The Effect of Complex Training on Muscle Architecture in Rugby League Players

David J. Scott[1], Phil Marshall[1], Samuel T. Orange[2,3] & Massimiliano Ditroilo[4]*

[1]Department of Sport, Health and Exercise Science, University of Hull, UK

[2]Newcastle University Centre for Cancer, Newcastle University, Newcastle upon Tyne, UK

[3]School of Biomedical, Nutritional and Sport Sciences, Faculty of Medical Sciences, Newcastle University, Newcastle upon Tyne, UK

[4]School of Public Health, Physiotherapy and Sports Science, University College Dublin, UK

***Corresponding Author:**

Dr Massimiliano Ditroilo

School of Public Health, Physiotherapy and Sports Science
University College Dublin
Health Sciences Centre
4 Stillorgan Road
Belfield
Dublin 4
Ireland
Email: massimiliano.ditroilo@ucd.ie

RUNNING HEAD: Complex Training and Muscle Architecture

Accepted author manuscript version reprinted, by permission, from International Journal of Sports Physiology and Performance, 2023, 18 (3): 231-239, https://doi.org/10.1123/ijspp.2021-0570.

ABSTRACT

Purpose: To compare the effects of variable resistance complex training (VRCT) versus traditional complex training (TCT) on muscle architecture in rugby league players during a 6-week mesocycle.

Methods: Twenty-four rugby league players competing in the BUCS Premier North Division were randomised to VRCT (n=8), TCT (n=8) or control (n=8). Experimental groups completed a 6-week lower-body complex training intervention (2x/week), which involved alternating high-load resistance exercise with plyometric exercise in the same session. The VRCT group performed resistance exercises at 70% of 1RM + 0-23% of 1RM from band resistance with a 90 second intra-contrast rest interval (ICRI), whereas the TCT group performed resistance exercise at 93% of 1RM with a 4-minute ICRI. Muscle thickness (MT), pennation angle (P_{ang}) and fascicle length (L_f) were assessed for the vastus lateralis (VL) and gastrocnemius medialis (GM) using ultrasound imaging.

Results:

Both TCT and VRCT groups significantly improved VL MT and VL L_f compared to control (all p<0.05). Standardised within-group changes in MT and L_f (Cohen's $d_{av} \pm$ 95% confidence interval) were moderate for TCT (d_{av} = 0.91±1.0; d_{av} = 1.1±1.1) and *unclear* for VRCT (d_{av} = 0.44±0.99; d_{av} = 0.47±0.99), respectively. Differences in change scores between TCT and VRCT were unclear.

Conclusions: VRCT and TCT can be utlilised during the competitive season to induce favourable MT and L_f muscle architecture adaptations for the VL. TCT may induce greater muscle architecture adaptations of the VL whereas, VRCT may be of more practical value given the shorter ICRI between resistance and plyometric exercises.

Keywords: Variable resistance complex training, traditional complex training, muscle architecture, length-tension relationship, rugby league, in-season conditioning.

INTRODUCTION

The ability of skeletal muscle to generate maximum force and power is strongly influenced by its architecture.[1,2] Specifically, muscle architecture characteristics such as, muscle thickness (MT), pennation angle (P_{ang}) and fascicle length (L_f) affect the transmission of force from muscle to tendon.[3] Given the plastic nature of muscle architecture, it is important for sport science practitioners to understand how different training modalities modify muscle architecture and in turn muscle function, which eventually affect athletic performance.[2]

Increases in vastus lateralis (VL) P_{ang} and L_f,[4,5] as well as MT,[4] have been observed in response to heavy concentric and eccentric resistance training. Interestingly though, a recent study found distinct VL adaptations associated with eccentric exercise (predominantly L_f) or concentric exercise (predominantly P_{ang}).[6] Increases in both P_{ang} and L_f will affect muscle size (i.e. MT), which results in greater force generating capacity.[7] Additionally, it has been suggested that an increase in P_{ang} enables muscles to work closer to their optimum length as they have to shorten less for a given tendon displacement, which again helps generate more force.[1] A limited number of studies have examined the effect of plyometric training on muscle architecture.[8,9] An increase in L_f (+13%) and a decrease in P_{ang} (-9%) of the VL have been reported in a small sample of elite female rowers following 16 weeks of concurrent endurance and heavy resistance training, including plyometric training.[9] In contrast, another study found a significant increase in MT (+4-6%), L_f (+6-8%) and P_{ang} (+4-8%) of the VL in recreationally active young and older males following 6 weeks of plyometric training.[8]

Traditional approaches to the periodization of strength training typically involves periods of maximal strength work, employing heavy resistance training, prior to power training.[10] This sequencing takes advantage of the changes in muscle architecture elicited by heavy resistance training to further enhance adaptations in a subsequent period of power training and allows both extremes of the force-velocity curve to be trained. However, this approach is typically applied over a period of weeks or months.

Complex training, or more specifically contrast training (a specific subset of complex training), alternates high-load resistance exercise with plyometric exercise on a set for set basis in the same session, with the aim of improving slow and fast force production.[11,12] Complex training has been shown to be just as (or more) effective for improving strength and power in comparison to either modality alone.[13] This is attributed to post-activation performance enhancement (PAPE), a phenomenon which theorises that force production and rate of force development are temporarily augmented in skeletal muscle following a near maximal voluntary contraction, at least partly due to changes in muscle activation, muscle temperature, and intracellular water accumulation.[14]

An appropriate intra-contrast rest interval (ICRI) between resistance and plyometric exercises is needed to allow fatigue to dissipate.[15] Although heavy load (≥ 85% of 1-repetition maximum [RM]) exercises performed at slow velocities are typically used to elicit the PAPE response[16,17], research suggests that moderate loads (60-85% of 1RM), combined with variable resistance, performed explosively can also induce PAPE.[18,19] The selection of heavy or moderate loads depends on a multitude of factors, including the desired outcome and training experience.

