performed by a registered clinical radiologist using a curvilinear probe with a frequency of 4–9 Hz. Participants were positioned supine with their knees fully extended to minimize muscle tension. VLMT at each region was determined as the perpendicular distance between the deep fascia and superficial fascia of the muscle. For enhanced measurement reliability, multiple scans were obtained and averaged. Sample VLMT images are presented in Figure 1b.

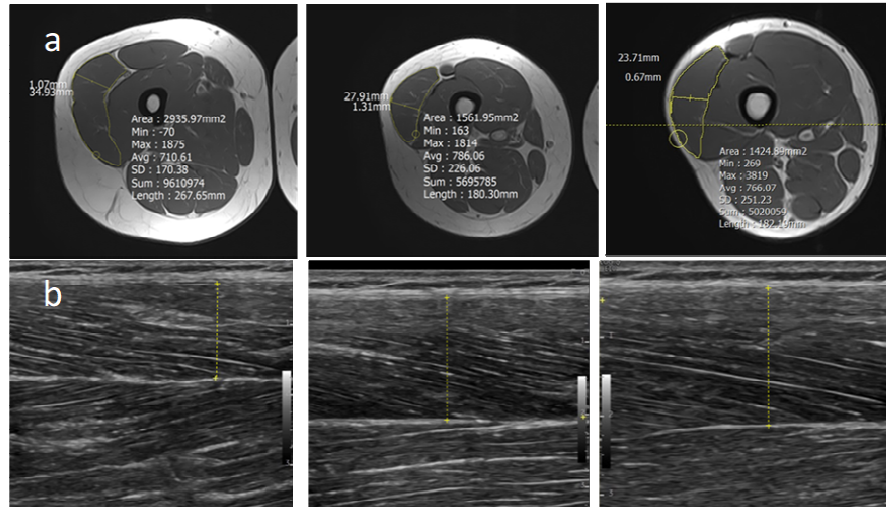


Figure 1. Example images of MRI-derived vastus lateralis muscle cross-sectional area (a) and US-derived vastus lateralis muscle thickness (b) from random regions of random participants

Statistical analysis

Descriptive statistics, including the mean and standard deviation, were calculated for VLCSA and VLMT across the proximal, middle, and distal regions, as well as the sums of these three regions. A one-way analysis of variance (ANOVA) was performed to compare VLCSA and VLMT among the different regions. When a significant difference was observed, post-hoc analysis with Bonferroni correction was performed to determine pairwise differences. Pearson's correlation coefficient analyses were additionally performed to investigate the relationships between VLCSA and VLMT at each corresponding region (proximal, middle, and distal regions) and the sum of the three regions. The interpretation of Pearson's correlation coefficient was as follows: 0.00–0.19 = *Very weak*, 0.20–0.39 = *Weak*, 0.40–0.59 = *Moderate*, 0.60–0.79 = *Strong*, and 0.80–1.00 = *Very strong*. Scatter plots were generated to illustrate these correlations. All analyses were performed using SPSS software version 21, with statistical significance set at $p < 0.05$.

Results

Of the initial 20 participants, 2 withdrew during the study. Therefore, the final analysis included 18 participants (age = 21.1 ± 0.5 years; height = 174.1 ± 5.3 cm; body weight = 68.8 ± 11.3 kg).

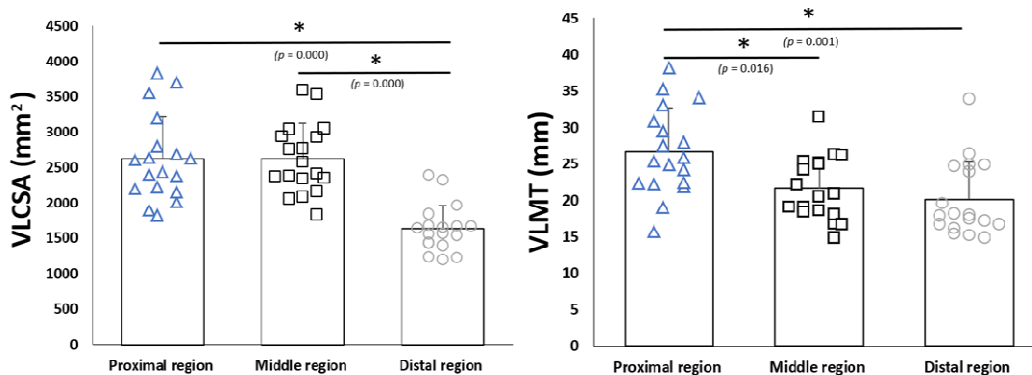


Figure 2. Mean and standard deviation values of regional muscle cross-sectional area (VLCSA) and muscle thickness (VLMT) of the VL, including individual data points

