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Lean Body Mass, Muscle Architecture and Powerlifting Performance at Preseason and at Competition

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Abstract: Lean body mass (LBM) is correlated with powerlifting performance in athletes competing in different bodyweight classes. However, it remains unknown whether changes in LBM are correlated with performance changes in powerlifters preparing for a competition. Aim of the study was to investigate the changes in LBM and performance in powerlifters preparing for a competition. Eight male powerlifters (age 31.7±9.8years, height 1.77±0.06m, weight 99.2±14.6kg) and three female powerlifters (age 32.7±16.3years, height 1.54±0.06m, weight 66.6±20.9kg), participated in the study. Athletes followed individualized periodized training programs for 12 weeks aiming to maximize their performance for the national championship. Maximum strength (1-RM) in squat, bench press, and deadlift, body composition, grip strength, anaerobic power, quadriceps' cross sectional area and vastus lateralis muscle architecture were measured before and after the training period. Significant increases were found after the training period in squat (5.8±7.0%, $P<0.05$), bench press (4.9±9.8%, $P=0.05$) and deadlift (8.3±16.7%, $P<0.05$). Significant correlations were found between 1-RM and LBM before and after the training period ($r>0.75$, $P<0.05$). Changes in 1-RM after the training intervention correlated with changes in total LBM ($P<0.05$). Results suggest that individual changes in LBM due to systematic resistance training towards a competition may dictate increases in 1-RM strength in powerlifters.

Keywords: body composition; ultrasonography; resistance training; muscle strength; muscle hypertrophy

1. Introduction

Powerlifting is a dynamic strength sport in which three multi-joint lifts are performed in competition: the back squat (SQ), the bench press (BP), and the deadlift (DL). Each lift represents approximately 36%, 24%, and 40%, respectively, of the total lifting performance (8). Accepting specific judging criteria, the aim of each athlete is to lift the heaviest possible load during competition. The International Powerlifting League (IPL) organizes the raw, the classic raw and the equipped competitions, with raw accepting wearing specific knee sleeves, belt, and wrist wraps, besides the singlet (10). The present study is about the raw powerlifting competition.

Maximum muscle strength is the main parameter determining performance in powerlifting. Muscle strength is determined mainly by the muscle volume besides other biomechanical, muscle architectural and neural factors (15). Powerlifters compete in specific bodyweight categories; therefore, it is anticipated that heavier athletes would have greater muscle mass and would be generally stronger compared to lighter athletes. Indeed, strong correlations have been reported between powerlifting performance and different measures of muscle mass. For example, muscle thickness at several body sites measured with ultrasonography was highly correlated with SQ, BP, and DL performance, in trained powerlifters (3). Similar results were reported in 20 trained powerlifters using ultrasonography to estimate fat-free mass and muscle mass (18). A recent study employed lean body mass (LBM) measurements via dual x-ray absorptiometry (DXA) as a surrogate to muscle mass and reported very high correlations between SQ, BP, and DL performance with total LBM, i.e., r = 0.94, r = 0.88, r = 0.86, (P < 0.001), respectively, in trained powerlifters (9). The results of that previous study were confirmed by a recent study by the same research group also demonstrating high correlations between the LBM and performance in powerlifters (7).

The strong relationship between maximum strength and muscle mass in powerlifters suggests that training-induced increases in muscle mass may result in maximum strength increases, perhaps even in competition. However, to our best knowledge, training induced changes in performance and LBM in powerlifters preparing for a competition have not been yet investigated. A recent study monitored a small number of powerlifters for a year providing body composition measurements; however, the possible link between the training induced changes in performance and LBM was not reported (7). Therefore, it remains uncertain whether training-induced changes in LBM may predict performance changes in these athletes. This information would be of value to the powerlifting athletes and coaches because they would aim for specific changes in LBM which would induce specific strength increases in competition.