Variable resistance modifies the force-velocity profile of resistance exercise, enabling greater accelerations and velocities during the concentric phase of the lift.[20] This is achieved by using latex bands or chains to add a percentage of the total resistance as the barbell travels through the range of movement.[20] Consequently, it is easier to accelerate during biomechanically disadvantageous positions, or 'sticking points', during the initial movement.[20] Additionally, greater force and power outputs in biomechanically advantageous positions have been reported.[14] This is attributed to variable resistance accounting for the length-tension relationship of skeletal muscle.[20]

Limited research investigating the effects of complex training on muscle architecture exists.[21] The stimuli (resistance and plyometric exercise) delivered to the muscle during complex training could induce conflicting muscle architecture adaptations.[9] Moreover, to date, no empirical evidence documents the associated muscle architecture adaptations of complex training modes which induce slow contraction velocities in comparison to faster contraction velocities. Therefore, the purpose of this research was to compare the muscle architecture adaptations of traditional complex training (TCT) and variable resistance complex training (VRCT).

METHODS

Participants

Twenty-four male rugby league players were recruited from a University rugby league team during the competitive season (Table 1). Given the multiple training modes players engage in, congested fixture schedules and short turn-around time between games, there is limited time for strength training.[22] During the competitive season, complex training may be advantageous in this population as it enables two training modes, which rugby league players regularly engage in, to be addressed in a single session.[23] All participants had no existing musculoskeletal injuries, were currently competing in the BUCS Premier North Division, and engaged in two resistance training sessions per week plus one weekly sports-specific field session (rugby league skills and conditioning) for the last six months.. The study received full ethical approval from the Department of Sport, Health and

Exercise Science Ethics Committee at the University of Hull in accordance with the Declaration of Helsinki. Each participant voluntarily gave their written informed consent to take part in the study.

Experimental Design

The study adopted a between-subject, randomised design. Participants were randomly allocated to either VRCT, TCT or a control (CON) group using online randomisation software. Both training groups completed 6-weeks of the corresponding training interventions which comprised of two sessions per week where the volume-load was identical between training groups. Participants in the CON group did not undertake any training. Outcome measures of MT, P_{ang} and L_f for the VL and Gastrocnemius Medialis (GM) were assessed pre- and post-intervention (Figure 1).

Experimental Procedures

Participants attended a familiarisation session during which, anthropometric measurements of height (The Leicester Height Measure, Seca, Birmingham, UK) and body mass (Seca 813 digital scales, Birmingham, UK) were recorded. For the purpose of muscle architecture assessment, leg dominance was determined using the step up, balance recovery and ball kick tests.[24] Leg dominancy was defined as the leg which was dominant in two of the three tests. Additionally, participants were familiarised with the standardised warm-up (Table 2), experimental testing protocol, and the resistance and plyometric exercises within the training programme.

Muscle architecture assessment of the VL and GM on the dominant leg of each participant was completed during a single visit. The muscular contractions of the VL and GM directly relate to key movement skills in rugby league such as running, jumping and multidirectional speed.[25] The following week, participants were randomly assigned to VRCT, TCT or CON. Training load for each exercise was determined over two days separated by 48-96 hours recovery. Day 1 consisted of a 1RM hex-bar deadlift (HBD). Day 2 involved a 3RM Romanian deadlift (RDL) and Bulgarian split squat (SS_{Bulg}). Participants commenced the 6-week training mesocycle the next week. Testing for the post-intervention outcome measures took place the week following the final complex training session.

Outcome Measures

This paper reports changes in muscle artichecture, including MT, P_{ang} and L_f for the VL and GM. Changes in back squat one repetition maximum (1RM), countermovement jump (CMJ) power, sprint speed and leg stiffness are reported in a separate 'twin' manuscript.[26]

Muscle architecture was examined using a 7.5 MHz, 45 mm linear array, B-mode ultrasound probe (MyLab 50 Xvision, Esaote, Genova, Italy) with a depth resolution of 50 mm. Participants lay supine with knees flexed at 30˚ to reduce fascicle curvature for VL assessment.[27] The probe was placed 50% of the distance from the greater trochanter of the femur to the articular cleft between the femoral and tibial condyles.[4] For GM assessment, participants lay prone with their ankles relaxed at 90˚.[28] The probe was placed 30% of the distance from the articular cleft between the femoral and tibial condyles to the lateral malleolus.[28] To allow fluid shift to occur, participants lay in the described positions for 20-minutes prior to any measurement.[29]

A water-soluble transmission gel was applied to the probe to aid acoustic coupling and remove pressure on the muscle. The probe was aligned with the sagittal plane of the muscle fascicles and perpendicular to the skin. The orientation of the probe was manipulated and considered appropriate when several muscle fascicles were determined without interruption across the image.[4,27] Consequently, the angle of the probe relative to the longitudinal axis varied between participants. A total of four images were recorded for each muscle.

Determination of Individual Training Loads

Training load was determined for the resistance exercises within the training programme over two sessions which were separated by 48-96 hours. Session one consisted of a 1RM HBD and session two comprised of a 3RM RDL and SS_{Bulg}. Following the same standardised warm-up, established procedures for RM assessment were adhered to.[30] Briefly, participants performed RM attempts with progressively increased loads. The attempt was only accepted if the exercise was completed with correct technique. Participants were allowed 2-4 minutes recovery between each attempt and were permitted a maximum of five attempts to derive the corresponding RM. Predicted 1RM scores for RDL and SS_{Bulg} were calculated using the training load chart.[31]

For VRCT, the variable resistance from the latex bands was determined following previously established methods.[18,19] Briefly, participants stood on Seca weighing scales with the bar and mass recorded. The bands (Pullum Sports, Leighton Buzzard, Bedfordshire) were secured to the bar and participants stood at the end range for each exercise and mass was recorded. Band tension was defined as the difference between these two measures. This process was repeated with bands of various tension until the accommodating resistance reached 23% 1RM at end range for each exercise.

Training Programme

Complex training sessions (or more specifically, contrast training; a specific subset of complex training)[11] were completed twice per week for six weeks, with 48-96 hours recovery between sessions. Each training session commenced with a standardised warm-up. Additionally, participants were allowed two warm-up sets of each resistance exercise, which comprised of six repetitions at 50% of 1RM and four repetitions at 70% of 1RM separated by 2-3 minutes rest. Both groups performed the HBD as explosively as possible during the concentric phase. To safely minimise the amount of work during the eccentric phase, the TCT group were instructed to drop the bar at the top of the lift whereas, the VRCT were instructed to perform the eccentric phase as quickly as possible. To replicate real-world application of complex training, multiple complex pairs (HBD + drop jumps, RDLs + pike jumps, SS_{Bulg} + lunge jumps) were prescribed (Table 3). Participants were encouraged to lift as explosively as possible during the concentric phase for RDL and SS_{Bulg} and complete the eccentric phase in a controlled manner.