ANOVA revealed significant differences among regions for both VLCSA ($F_{[2,51]} = 24.616$, $p = 0.000$) and VLMT ($F_{[2,51]} = 7.786$, $p = 0.001$). Post-hoc analyses with Bonferroni adjustments demonstrated significant differences in VLCSA between the proximal and middle regions ($p = 0.000$) and between the middle and distal regions ($p = 0.000$). Similarly, significant differences in VLMT were observed between the proximal and middle regions ($p = 0.016$) and between the proximal and distal regions ($p = 0.001$) (Figure 3). The mean sums of VLCSA and VLMT across the three regions were 6880.50 ± 1214.64 mm² and 68.34 ± 12.86 mm, respectively.

Pearson's correlation coefficient analysis revealed a significant, *Strong* correlation between VLCSA and VLMT only in the middle region ($r = 0.72, p = 0.001$). In contrast, non-significant *Weak* ($r = 0.35, p = 0.16$) and *Moderate* ($r = 0.45, p = 0.06$) correlations were observed at the proximal and distal regions, respectively (Figure 3).

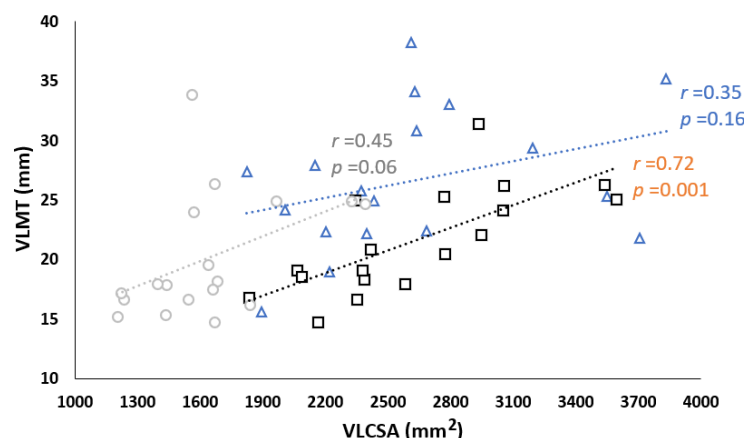


Figure 3. The correlations between vastus lateralis muscle thickness (VLMT) and vastus lateralis cross-sectional area (VLCSA) at the proximal (blue triangle), middle (black square), and distal regions (light grey circle)

However, when the three regions of VLMT and VLCSA were summed, Pearson's correlation coefficient analysis revealed a significant *Moderate* correlation between Σ VLMT and Σ VLCSA ($r = 0.54, p = 0.02$) (Figure 4).

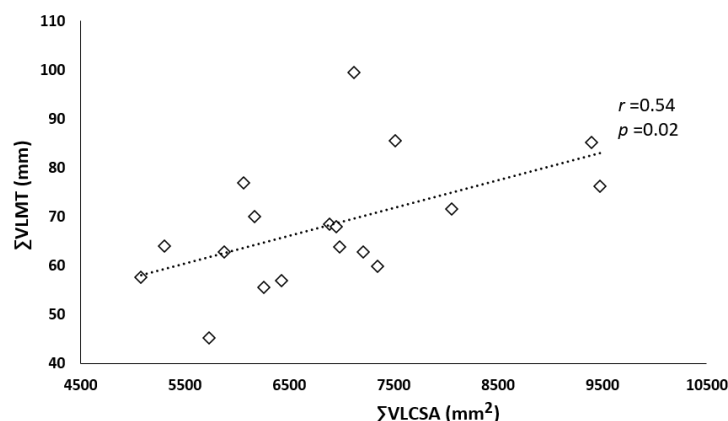


Figure 4. The correlation between the sum of vastus lateralis muscle thickness (Σ VLMT) and the sum of VL cross-sectional area (Σ VLCSA)

Discussion

To our knowledge, no previous studies have examined the regional correlations between MRI-derived VLCSA and US-derived VLMT. Our findings indicate that the central region of the VL had the strongest correlation between VLCSA and VLMT, while the proximal and distal regions exhibited weaker and non-significant correlations.