Skeletal muscle architecture (muscle thickness, pennation angle and fascicle length) as measured by ultrasonography, has been shown to effect athletic performance (6). As described above, muscle thickness at specific body sites was strongly correlated with muscle strength in powerlifters (3,18). Yet, some early evidence revealed that vastus lateralis (VL) pennation angle was not correlated with powerlifting performance while fascicle length was only moderately correlated with powerlifting performance (3). Previous studies reported increases in muscle thickness, pennation angle and fascicle length in well-trained athletes (2,13) in response to heavy resistance and power training. However, the effect of specific powerlifting training on muscle architecture and the possible link of these adaptations to powerlifting performance has not been investigated.

The aim of this study was to investigate the relationship between the training induced changes in LBM and muscle architecture with changes in performance in well-trained powerlifters, preparing towards a competition. It was hypothesized that changes in LBM and muscle thickness would correlate with changes in powerlifting performance.

2. Materials and Methods

2.1. ExperimentalApproach

Experienced powerlifters were trained for 12 weeks following their individualized periodized programs as they prepared for the national competition. Before (T1) and after (T2) the training period, body composition, quadriceps' cross-sectional area and VL muscle architecture, as well as the Wingate anaerobic bicycle test, the countermovement jump test (CMJ) and the handgrip test were evaluated. Maximum strength (1-RM) in SQ, BP and DL was measured at T1 during a training session. Specifically, athletes visited the laboratory on two different days at T1. During the first day the body composition analysis, the quadriceps cross sectional area (CSA) and the VL muscle architecture were evaluated. The second day included the performance measurements. The final 1-RM measurements (T2) were obtained from the official records of the national competition. Laboratory measurements at T2 were obtained at 72 hours after the national competition. Differences between T1 and T2 measurements were statistically compared while correlation analysis was used between the training-induced changes for all variables.

2.2. Participants

Eleven experienced powerlifters, eight males (age 31.7 ± 9.8 years, height 1.77 ± 0.06 m, body mass 99.2 ± 14.6 kg, best total powerlifting performance in SQ 250 ± 59.6 kg, BP 155.6 ± 35.4 kg and DL 266.6 ± 41.1 kg) and three females (age 32.7 ± 16.3 years, height 1.54 ± 0.06 m, body mass 66.6 ± 20.9 kg, best total powerlifting performance in SQ 132.5 ± 26.3 kg, BP 68.3 ± 21 kg and DL 135.8 ± 12.3

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kg) participated in the study. All athletes had at least 3 years of competitive experience. Four athletes participated in at least two international powerlifting events each year. Athletes were healthy, with no musculoskeletal injuries and all received > 2 gr of protein per kilogram of bodyweight, daily via normal diet and food supplements. They were informed orally and in written form about the research procedures and the possible risks and they provided written consent regarding their participation in the study. All procedures were performed in accordance with the principles outlined in the 1975 Declaration of Helsinki, as revised in 2000. All procedures were approved by the Bioethics Committee of the School of Physical Education and Sports Science of the National and Kapodistrian University of Athens (protocol number 1321/22-09-2021).

2.3. Procedures

2.3.1. Training

All athletes completed 12 weeks of individualized periodized training programs designed by their coaches aiming to maximize powerlifting performance at the national competition. Careful review of the individual training logs revealed that all training programs included three mesocycles. Training during the first 6 weeks aimed to enhance muscle hypertrophy and strength (4-5sets, 3-8reps, 80-93% of 1RM). The second 4-week mesocycle aimed to increase maximum strength production in the three competitive lifts (4-5 sets, 1-2 reps, 95 - 100% of 1RM). During the first and second mesocycles, athletes performed each main lift once per week, 48 hours apart, accompanied by 1-2 accessory exercises for the same muscle group. Finally, during the third 2-week tapering mesocycle, training aimed to reduce fatigue and increase performance before the national competition.