The volume-load of the prescribed exercises was consistent between training groups, where volume was defined as sets x repetitions x load. However, the barbell load and ICRIs varied. Studies have demonstrated that an ICRI of 4-12 minutes elicits optimal PAPE responses when heavy load (≥ 85% of 1RM) resistance exercises are utilised.[16,17] However, research suggests that shorter ICRIs of 90 seconds can evoke PAPE when a moderate load (60-85% of 1RM) is combined with variable resistance.[18,19] which may be of more practical value during the competitive season. Therefore, TCT comprised of resistance exercises performed at 93% of 1RM with a 4-minute ICRI whereas, VRCT involved resistance exercises performed at 70% of 1RM + 0-23% of 1RM from band resistance with a 90 second ICRI. The adherence rate for the VRCT and TCT groups were 94.8% and 95.8%, respectively. Participants maintained their in-season training routine during the study, which comprised one field session (rugby league skills and conditioning) and one match each week, but did not engage in any other form of resistance training or plyometrics.

Data Analysis and Variable Extraction

Image analysis (Figure 2) was conducted using publicly available imaging software (ImageJ, 1.48v, National Institutes of Health; http://rsb.info.nih.gov/ij/). MT was measured as the distance between the superficial aponeurosis and the deep aponeurosis at the centre of the image.[4,27] P_{ang} was measured as the angle between the deep aponeurosis and the fascicles.[27] L_f was measured as the length of the fascicle between the superficial and deep aponeurosis. The visible portion of the muscle fascicle in each image was measured by tracking the length of a single muscle fascicle using a segmented line. The non-visible portion was estimated by linear extrapolation which involved measuring the distance between the visible muscle fascicle to the intersection between a line drawn from the muscle fascicle and a line drawn from the aponeuroses.[29] A mean was calculated from the 4 images recorded for each variable. . Between-session coefficient of variations (CVs) and intraclass correlation coeffcients (ICCs) for MT (3.30%, 0.89), P_{ang} (3.64%, 0.93) and L_f (3.52%, 0.95) have been reported previously, indicating a high level of reliability..[32]

Statistical Analysis

Preliminary analysis was conducted to ensure normal distribution of the data. Statistical analysis was conducted using a 3 (condition: VRCT, TCT and CON) x 2 (time: pre- and post-training) ANOVA with repeated measures on time to analyse within-group changes between pre- and post-training. If significant main effects for time were detected, pairwise comparisons were applied with Bonferroni corrections to correct for type I errors. Between-group differences of the change score were analysed using a one-way ANOVA. Standardised effect size statistics (Cohen's *d*) were also calculated to interpret within-group changes from pre-training to post-training (mean change divided by the average SD at pre- and post-training; d_{av}), and between-group differences in change scores (mean difference divided by the SD of difference; d_s).[33] The magnitude of Cohen's *d* was interpreted as *trivial* (≤0.19), *small* (0.20-0.59), *moderate* (0.60-1.19), *large* (1.2-1.99), and *very large* (≥2.0).[34] Where the 95% CIs overlapped the thresholds for *small* positive and *small* negative, the effect was considered *unclear*. Statistical procedures were conducted using SPSS 26 (SPSS Inc., Chicago, IL) and standardised effect sizes were calculated using Microsoft Excel. Statistical significance was set at $p \leq 0.05$. Data are presented as mean ± SD or d ± 95% confidence interval (CI).

RESULTS

Descriptive statistics and within-group changes from baseline to follow-up are reported in Table 4. Both TCT and VRCT significantly improved VL MT and VL L_f from pre-to-post training (all $p<0.01$). The magnitude of within-group changes in VL MT and VL L_f were moderate for TCT (d_{av} = 0.91±1.0; d_{av} = 1.1±1.1) and *unclear* for VRCT (d_{av} = 0.44±0.99; d_{av} = 0.47±0.99), respectively. Change scores for VL MT and VL L_f following TCT and VRCT were significantly different compared to CON (all $p<0.05$; Table 4). However, differences in change scores between TCT and VRCT were *unclear* (presented in Figure 3).

VRCT and TCT both demonstrated significant improvements in back squat 1RM compared to control (reported in a separate paper[26]).

DISCUSSION

The main findings of this study were that both complex training conditions induced similar muscle architecture adaptations to VL MT and VL L_f. However, there is evidence to suggest that TCT favours improvements in these muscle architecture variables; this may have important implications in relation to the transmission of force from muscle fibres to the tendon. For example, changes in MT may result in higher transmission of force through tendons to the skeletal system[3] and changes in L_f may contribute to higher shortening velocities.[2] Both architectural adaptations can be considered important for enhacing performance in rugby league. Additionally, the training interventions had no effect on the GM muscle.VRCT may be advantageous during the competitive season because it is time-efficient and involves lifting lower loads at higher velocities..

Therefore, the implementation of either TCT or VRCT is a trade-off between the magnitude of muscle architecture adaptation and time.

Only one previous study has examined the effects of complex training on muscle architecture.[21] In agreement with this research, the present study demonstrated increased VL MT following the VRCT and TCT conditions. Interestingly, MT is indicative of muscle cross sectional area[35] and is associated with enhanced force production capabilities of skeletal muscle,[36] ostensibly due to a greater number of sarcomeres in parallel. This is important given that strength and power are integral for successful performance in rugby league.[23] The change in MT may also benefit subsequent adaptations to training by facilitating an improved ability to handle higher training loads and therefore allow for application of greater overload stimulus. Increased muscle cross sectional area is synonymous with hypertrophy.[3] Although the present study did not directly assess hypertrophy, previous research has demonstrated that complex training evokes significant increases in cross sectional area of type I and II VL muscle fibres. It is conceivable that both complex training conditions elicited hypertrophic responses however, this requires further investigation.