These findings corroborated previous studies that recognized the middle region as a dependable anatomical benchmark for evaluating muscle imaging (Franchi et al., 2018; Ruple et al., 2022; Giles et al., 2015; Lacerda et al., 2020). Notably, a previous study observed a strong correlation between US-determined VLMT and MRI-derived VLCSA at the middle region in individuals with patellofemoral pain ($r = 0.83$) (Giles et al., 2015) and healthy active individuals ($r = 0.82$) (Franchi et al., 2018). Similarly, another study reported a strong correlation ($r = 0.91$) between quadriceps MT and CSA in the middle region (Abe et al., 1997). The anatomical features of the middle region, characterized by a more substantial muscle belly, potentially contributed to the enhanced correlation observed in this area. This property may minimize measurement errors and improve the accuracy of US assessments, particularly in comparison to regions closer to the tendon, where MT decreases and becomes more challenging to measure accurately. This rationale aligns with a study investigating the soleus

muscle, which reported a negligible and non-significant correlation between soleus MT and CSA in the region adjacent to the tendon ($r = 0.03$) (Miyachi et al., 2020).

Notably, our findings aligned with those of a previous study that reported a strong and significant correlation between VLMT and VLCSA at the middle region ($r = 0.73$, $p < 0.01$) (Franchi et al., 2018) because our study demonstrated a comparable correlation coefficient in this region ($r = 0.72$, $p = 0.001$). However, we extended current knowledge by examining the regional correlations between VLMT and VLCSA in both proximal and distal regions, where no significant correlations were detected ($p > 0.05$). These observations suggest that measuring VLMT in the middle region might be more reliable for estimating VLCSA in the same region, whereas MT measurements in proximal or distal regions may not reflect CSA accurately. This discrepancy could potentially stem from the heterogeneous distribution of muscle size across distinct regions (Zabaleta-Korta et al., 2021). From a rudimentary mathematical standpoint, a proportional correlation in every region between VLMT and VLCSA would only be expected if the muscle exhibited a perfectly regular geometric shape (such as a cylinder or cube), a characteristic rarely encountered in human body muscles.

Furthermore, our findings align with the growing body of literature that advocates for the use of B-mode US as a practical and cost-effective alternative to MRI for muscle imaging (Nunes et al., 2024; Reeves et al., 2009; Ruple et al., 2022; Sanada et al., 2006). Notably, several studies have reported strong correlations between MRI-derived VLCSA and US-derived VLCSA obtained using the image stitching technique ($r > 0.8$) (Stokes et al., 2021; Lixandrão et al., 2024). While the image stitching technique requires specialized knowledge and advanced skills, our study suggests that using VLMT alone, measured with B-mode US, could provide a more accessible approach for estimating VLCSA. This approach is more time-efficient, eliminating the need for extensive imaging resources, and is particularly advantageous in environments where MRI is not readily accessible. Moreover, another compelling study revealed that US-derived VL architecture, such as fascicle length, also exhibited a significant association with biopsy-derived percentage CSA of fast twitch fibers ($r = 0.38$, $p < 0.05$) (Mpampoulis et al., 2021). This further underscores the ability of US to reliably capture not only muscle size but also muscle composition, making it a valuable tool in both clinical and research settings.