2.3.2. 1-RM Strength

Powerlifting performance was measured before the initiation of the training period (T1) at the training facility where each athlete was training, 3 days before the initiation of the 12-week training period, under the supervision of at least two of the researchers according to the International Powerlifting League regulations (10). All athletes followed an individual warm-up consisting of static and dynamic stretching exercises and several repetitions with unloaded barbell in each lift. Subsequently, athletes performed 2 - 3 sets of 4 - 6 repetitions with incremental submaximal efforts and then single repetitions until they could lift the heaviest load. Three to five minutes of rest was allowed between attempts. This protocol was followed for all 3 lifts with 30-minute of rest between lifts (first the SQ, then the BP and finally the DL). The highest load for each lift was used for the statistical analysis. Powerlifting performance at T2 was collected from the national championship records following the regulations of the IPL. The best of the three maximum attempts for each lift was used for the statistical analysis. The sum of all three lifts was used for the total lift performance of the athletes.

2.3.3. Body Composition

Body composition was assessed 1 day before the initial 1-RM measurements (T1) and 2 days following the powerlifting competition (T2). Athletes were instructed to fast for 12 h and refrain from any strenuous exercise for 24 h prior to measurements (20). Body mass was evaluated on a body scale (Tanita BC-545n, Tokyo, Japan), and body height was measured with a stadiometer (Seca 213, Surrey, UK). After the evaluation of the anthropometric characteristics, body composition was assessed via dual X-ray absorptiometry (DXA; Prodigy Pro, General Electric, Madison, WI, USA). The Lunar encore v.18 software was used to determine bone mineral density (BMD), bone mineral content (BMC), body fat mass, percentage body fat and percent total and regional LBM, and visceral fat. The intra-class correlation coefficient (ICC) for body fat mass was 0.99 and for total, legs, arms, and trunk LBM were 0.99, 0.99, 0.98, 0.98, and 0.98, respectively.

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2.3.4. Ultrasonography

Ultrasonography was performed immediately after the DXA scans both at T1 and T2, on the dominant lower extremity, always by the same researcher. B-mode ultrasound (Logiq P9, General Electric, USA) images were obtained with a 10-12 MHz linear-array probe for quadriceps femoris CSA, while for the VL images obtained with a 15 MHz linear-array probe. For the quadriceps CSA imaging, a line was marked from the center of the patella to the medial aspect of the anterior superior iliac spine and then an axial perpendicular line was drawn at 40% of this distance (proximal to the knee). The probe was moved transversely across the thigh, on this marked line, taking a continuous single view which pictured the entire CSA of the quadriceps (16). The CSA of the four quadriceps' heads were analysed every single time by the same researcher using an image analysis software (ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA). Analysis of the architecture of VL was performed with the transducer placed longitudinally on the femur, oriented in parallel to the muscle fascicles and perpendicular to the skin. A line was drawn front and back of the 40% of the distance from the center of the patella to the medial aspect of the anterior superior iliac spine, to identify and capture the largest, continuous fascicle visualization. A continuous single view was taken by moving the probe along the marked, dashed line. Images were analyzed always by the same researcher for muscle thickness, fascicle angle, and fascicle length with image analysis software (ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA). Muscle thickness was defined as the distance between the superficial and deep aponeurosis, fascicle angle as the angle of insertion of muscle fascicles onto the deep aponeurosis, and fascicle length as the fascicular path between the insertions of the fascicle onto the upper and deeper aponeurosis. The ICC for CSA of VL, RF, VI, VM and total quadriceps' CSA were 0.96, 0.94, 0.95, 0.87 and 0.97, respectively. The repeatability of the entire procedure, including location of imaging sites and calculation of architectural parameters, test-retest was performed on 10 participants on two separate days when skin markings were completely removed. ICCs with 95% CI (2-way random effects with absolute agreement) were calculated (Stasinaki et al. 2019). The ICCs for VL muscle thickness, fascicle angle and fascicle length were 0.97, 0.88 and 0.84, respectively.