There is evidence to suggest that adaptations to VL L_f were induced following TCT. Although improvements were observed in both conditions, only adaptations in TCT were greater than the minimum detectable change (MDC; 0.94cm) previously reported by the researcher.[32] Greater L_f is associated with an increase in the number of sarcomeres in series which enables faster fibre shortening velocities.[1] This can be explained by a shift to the right in the length-tension curve since peak tension occurs at longer sarcomere lengths and less work is done on the descending part of the curve where force production is inhibited.[37] This may be important in relation to multidirectional tasks during rugby league match-play since faster individuals typically possess longer muscle L_f .[38] The increased amount of time spent under tension with a greater constant barbell load during

TCT[39] may explain this finding since an increase in the number of sarcomeres in series may result from increased e heccentric muscle loading[37] This finding is in conflict with previous research[21] and therefore warrants further examination. It is conceivable that this is due to differences in exercise selection, volume-load, barbell load and ICRIs utilised in this study and previous research.

The current study demonstrated no change in VL P_{ang} which is also in disagreement with previous research.[21] Similar to MT, increases in P_{ang} are associated with the arrangement of a greater number of sarcomeres in parallel and the packing of muscle fibres within a given anatomical cross-sectional area.[1,3] However, increased P_{ang} is reported to decrease muscle fibre shortening velocity because of reduced force transmission from muscle fibres to the tendon due to the increased oblique angle of pull.[3,15] Therefore, increases in MT and L_f, as observed in this study, may be favourable to counteract the reduction in fibre shortening velocity.

No changes to GM muscle architecture were observed in the present study. This contrasts with previous research which reported increased GM P_{ang} and decreased L_f.[21] The GM acts as a stabiliser of the lower leg during closed chain resistance exercises and its contribution to such exercises are dependent on knee and joint angles due to its biarticular nature.[40,41] Therefore, it is conceivable that the GM did not act as prime mover of the exercises administered within the current study. The loaded (30% of 1RM) plyometric exercises utilised in previous research[21] may have induced greater muscle activation during plantar flexion which could explain these findings.[41]

The differences in findings between the present study and previous research could also be explained by the selected training variables. For example, Stasinaki et al.[21] implemented 85% and 30% of 1RM loads for resistance and plyometric exercises, respectively. The weighted plyometric exercises are likely to have altered the force-velocity profile of the movements in comparison to the body weight plyometric exercises within the current study, which is important given that muscle architecture adaptations are velocity-specific.[7] The resistance exercises in previous research were machine based which may not be a PAPE specific stimulus since muscle activation is reduced.[40] An ICRI of 3-minutes was utilised which may not have enabled PAPE to manifest, especially given the training status of the participants.

There are some limitations to this study. Although participants were, at least, moderately trained, their training status varied which may have influenced the magnitude of muscle architecture adaptation.[42] Despite that participants were randomy allocated to groups, the VRCT group had a lower body mass than the other groups at baseline, although there is no evidence that this would modify muscle architectural adaptations to complex training. The sample size was small, however, it is challenging to recruit rugby league players for a training intervention study during their structured in-season training schedule. Since the training programmes were conducted in-season, it was not possible to control for on-field training loads, which could have influenced muscle architecture adaptations. Training variables were not manipulated as the training programme progressed therefore, PAPE may not have been elicited since the response is modified following training.[43] Furthermore, the highly individualised nature of PAPE[16] means that it cannot be guaranteed that an optimal response was evoked in all participants. The selected ICRIs were based on the HBD and may not have been appropriate for RDL and SS_{Bulg} since the magnitude of PAPE and recovery intervals have not been reported in academic literature. Although the study attempted to replicate real-world training scenarios using multiple complex pairs, the results from the study cannot be attributed to one form of training (i.e. resistance or plyometric training) which should be considered in future research.

PRACTICAL APPLICATIONS

This study suggests that VRCT and TCT induce similar muscle architecture adaptations of the VL, which may be beneficial for rugby league players in relation to force and power production. TCT may favour muscle architecture changes therefore enhancing force transmission from muscle fibres to the tendon whereas, VRCT may be advantageous during the competitive season due to the shorter ICRI. Therefore, coaching staff should consider the objective of their training programme and judge whether the potential muscle architecture benefits associated with TCT outweigh the time efficiency of VRCT. Nevertheless, both modalities appear to be suitable for training both extremes of the force-velocity curve during a single session when ICRIs recommended in academic literature are implemented.

CONCLUSIONS

This is the first study to demonstrate the muscle architecture adaptations associated with TCT and VRCT during a 6-week mesocycle throughout the competitive rugby league season. TCT may lead to greater muscle architecture adaptations of the VL whereas, VRCT is likely to be of more practical value given the shorter ICRI between resistance and plyometric exercises. How these muscle architecture adaptations are reflected into the sport performance of rugby league requires further examination.

ACKNOWLEDGEMENTS

The authors would like to thank the university rugby league players who participated in this study.

REFERENCES

1. Cormie P, McGuigan MR, Newton RU. Developing Maximal Neuromuscular Power. *Sports Med*. 2011;41(1):17-38. doi:10.2165/11537690-000000000-00000

2. Lieber RL, Fridén J. Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve*. 2000;23(11):1647-1666. doi:10.1002/1097-4598(200011)23:11<1647::aid-mus1>3.0.co;2-m

3. Folland JP, Williams AG. The adaptations to strength training : morphological and neurological contributions to increased strength. *Sports Med*. 2007;37(2):145-168.

4. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol*. 2007;103(5):1565-1575. doi:10.1152/japplphysiol.00578.2007

5. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol*. 2007;102(1):368-373. doi:10.1152/japplphysiol.00789.2006

6. Franchi MV, Atherton PJ, Reeves ND, et al. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol (Oxf)*. 2014;210(3):642-654. doi:10.1111/apha.12225

7. Blazevich AJ, Gill ND, Bronks R, Newton RU. Training-specific muscle architecture adaptation after 5-wk training in athletes. *Med Sci Sports Exerc*. 2003;35(12):2013-2022. doi:10.1249/01.MSS.0000099092.83611.20

8. Franchi MV, Monti E, Carter A, et al. Bouncing Back! Counteracting Muscle Aging With Plyometric Muscle Loading. *Front Physiol*. 2019;10:178. doi:10.3389/fphys.2019.00178