Furthermore, a recent study investigated the effects of 10 weeks of resistance training and assessed the agreement in muscle size changes using multiple methods, including the relationship between changes in VLMT and VLCSA at the middle region. The study reported a moderate correlation between the percentage change in VLCSA and the percentage change in VLMT following the training intervention ($r = 0.54$, $p < 0.05$) (Ruple et al., 2022). Additionally, the percentage change in VLMT also exhibited a moderate correlation with the percentage change in Dual-energy x-ray absorptiometry derived thigh lean mass ($r = 0.55$, $p < 0.05$) (Ruple et al., 2022). Similarly, another study corroborated these findings by demonstrating that VLMT exhibited a strong and significant correlation with VLCSA at both baseline ($r = 0.82$, $p < 0.01$) and after 12 weeks of resistance training ($r = 0.73$, $p < 0.01$) (Franchi et al., 2018).

Furthermore, they found that VLMT also had a strong correlation with MRI-derived muscle volume ($r = 0.73$, $p < 0.01$) (Franchi et al., 2018). Collectively, these findings underscore the utility of US-derived VLMT as a reliable and accessible method for evaluating muscle size and its adaptations. VLMT offers a valuable alternative for tracking changes in VLCSA and muscle volume in settings where advanced imaging techniques such as MRI or DXA may not be readily available. However, future studies should expand upon these findings by investigating regional correlations beyond the middle region, as examined in these two studies, by incorporating proximal and distal regions as done in our study.

Furthermore, we observed that when VLMT and VLCSA from the three regions were summed, a significant and positive moderate correlation emerged between the two methods ($r = 0.54$, $p = 0.02$). This finding underscores the potential advantage of considering a summed approach for US assessments of VLMT, particularly when the aim is to estimate total VLCSA. While the middle region alone remained a robust predictor, summing measurements from multiple regions may capture additional variability in muscle size that could be missed when focusing on a single region.

Furthermore, previous studies have cautioned against relying solely on measurements from a single random region to assess muscle morphology (Nunes et al., 2024) because this approach may fail to accurately reflect overall muscle structure (Seger et al., 1998). Our findings support this recommendation and suggest that, whenever possible, researchers should measure at least three regions. This approach acknowledges the non-uniform distribution of muscle size across regions, as evidenced by the absence of strong correlations between VLMT and VLCSA in the proximal and distal regions compared to the middle region. In cases where resources are constrained, we recommend that when assessing the VL muscle, the middle region should be prioritized for US assessments of VLMT owing to its more robust correlation with VLCSA observed through MRI.

This study has limitations. The relatively small sample size limits the generalizability of our findings. Future research with larger populations is necessary to confirm our results and explore potential regional differences in other muscles, such as the biceps brachii or biceps femoris. Additionally, our study focused only on healthy, active individuals, and the correlations observed may vary in different age groups, genders, or populations.

Conclusions

This study demonstrated that the middle region of the VL exhibited the strongest correlation between MT and CSA. This finding suggests that the middle region is the most reliable site for VLMT assessment via US. For resource-limited settings where US is used as an alternative to MRI, prioritizing the middle region of the VL is recommended over the proximal and distal regions. Additionally, summing VLMT measurements from multiple regions could enhance VLCSA estimation, further reinforcing the utility of US as a cost-effective alternative to MRI. These results support the broader application of US imaging for muscle assessment and provide a foundation for future research to explore its applicability across different muscles.

Conflicts of interest The authors declare no conflicts of interest.