2.3.5. Handgrip Strength

On a different day athletes visited the laboratory for the performance measurements. After a warm-up on a stationary bike and dynamic stretching, the handgrip strength was evaluated first, using a hydraulic Jamar hand dynamometer (Jamar, Patterson Medical, Warrenville, IL, USA). Athletes were at a standing position and the elbow in full extension (14). Handgrip strength was measured in both upper extremities allowing 3 efforts for each hand with 1 minute rest between attempts. The highest strength value for the sum of the best performance of both hands was used in statistical analysis. The ICC for handgrip strength was calculated earlier in our laboratory (ICC = 0.96).

2.3.6. Countermovement Jump

After the handgrip strength measurements, athletes performed two CMJs with submaximal intensity. Subsequently, they performed two maximal CMJs with 2 minutes of rest between each jump, on a force platform (Applied Measurements Ltd Co., UK; WP1000, 1 kHz sampling frequency) with arms akimbo. The signal was filtered using a secondary low-pass Butterworth filter with a cutoff frequency of 20 Hz. Data from the force platform were recorded and analyzed (Kyowa sensor interface PCD-320A) to calculate the following variables: jump height (cm) = ((0.5 * flight time)2 * 2 - 1) * 9.81; maximum power (W) = (body weight + Fmax) * 9.81 * flight time). The best performance in jump height was used for further analysis. The ICC values for jump height and power were 0.87 and 0.91, respectively.

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2.3.7. Wingate Test (Modified)

Peak power (PP) during the initial 10 sec of the Wingate anaerobic test was measured on a mechanically braked bicycle ergometer (Monark Ergomedic 834E, Monark Vansbro, Sweden), 5-10 minutes after the CMJ testing. The external load was set at 0.075 kg·kg-1. After 2 minutes warm up on the bicycle ergometer athletes were instructed to pedal at 60 revolutions per minute for 2 minutes with light external resistance. During this time two 3-sec familiarization attempts were performed with the testing external load. Two minutes after this familiarization, the external testing resistance was applied, and athletes continued to pedal at maximum voluntary speed for 10 seconds (the test was terminated 10 seconds after initiation) (19). Athletes were verbally encouraged to pedal as fast as possible throughout the 10-second test duration. The number of revolutions was recorded at real time (1 kHz). Peak power was achieved 3-6 sec after the application of the external resistance. The ICC for Wingate PP in our laboratory is 0.92.

2.4. Statistical Analysis

Descriptive statistics were used for statistical analysis: mean ± standard deviation. Differences before and after the training period were analyzed with student paired sample T-Test. Cohen's d effect sizes were calculated. Correlation between variables was examined with the r-Pearson correlation coefficient. The level of significance was set at $P \leq 0.05$. Reliability for all measurements was performed using a two way random effect intra class correlation coefficient (ICC). Statistical analysis was performed with JASP software v. 0.18 (University of Amsterdam, Netherlands).

3. Results

3.1. Differences Between Pre and Post Training

Squat performance increased by 5.8 ± 7.0 % ($P < 0.05$), bench press increased by 4.9 ± 9.8 % ($P = 0.05$), deadlift increased by 8.3 ± 16.7 % ($P < 0.05$), and total powerlifting performance increased by 6.5 ± 10.4 % ($P< 0.05$, Table 1). Handgrip strength and CMJ performance/power were not altered with training (Table 1). Peak power at the Wingate test was significantly increased by 10.9 ± 9.0 % ($P < 0.05$). Body mass was increased by 2.2 ± 3.7 % ($P < 0.05$). Lean body mass of the trunk region increased by 3.1 ± 4.7 % ($P < 0.05$), but it was not altered significantly in any other body area. Bone mineral density, bone mineral content, body fat mass, body fat %, as well as visceral fat were not altered after the training period (Table 1). There was no statistically significant change in VL muscle architecture and thickness. The CSA of all the quadriceps heads was not altered significantly after training (Table 1).

Table 1. Performance, body composition and muscle architecture in eleven experienced powerlifters before and after 12 weeks of training preparation for the national competition.