9. van der Zwaard S, Koppens TFP, Weide G, et al. Training-Induced Muscle Adaptations During Competitive Preparation in Elite Female Rowers. *Front Sports Act Living*. 2021;3:781942. doi:10.3389/fspor.2021.781942

10. Bompa TO, Buzzichelli CA. *Periodization: Theory and Methodology of Training*. 6th ed. Human Kinetics; 2019.

11. Cormier P, Freitas TT, Loturco I, et al. Within Session Exercise Sequencing During Programming for Complex Training: Historical Perspectives, Terminology, and Training Considerations. *Sports Med*. Published online July 11, 2022. doi:10.1007/s40279-022-01715-x

12. Verkhoshansky Y V. *Programming and Organization of Training*. Fizkultura i Sport; 1985.

13. MacDonald CJ, Lamont HS, Garner JC. A Comparison of the Effects of 6 Weeks of Traditional Resistance Training, Plyometric Training, and Complex Training on Measures of Strength and Anthropometrics. *The Journal of Strength & Conditioning Research*. 2012;26(2):422-431. doi:10.1519/JSC.0b013e318220df79

14. Blazevich AJ, Babault N. Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. *Front Physiol*. 2019;10:1359. doi:10.3389/fphys.2019.01359

15. Tillin N, Bishop D. Factors Modulating Post-Activation Potentiation and its Effect on Performance of Subsequent Explosive Activities. *Sports Med*. 2009;39(2):147-166. doi:10.2165/00007256-200939020-00004

16. Crewther BT, Kilduff LP, Cook CJ, Middleton MK, Bunce PJ, Yang GZ. The Acute Potentiating Effects of Back Squats on Athlete Performance. *The Journal of Strength & Conditioning Research*. 2011;25(12):3319-3325. doi:10.1519/JSC.0b013e318215f560

17. Scott DJ, Ditroilo M, Marshall PA. Complex Training: The Effect of Exercise Selection and Training Status on Postactivation Potentiation in Rugby League Players. *The Journal of Strength & Conditioning Research*. 2017;31(10):2694-2703. doi:10.1519/jsc.0000000000001722

18. Baker D. Increases in jump squat peak external power output when combined with accommodating resistance box squats during contrasting resistance complex training with short rest periods. *J Austral Strength Cond*. 2008;16(2):10-18.

19. Scott DJ, Ditroilo M, Marshall P. Effect of Accommodating Resistance on the Postactivation Potentiation Response in Rugby League Players. *J Strength Cond Res*. 2018;32(9):2510-2520. doi:10.1519/JSC.0000000000002464

20. Wyland TP, Van Dorin JD, Reyes GFC. Postactivation Potentation Effects From Accommodating Resistance Combined With Heavy Back Squats on Short Sprint Performance. *The Journal of Strength & Conditioning Research*. 2015;29(11):3115-3123. doi:10.1519/jsc.0000000000000991

21. Stasinaki AN, Gloumis G, Spengos K, et al. Muscle Strength, Power, and Morphologic Adaptations After 6 Weeks of Compound vs. Complex Training in Healthy Men. *J Strength Cond Res*. 2015;29(9):2559-2569. doi:10.1519/JSC.0000000000000917

22. Moreira A, Kempton T, Aoki MS, Sirotic AC, Coutts AJ. The Impact of 3 Different-Length Between-Matches Microcycles on Training Loads in Professional Rugby League Players. *Int J Sports Physiol Perform*. 2015;10(6):767-773. doi:10.1123/ijspp.2015-0100

23. Johnston R, Gabbett T, Jenkins D. Applied Sport Science of Rugby League. *Sports Med*. 2014;44(8):1087-1100. doi:10.1007/s40279-014-0190-x

24. Hass CJ, Schick EA, Tillman MD, Chow JW, Brunt D, Cauraugh JH. Knee biomechanics during landings: comparison of pre-and postpubescent females. *Medicine and science in sports and exercise*. 2005;37(1):100-107.

25. Schoenfeld BJ. Squatting kinematics and kinetics and their application to exercise performance. *J Strength Cond Res*. 2010;24(12):3497-3506. doi:10.1519/JSC.0b013e3181bac2d7

26. Scott D J, Ditroilo M, Orange ST, Marshall P. The Effect of Complex Training on Physical Performance in Rugby League Players. *Int J Sports Physiol Perform*. Published online 2022.

27. Blazevich AJ, Gill ND, Deans N, Zhou S. Lack of human muscle architectural adaptation after short-term strength training. *Muscle Nerve*. 2007;35(1):78-86. doi:10.1002/mus.20666

28. Legerlotz K, Smith HK, Hing WA. Variation and reliability of ultrasonographic quantification of the architecture of the medial gastrocnemius muscle in young

children. *Clin Physiol Funct Imaging*. 2010;30(3):198-205. doi:10.1111/j.1475-097X.2010.00925.x

29. Reeves ND, Maganaris CN, Narici MV. Ultrasonographic assessment of human skeletal muscle size. *Eur J Appl Physiol*. 2004;91(1):116-118. doi:10.1007/s00421-003-0961-9

30. Brown LE. *Strength Training*. Human Kinetics; 2007. https://books.google.co.uk/books?id=SOjE7VQ2iWkC

31. Landers J. Maximum based on reps. *National Strength and Conditioning Association*. 1985;6(60):61.

32. Scott DJ, Marshall P, Ditroilo M. Within-and Between-Session Reliability of Ultrasound Imaging Measures in Vastus Lateralis and Gastrocnemius Medialis Muscles. *J Athl Enhanc*. 2018;7(5). doi:10.4172/2324-9080.1000312

33. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol*. 2013;4:863. doi:10.3389/fpsyg.2013.00863

34. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3-13. doi:10.1249/MSS.0b013e31818cb278

35. Franchi MV, Longo S, Mallinson J, et al. Muscle thickness correlates to muscle cross-sectional area in the assessment of strength training-induced hypertrophy. *Scand J Med Sci Sports*. 2018;28(3):846-853. doi:10.1111/sms.12961

36. Secomb JL, Lundgren LE, Farley ORL, Tran TT, Nimphius S, Sheppard JM. Relationships Between Lower-Body Muscle Structure and Lower-Body Strength, Power, and Muscle-Tendon Complex Stiffness. *The Journal of Strength & Conditioning Research*. 2015;29(8):2221-2228. doi:10.1519/JSC.0000000000000858

37. Brughelli M, Cronin J. Altering the length-tension relationship with eccentric exercise : implications for performance and injury. *Sports Med*. 2007;37(9):807-826. doi:10.2165/00007256-200737090-00004

38. Earp JE, Kraemer WJ, Newton RU, et al. Lower-body muscle structure and its role in jump performance during squat, countermovement, and depth drop jumps. *The Journal of Strength & Conditioning Research*. 2010;24(3):722-729.