References

- Abe, T., Kawakami, Y., Suzuki, Y., Gunji, A., & Fukunaga, T. (1997). Effects of 20 days bed rest on muscle morphology. *Journal of gravitational physiology: a journal of the International Society for Gravitational Physiology*, 4(1), S10–S14.
- Ahtiainen, J. P., Hoffren, M., Hulmi, J. J., Pietikäinen, M., Mero, A. A., Avela, J., & Häkkinen, K. (2010). Panoramic ultrasonography is a valid method to measure changes in skeletal muscle cross-sectional area. *European journal of applied physiology*, 108(2), 273–279. <https://doi.org/10.1007/s00421-009-1211-6>
- Engelke, K., Chaudry, O., Gast, L., Eldib, M. A., Wang, L., Laredo, J. D., Schett, G., & Nagel, A. M. (2023). Magnetic resonance imaging techniques for the quantitative analysis of skeletal muscle: State of the art. *Journal of orthopaedic translation*, 42, 57–72. <https://doi.org/10.1016/j.jot.2023.07.005>
- Franchi, M. V., Raiteri, B. J., Longo, S., Sinha, S., Narici, M. V., & Csapo, R. (2018). Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound in medicine & biology*, 44(12), 2492–2504. <https://doi.org/10.1016/j.ultrasmedbio.2018.07.010>
- Franchi, M. V., Longo, S., Mallinson, J., Quinlan, J. I., Taylor, T., Greenhaff, P. L., & Narici, M. V. (2018). Muscle thickness correlates to muscle cross-sectional area in the assessment of strength training-induced hypertrophy. *Scandinavian journal of medicine & science in sports*, 28(3), 846–853. <https://doi.org/10.1111/sms.12961>
- Giles, L. S., Webster, K. E., McClelland, J. A., & Cook, J. (2015). Can ultrasound measurements of muscle thickness be used to measure the size of individual quadriceps muscles in people with patellofemoral pain?. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine*, 16(1), 45–52. <https://doi.org/10.1016/j.ptspt.2014.04.002>
- Lacerda, L. T., Marra-Lopes, R. O., Diniz, R. C. R., Lima, F. V., Rodrigues, S. A., Martins-Costa, H. C., Bembem, M. G., & Chagas, M. H. (2020). Is Performing Repetitions to Failure Less Important Than Volume for Muscle Hypertrophy and Strength?. *Journal of strength and conditioning research*, 34(5), 1237–1248. <https://doi.org/10.1519/JSC.0000000000003438>
- Lixandrão, M. E., Ugrinowitsch, C., Bottaro, M., Chacon-Mikahil, M. P., Cavaglieri, C. R., Min, L. L., de Souza, E. O., Laurentino, G. C., & Libardi, C. A. (2014). Vastus lateralis muscle cross-sectional area ultrasonography validity for image fitting in humans. *Journal of strength and conditioning research*, 28(11), 3293–3297. <https://doi.org/10.1519/JSC.0000000000000532>
- Longrak, R., Sonchan, W., & Jaidee, W. (2024). Regional morphological adaptations of vastus lateralis muscle in response to different progressive resistance training programs: A randomised controlled trial. *South African journal of sports medicine*, 36(1), v36i1a18549. <https://doi.org/10.17159/2078-516X/2024/v36i1a18549>
- Mankowski, R. T., Anton, S. D., & Aubertin-Leheudre, M. (2015). The role of muscle mass, muscle quality, and body composition in risk for the metabolic syndrome and functional decline in older adults. *Current Geriatrics Reports*, 4(3), 221–228. <https://doi.org/10.1007/s13670-015-0132-y>
- Miyachi, R., Yamazaki, T., Ohno, N., & Miyati, T. (2020). Relationship between Muscle Cross-Sectional Area by MRI and Muscle Thickness by Ultrasonography of the Triceps Surae in the Sitting Position. *Healthcare (Basel, Switzerland)*, 8(2), 166. <https://doi.org/10.3390/healthcare8020166>
- Mpampoulis, T., Methenitis, S., Papadopoulos, C., Papadimas, G., Spiliopoulou, P., Stasinaki, A. N., Bogdanis, G. C., Karampatsos, G., & Terzis, G. (2021). Weak Association Between Vastus Lateralis Muscle Fiber Composition and Fascicle Length in Young Untrained Females. *Sports (Basel, Switzerland)*, 9(5), 56. <https://doi.org/10.3390/sports9050056>
- Nakatani, M., Takai, Y., Akagi, R., Wakahara, T., Sugisaki, N., Ohta, M., Kawakami, Y., Fukunaga, T., & Kanehisa, H. (2016). Validity of muscle thickness-based prediction equation for quadriceps femoris volume in middle-aged and older men and women. *European journal of applied physiology*, 116(11-12), 2125–2133. <https://doi.org/10.1007/s00421-016-3464-1>
- Nunes, J. P., Blazevich, A. J., Schoenfeld, B. J., Kassiano, W., Costa, B. D. V., Ribeiro, A. S., Nakamura, M., Nosaka, K., & Cyrino, E. S. (2024). Determining Changes in Muscle Size and Architecture After Exercise Training: One Site Does Not Fit all. *Journal of strength and conditioning research*, 38(4), 787–790. <https://doi.org/10.1519/JSC.0000000000004722>