	T1	T2	Effect size *d*	P
Performance				
SQ (kg)	198.3±71.5	208.4±73.1	1.203	0.003
BP(kg)	126.8±44.7	132.7±47.2	0.672	0.050
DL (kg)	221.4±69.3	235.6±68.6	0.749	0.030
Total lifts (kg)	546.6±181.8	576.8±184.4	0.992	0.008
HandgriP(sum, kg)	102.0±30.7	102.5±33.3	0.059	0.840
CMJ power ($W \cdot kg^{-1}$)	39.5±3.4	39.5±3.2	0.028	0.928
PPWingate (W)	910±255	1011±303	1.236	0.002
Body composition				
Body mass (kg)	90.3±21.6	92.2±22.2	0.729	0.036
Fat mass (kg)	20.5±10.1	21.1±11.1	0.195	0.530

Fat (%)	23.3±9.4	23.3±9.6	0.017	0.950
LBM total (kg)	66.5±16.6	67.9±16.7	0.573	0.087
LBM Arms (kg)	9.5±3.3	9.7±3.2	0.449	0.168
LBM Trunk (kg)	31.1±7.4	32.0±7.7	0.675	0.049
LBM Legs (kg)	22.5±5.8	22.6±5.6	0.155	0.619
BMC (kg)	3.251±0.771	3.261±0.760	0.262	0.406
BMD (g·cm²)	1.453±0.178	1.455±0.168	0.084	0.787
Visceral fat (gr)	421±600	416±652	0.067	0.830
Vastus lateralis architecture				
Pennation angle (°)	20.9±3.3	20.7±4.4	0.053	0.865
Fascicle length (cm)	8.1±0.9	8.2±1.0	0.106	0.733
Thickness (cm)	2.76±0.46	2.83±0.56	0.585	0.081
Quadriceps CSA				
VL (cm²)	32.2±10.7	32.9±10.4	0.522	0.114
RF (cm²)	7.2±2.1	7.5±1.9	0.610	0.071
VI (cm²)	35.4±11.3	35.4±10.2	0.019	0.951
VM (cm²)	19.2±5.3	19.3±5.1	0.015	0.961
Total CSA (cm²)	94.2±28.4	95.2±26.0	0.233	0.457

SQ = squat, BP = bench press, DL = deadlift, LBM = lean body mass, BMC = bone mineral content, BMD = bone mineral density, CSA = cross sectional area, VL = vastus lateralis, RF = rectus femoris, VI = vastus intermedius, VM = vastus medialis, PP = peak power, CMJ = countermovement jump.

3.2. Correlations at Pre and Post Training

Before the initiation of the 12-week preparation period (T1), powerlifting performance was significantly correlated with body mass, with lean body mass of all body parts measured, with the CSA of all heads of the quadriceps, as well as with VL thickness and pennation angle (Table 2). After the training period (T2), powerlifting performance was significantly correlated with body mass, with LBM of all body parts, with the CSA of all heads of the quadriceps, as well as with VL thickness (Table 3).

Table 2. Correlations between powerlifting performance, body composition and vastus lateralis muscle architecture, and quadriceps CSA, in eleven experienced powerlifters at the initiation (**T1**) of 12 weeks training preparation for the national competition.

	Squat	Bench press	Deadlift	Sum of lifts
Body composition				
Body mass (kg)	0.807**	0.774**	0.779**	0.805**
LBM total (kg)	0.899***	0.915***	0.901***	0.923***
LBM Arms (kg)	0.889***	0.930***	0.881***	0.915***
LBM Trunk (kg)	0.884***	0.910***	0.890***	0.911***
LBM Legs (kg)	0.881***	0.869***	0.881***	0.897***
Vastus lateralis architecture				
Pennation angle (°)	0.653*	0.644*	0.642*	0.660*
Fascicle length (cm)	0.418	0.374	0.438	0.424
Thickness (cm)	0.817**	0.813**	0.841**	0.843**
Quadriceps CSA				

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VL (cm^2)	0.870***	0.871***	0.907***	0.903***
RF (cm^2)	0.786**	0.837***	0.876***	0.849***
VI (cm^2)	0.876***	0.890***	0.860***	0.900***
VM (cm^2)	0.898***	0.795***	0.849***	0.873***
Total CSA (cm^2)	0.914***	0.896***	0.911***	0.928***

LBM = lean body mass, CSA = cross sectional area, VL = vastus lateralis, RF = rectus femoris, VI = vastus intermedius, VM = vastus medialis, * P < 0.05, ** P < 0.01, *** P < 0.001.