39. Tran Q, Docherty D, Behm D. The effects of varying time under tension and volume load on acute neuromuscular responses. *Eur J Appl Physiol*. 2006;98(4):402-410. doi:10.1007/s00421-006-0297-3

40. Clark DR, Lambert MI, Hunter AM. Muscle activation in the loaded free barbell squat: a brief review. *J Strength Cond Res*. 2012;26(4):1169-1178. doi:10.1519/JSC.0b013e31822d533d

41. Riemann BL, Limbaugh GK, Eitner JD, LeFavi RG. Medial and lateral gastrocnemius activation differences during heel-raise exercise with three different

foot positions. *J Strength Cond Res*. 2011;25(3):634-639. doi:10.1519/JSC.0b013e3181cc22b8

42. Tredrea MSJ. Applied complex training: An updated review and practical applications. *Journal of Australian Strength and Conditioning*. 2017;25(3):71-85.

43. Walker S, Ahtiainen JP, Häkkinen K. Acute neuromuscular and hormonal responses during contrast loading: effect of 11 weeks of contrast training. *Scand J Med Sci Sports*. 2010;20(2):226-234. doi:10.1111/j.1600-0838.2009.00914.x

Figure captions

Figure 1. A schematic representation depicting the design and time frame of the study. VL = Vasuts lateralis; GM = Gastrocnemius medialis; RM = repetition maximum.

Figure 2. Sagittal plane ultrasound images of the vastus lateralis (VL) and gastrocnemius medialis (GM). Panels A & B show the measurement of muscle thickness, pennation angle, and fascicle length in the VL (A) and GM (B). Panels C & D show ultrasound images of the VL from a representative participant pre- and post-traditional complex training (TCT).

Figure 3. Standardised between-group differences (d_s ± 95% CI) in change scores and their corresponding 95% confidence intervals between TCT and VRCT groups. Area shaded in grey represents a trivial standardised difference (±0.20). VL = Vastus lateralis; GM = Gastrocnemius medialis; VRCT = variable resistance complex training; TCT = traditional complex training.

Table 1. Participant characteristics at baseline. Data are presented as mean ± SD.

	VRCT (n = 8)	TCT (n = 8)	CON (n = 8)
Age (years)	20.3 ± 1.0	22.8 ± 3.6	26.0 ± 4.0
Height (cm)	178 ± 8.7	185 ± 4.7	181 ± 6.9
Weight (kg)	84.74 ± 10.65	96.17 ± 10.45	92.24 ± 9.95
Back squat 1RM (kg)	134 ± 24	119 ± 27	154 ± 36
CMJ peak power (W)	4432 ± 682	4294 ± 662	4842 ± 472

1RM = one repetition maximum; CMJ = countermovement jump; CON = control; TCT = traditional complex training group; VRCT = variable resistance complex training group.

Table 2. Standardised warm-up for experimental protocol and training sessions.

Exercise	Sets x reps (intensity)
Cycling	1 x 3 minutes (60 W)
Body weight squats	1 x 6
Mountain climbers	1 x 6 e/s
Thoracic rotations	1 x 6 e/s
Glute bridge	1 x 6
Band pull apart	1 x 6
Submaximal CMJs	1 x 3-4
Corresponding resistance exercise	1 x 6 (50% 1RM); 1 x 4 (70% 1RM)

e/s = each side; CMJ = countermovement jump; RM = repetition maximum. Warm-up sets of the corresponding resistance exercise were administered during the training sessions.

Table 3. Overview of the complex training programmes.

VRCT				TCT			
Complex pairs	Sets x reps	Load	ICRI	Complex pairs	Sets x reps	Load	ICRI
1a. Hex-bar deadlift	3 x 3	70 + 0-23% 1RM	90 seconds	1a. Hex-bar deadlift	3 x 3	93% 1RM	4 minutes
1b. Drop jumps (40 cm)	3 x 6	Body weight		1b. Drop jumps (40 cm)	3 x 6	Body weight	
2a. Romanian deadlift	3 x 3	70 + 0-23% 1RM	90 seconds	2a. Romanian deadlift	3 x 3	93% 1RM	4 minutes
2b. Pike jumps	3 x 6	Body weight		2b. Pike jumps	3 x 6	Body weight	
3a. Bulgarian split squat	3 x 3	70 + 0-23% 1RM	90 seconds	3a. Bulgarian split squat	3 x 3	93% 1RM	4 minutes
3b. Lunge jumps	3 x 6	Body weight		3b. Lunge jumps	3 x 6	Body weight	

Training sessions were performed twice per week. A 3-5 minute recovery interval was allowed between complex sets. A 48-96 hour recovery period was allowed between training sessions.