- Reeves, N. D., Maganaris, C. N., Longo, S., & Narici, M. V. (2009). Differential adaptations to eccentric versus conventional resistance training in older humans. *Experimental physiology*, 94(7), 825–833. <https://doi.org/10.1113/expphysiol.2009.046599>
- Ruple, B. A., Smith, M. A., Osburn, S. C., Sexton, C. L., Godwin, J. S., Edison, J. L., Poole, C. N., Stock, M. S., Fruge, A. D., Young, K. C., & Roberts, M. D. (2022). Comparisons between skeletal muscle imaging techniques and histology in tracking midthigh hypertrophic adaptations following 10 wk of resistance training. *Journal of applied physiology* (Bethesda, Md. : 1985), 133(2), 416–425. <https://doi.org/10.1152/jappphysiol.00219.2022>
- Sanada, K., Kearns, C. F., Midorikawa, T., & Abe, T. (2006). Prediction and validation of total and regional skeletal muscle mass by ultrasound in Japanese adults. *European journal of applied physiology*, 96(1), 24–31. <https://doi.org/10.1007/s00421-005-0061-0>
- Seger, J. Y., Arvidsson, B., & Thorstensson, A. (1998). Specific effects of eccentric and concentric training on muscle strength and morphology in humans. *European journal of applied physiology and occupational physiology*, 79(1), 49–57. <https://doi.org/10.1007/s004210050472>
- Sterczala, A. J., Miller, J. D., Dimmick, H. L., Wray, M. E., Trevino, M. A., & Herda, T. J. (2020). Eight weeks of resistance training increases strength, muscle cross-sectional area and motor unit size, but does not alter firing rates in the vastus lateralis. *European journal of applied physiology*, 120(1), 281–294. <https://doi.org/10.1007/s00421-019-04273-9>
- Stokes, T., Tripp, T. R., Murphy, K., Morton, R. W., Oikawa, S. Y., Lam Choi, H., McGrath, J., McGlory, C., MacDonald, M. J., & Phillips, S. M. (2021). Methodological considerations for and validation of the ultrasonographic determination of human skeletal muscle hypertrophy and atrophy. *Physiological reports*, 9(1), e14683. <https://doi.org/10.14814/phy2.14683>
- Sukkho, P., Leelarungrayub, J., & Khamboon, C. (2024). Association and forecasting model for leg strength based on physical characteristics and quadriceps muscle thickness in young participants: A preliminary study. *Journal of Physical Education and Sport*, 24(5), 1191–1197. <https://doi.org/10.7752/jpes.2024.05137>
- Tothill, P., & Stewart, A. D. (2002). Estimation of thigh muscle and adipose tissue volume using magnetic resonance imaging and anthropometry. *Journal of sports sciences*, 20(7), 563–576. <https://doi.org/10.1080/026404102760000062>
- Wolfe R. R. (2006). The underappreciated role of muscle in health and disease. *The American journal of clinical nutrition*, 84(3), 475–482. <https://doi.org/10.1093/ajcn/84.3.475>
- Young, T. R., Duncan, B. T., & Cook, S. B. (2021). Evaluation of muscle thickness of the vastus lateralis by ultrasound imaging following blood flow restricted resistance exercise. *Clinical physiology and functional imaging*, 41(4), 376–384. <https://doi.org/10.1111/cpf.12704>
- Zabaleta-Korta, A., Fernández-Peña, E., Torres-Unda, J., Garbisu-Hualde, A., & Santos-Concejero, J. (2021). The role of exercise selection in regional Muscle Hypertrophy: A randomized controlled trial. *Journal of sports sciences*, 39(20), 2298–2304. <https://doi.org/10.1080/02640414.2021.1929736>
- Zaroni, R. S., Brigatto, F. A., Schoenfeld, B. J., Braz, T. V., Benvenutti, J. C., Germano, M. D., Marchetti, P. H., Aoki, M. S., & Lopes, C. R. (2019). High Resistance-Training Frequency Enhances Muscle Thickness in Resistance-Trained Men. *Journal of strength and conditioning research*, 33 Suppl 1, S140–S151. <https://doi.org/10.1519/JSC.0000000000002643>