Table 3. Correlations between powerlifting performance, body composition and vastus lateralis muscle architecture, and quadriceps CSA, in eleven experienced powerlifters after 12 weeks training preparation for the national competition (**T2**).

	Squat	Bench press	Deadlift	Sum of lifts
Body composition				
Body mass (kg)	0.799**	0.755**	0.736**	0.784**
LBM total (kg)	0.921***	0.879***	0.943***	0.941***
LBM Arms (kg)	0.923***	0.905***	0.950***	0.951***
LBM Trunk (kg)	0.927***	0.885***	0.953***	0.949***
LBM Legs (kg)	0.873***	0.823**	0.886***	0.886***
Vastus lateralis architecture				
Pennation angle (°)	0.191	0.236	0.217	0.217
Fascicle length (cm)	0.557	0.565	0.540	0.566
Thickness (cm)	0.775*	0.770**	0.731*	0.777**
Quadriceps CSA				
VL (cm^2)	0.828**	0.831**	0.790**	0.835**
RF (cm^2)	0.809**	0.818**	0.799**	0.827**
VI (cm^2)	0.873***	0.865**	0.840**	0.880***
VM (cm^2)	0.836***	0.673*	0.797**	0.800***
Total CSA (cm^2)	0.899***	0.866***	0.862***	0.899***

LBM = lean body mass, CSA = cross sectional area, VL = vastus lateralis, RF = rectus femoris, VI = vastus intermedius, VM = vastus medialis, * P < 0.05, ** P < 0.01, *** P < 0.001.

3.3. Correlations between Changes at Pre and Post Training

The percentage change in SQ performance was correlated with the percentage change in body mass (r = 0.838, P = 0.001), the percentage change in LBM of the lower extremities (r = 0.807, P = 0.003), the percentage change in LBM of the trunk (r = 0.666, P = 0.025), the percentage change in total body LBM (r = 0.782, P = 0.004, Figure 1), and the percentage change in CSA of the quadriceps (r = 0.675, P = 0.023). The percentage change in BP performance was correlated with the percentage change in body mass (r = 0.764, P = 0.006), and the percentage change in total LBM (r = 0.633, P = 0.037). The percentage change in DL performance was correlated with the percentage change in body mass (r = 0.803, P = 0.003), the percentage change in LBM of the lower extremities (r = 0.665, P = 0.026), the percentage change in LBM of the trunk (r = 0.670, P = 0.024), and the percentage change in total LBM (r = 0.698, P = 0.017). The percentage change in the sum of all three lifts was correlated with the percentage change in body mass (r = 0.868, P = 0.000), the percentage change in LBM of the lower extremities (r = 0.744, P = 0.009), the percentage change in LBM of the trunk (r = 0.713, P = 0.014), and the percentage change in total LBM (r = 0.764, P = 0.006).