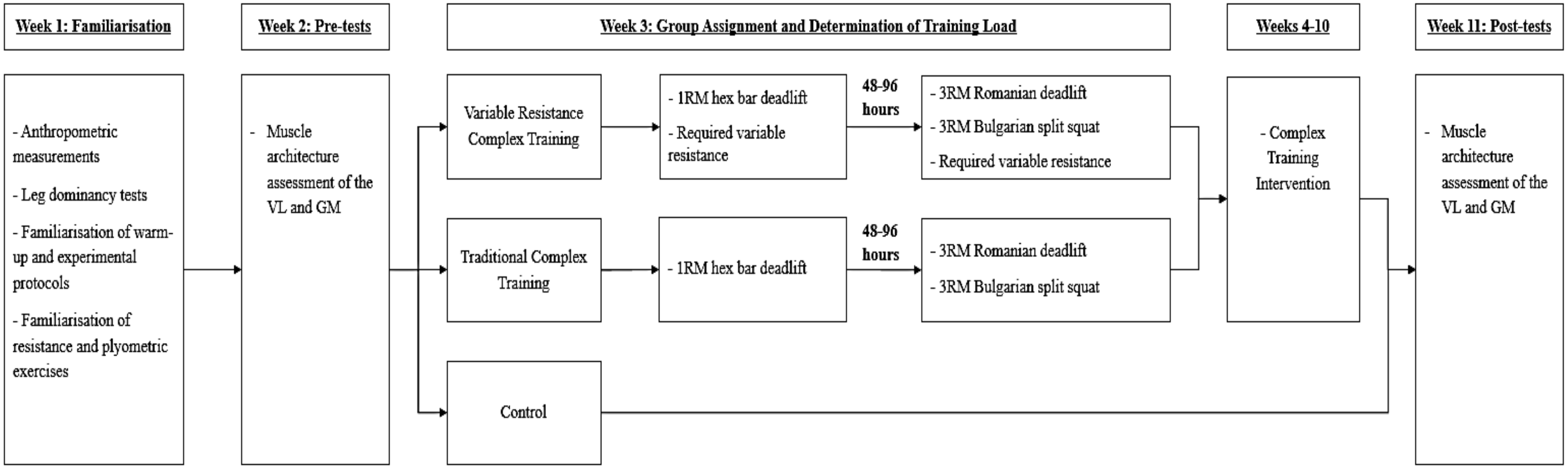
VRCT = variable resistance complex training; TCT = traditional complex training; ICRI = intra-contrast rest interval.

Table 4. Within-group effect sizes for muscle architecture measurements of the vastus lateralis and gastrocnemius medialis before and after the training interventions. Data are presented as mean ± SD and d_{av} ± 95% CI.

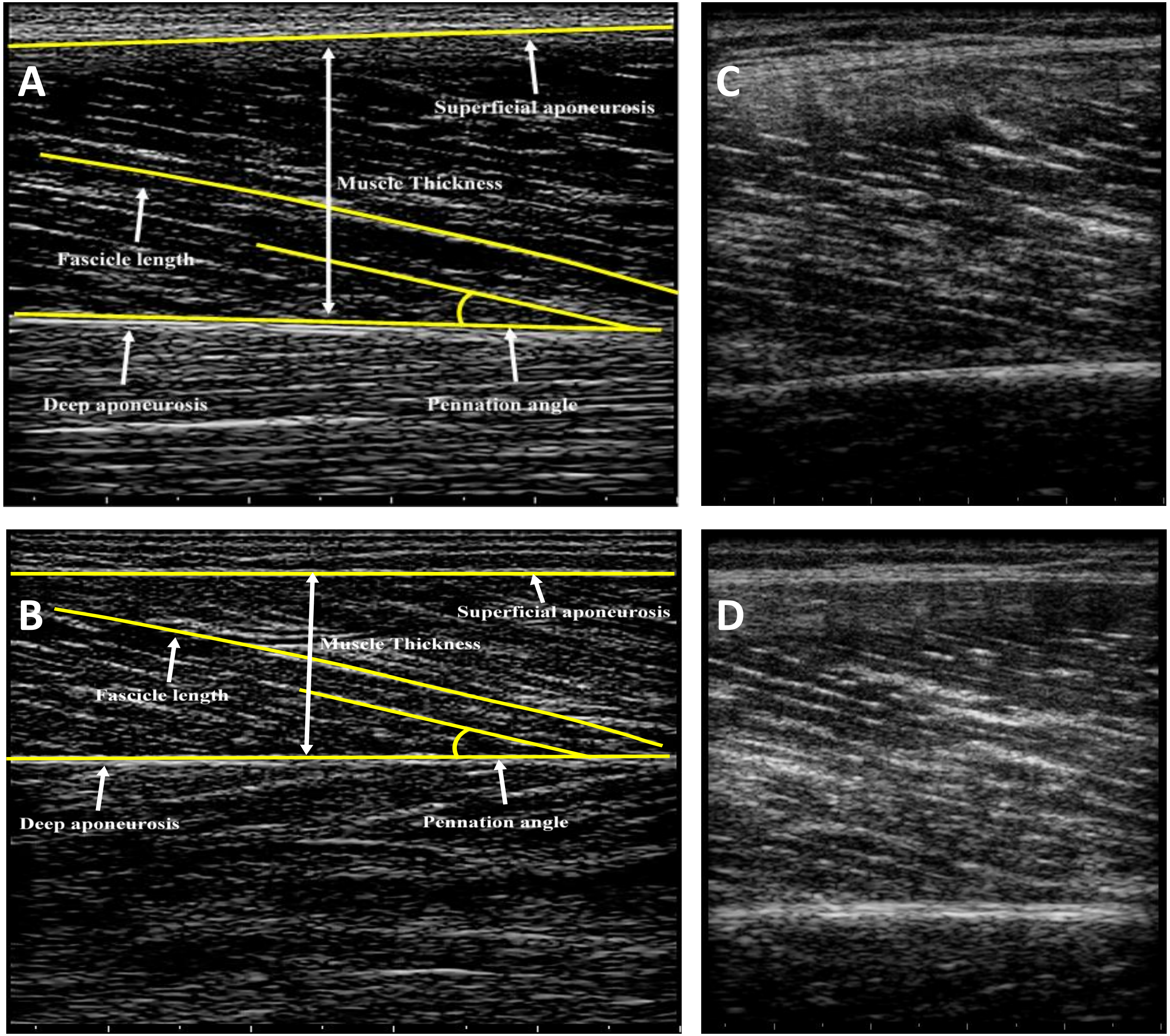
		Vastus Lateralis			Gastrocnemius Medialis		
		Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)
VRCT	Pre	2.99 ± 0.54	16.32 ± 2.71	10.70 ± 1.75	1.95 ± 0.16	24.65 ± 2.09	4.93 ± 0.62
	Post	3.21 ± 0.45*	16.08 ± 1.61	11.50 ± 1.65*	2.01 ± 0.17	24.86 ± 2.14	4.93 ± 0.64
	Change Score	0.21 ± 0.12†	-0.24 ± 1.71	0.80 ± 0.54†	0.07 ± 0.09	0.21 ± 2.46	0.00 ± 0.28
	Cohen's d_{av}	0.44 ± 0.99	-0.11 ± 0.98	0.47 ± 0.99	0.36 ± 0.99	0.10 ± 0.98	0.00 ± 0.98
TCT	Pre	2.89 ± 0.54	15.78 ± 1.22	10.66 ± 0.85	2.06 ± 0.16	24.29 ± 2.98	5.33 ± 0.52
	Post	3.15 ± 0.31*	15.54 ± 1.86	11.78 ± 1.22*	2.12 ± 0.21	23.88 ± 1.98	5.32 ± 0.64
	Change Score	0.26 ± 0.09†	-0.25 ± 1.45	1.12 ± 0.58†	0.06 ± 0.14	-0.41 ± 1.32	-0.02 ± 0.17
	Cohen's d_{av}	0.91 ± 1.03	-0.15 ± 0.98	1.07 ± 1.05	0.32 ± 0.99	-0.16 ± 0.98)	-0.02 ± 0.98
CON	Pre	3.16 ± 0.38	16.42 ± 0.94	11.25 ± 1.24	1.91 ± 0.25	23.86 ± 3.34	5.00 ± 0.67
	Post	3.15 ± 0.40	16.23 ± 0.82	11.32 ± 1.20	1.94 ± 0.24	23.99 ± 3.33	4.95 ± 0.65
	Change Score	-0.01 ± 0.08	-0.18 ± 0.50	0.08 ± 0.09	0.02 ± 0.03	0.14 ± 0.62	-0.05 ± 0.10
	Cohen's d_{av}	-0.03 ± 0.98	-0.22 ± 0.98	0.06 ± 0.98	0.12 ± 0.98	0.04 ± 0.98	-0.08 ± 0.98

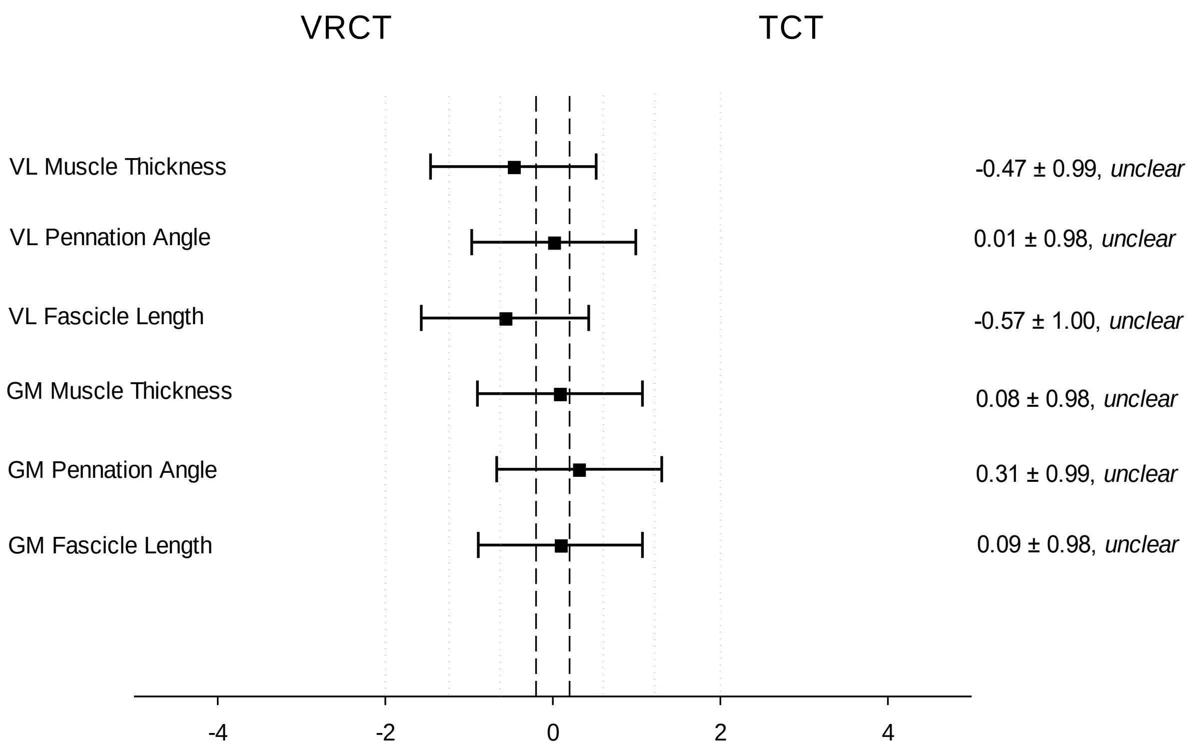
* denotes a significant change from pre- to post-training (all $p<0.01$).

† denotes a significant difference in change scores compared to control (all $p<0.05$).VRCT = variable resistance complex training group; TCT = traditional complex training group; CON = control.


Week 1: Familiarisation
Week 2: Pre-tests
Week 3: Group Assignment and Determination of Training Load
Weeks 4-10
Week 11: Post-tests
- Anthropometric measurements
- Leg dominancy tests
- Familiarisation of warm-up and experimental protocols
- Familiarisation of resistance and plyometric exercises
- Muscle architecture assessment of the VL and GM
Variable Resistance Complex Training
- 1RM hex bar deadlift
- Required variable resistance
48-96 hours
- 3RM Romanian deadlift
- 3RM Bulgarian split squat
- Required variable resistance
Traditional Complex Training
- 1RM hex bar deadlift
48-96 hours
- 3RM Romanian deadlift
- 3RM Bulgarian split squat
Control
- Complex Training Intervention
- Muscle architecture assessment of the VL and GM

536


A
Superficial aponeurosis
Muscle Thickness
Fascicle length
Deep aponeurosis
Pennation angle
C
B
Superficial aponeurosis
Muscle Thickness
Fascicle length
Deep aponeurosis
Pennation angle
D


VRCT
TCT
VL Muscle Thickness
-0.47 ± 0.99, *unclear*
VL Pennation Angle
0.01 ± 0.98, *unclear*
VL Fascicle Length
-0.57 ± 1.00, *unclear*
GM Muscle Thickness
0.08 ± 0.98, *unclear*
GM Pennation Angle
0.31 ± 0.99, *unclear*
GM Fascicle Length
0.09 ± 0.98, *unclear*
-4
-2
0
2
4

537