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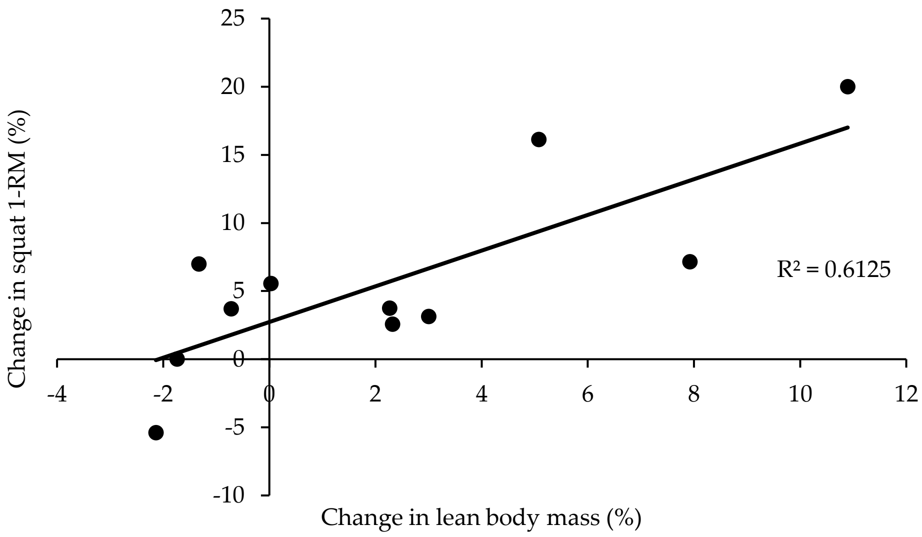

Figure 1. Correlation between the percentage change in total lean body mass with the percentage change in squat performance, after 12 weeks of preparation towards the national competition event in eleven powerlifters.

4. Discussion

The aim of the study was to investigate the relationship between the training-induced changes in LBM and muscle architecture with changes in performance in well-trained powerlifters, preparing for a competition. The main finding of this investigation was the significant positive correlations between the percentage increase in LBM and the percentage increase in powerlifting performance. Performance in powerlifting is determined by the maximum load lifted by the athlete. Besides anthropometric factors and neural activation, the quantity of skeletal muscle is perhaps the most important biological factor contributing to muscle strength (1). Several studies have presented the close correlation between measures of muscle mass and powerlifting performance (3,9,7,18), which was also confirmed in the present study. However, this correlation is influenced by the bodyweight category of the athletes participated in these studies. Namely, as the bodyweight category of the athletes increases, muscle mass is expected to increase and muscle strength is expected to increase almost proportionally. Thus, the correlation between powerlifting performance and LBM at a specific time point including athletes with large body mass variability, mostly presents the well-known relationship between muscle mass and strength. The main question of the present study was whether individual changes in LBM would be correlated with individual changes in powerlifting performance after a training period. The current data seem to support such premise. The increase in SQ performance was highly correlated with the increase in LBM of the lower extremities and the trunk which is anticipated because of the involvement of these body parts in SQ (4). In contrast, there was no significant correlation between the increase in SQ performance and LBM of the upper extremities, as was anticipated, because of the relatively small involvement of the upper extremities in SQ. We believe that this set of correlations reinforces the current results. Moreover, the significant correlation between the increase in SQ performance and the increase in quadriceps CSA is along the line of the current data. This also suggests that quadriceps' CSA measured with ultrasonography may be useful to estimate changes in SQ performance in well-trained powerlifters. At this point it should be stressed that neither the quadriceps CSA nor the LBM (except of trunk) were significantly altered following training. In fact, for 2-3 athletes there was a slight decrease in these parameters and these athletes experienced small decrements in strength. This suggests that measurements of LBM and muscle CSA together with changes in performance should be systematically evaluated on an individual basis in powerlifters.

The increase in BP performance was correlated with the increase change in total LBM but not the lean mass of the arms. It seems that the musculature of the body and the trunk are more important for small training-induced changes in well-trained powerlifters compared to the musculature of the arms. The increase in deadlift performance was correlated with the increase in LBM of the lower extremities and the trunk which is in accordance with previous studies regarding the musculature involved in this resistance exercise (11). One interesting finding of the present study was that body mass was increased after the training period by 2.2 ± 3.7%, and this increase was strongly correlated with changes in powerlifting performance. It seems that this increase in body mass was the result of LBM increase although the latter did not reach statistical significance. Yet, these results may suggest that in well-nourished powerlifters preparing for a competition, the increase in body mass may be an effortless method to predict performance changes. However, coaches should be careful with such increases in body mass since they might affect athlete's bodyweight category. Future studies should address this issue.

Both before and after the 12-week preparation period, SQ and DL performance were significantly correlated with the CSA of all the heads of the quadriceps, as well as with the VL thickness. Muscle thickness at various body sites is highly correlated with performance in powerlifters (3). Here we report that besides muscle thickness, whole quadriceps CSA is also closely correlated with powerlifting performance, both at the begging of a preparation cycle and at the competition. These results suggest that ultrasonography may be a useful tool to identify differences in the quadriceps muscle mass among well-trained powerlifters and therefore estimate performance, although larger scale studies need to confirm these data.

The bone mineral density of powerlifters is of the highest reported in sports (9). Here we reported high BMD and BMC values (Table 1). This is probably due to the high loading of the human skeleton with chronic resistance training. Previous studies revealed statistically significant increases in BMD and BMC with resistance training, e.g. with high-intensity isokinetic resistance training of 5 months duration in young individuals (12). However, in the current study, athletes did not experience any change in BMD and BMC after training probably because of the already high initial values. Similarly, body fat (both percentage and mass) was not altered following the training period. Athletes were competing in specific bodyweight categories therefore they managed their diet and training aiming to avoid increases in body fat deposits. Visceral fat was higher than 1kg in two of the participants. Visceral fat was significantly correlated with fat mass ($r = 0.68$, $P < 0.05$) and this suggests that powerlifters with increased body fat deposits should aim to reduce body fat to reduce health-related risk related with visceral fat stores (17).

Muscle architecture is an important parameter for strength and power performance. Unfortunately, this analysis is laborious and has been realized in few human skeletal muscles, mostly the VL. Muscle thickness was correlated with powerlifting performance at T1 and T2 but the training-induced changes in muscle thickness were not correlated with performance changes. This suggests that the measurement of the CSA of the quadriceps is a more informative parameter to evaluate changes in muscle mass and performance compared to VL muscle thickness at a single time point, in powerlifters. Pennation angle was correlated with powerlifting performance at T1, but not at T2. This is an interesting finding which is difficult to explain especially in the light of lack of correlation between these parameters as revealed in a previous study (3). Vastus lateralis fascicle length was not correlated with powerlifting performance as also previously reported (3). Moreover, the fascicle length in this muscle was not altered with training which suggests a limited adaptations in this parameter with advanced powerlifting training.

There was no increase in handgrip strength after the training period. It seems that these athletes had already achieved a high level of handgrip strength and further increases with 12 weeks training were not realized. Additionally, these athletes did not perform any specific training to increase their handgrip strength during this period which supports the lack of handgrip strength increase. Similarly, there was no increase in lower body explosive strength (CMJ) after the 12-week training period which is also probably the result of the lack of specific jumping training of the athletes. In contrast, there was an increase in the Wingate peak power of the lower extremities following training.

This was probably the result of the increase in lower body muscle strength of the athletes which is shown to result in higher peak power in the Wingate test (19). Compared to the CMJ, pedalling during the Wingate test is a much slower and longer-duration movement, therefore, there is more time to apply the increased strength achieved due to 12 weeks of powerlifting training.

The increase in performance in each of the lifts, was lower than that presented in a previous study (~11%, 5). This discrepancy might be related to the lower initial performance level of the participants in that previous study. However, the relatively small number of participants and the inclusion of only a small number of female powerlifters may be a limitation of the present study. Moreover, despite the high correlations between LBM and strength, other parameters also influence powerlifting performance such as the neural activation and anthropometrics (e.g. bone lengths) which were not measured. Another limitation of the present study is the lack of control of the athletes' diet which might have influenced the changes in body composition. Further studies should address these important issues.

5. Conclusions

In conclusion, the current data revealed a high correlation between individual changes in LBM and performance in well trained powerlifters following a 12-week training period towards a competitive event. Changes in LBM provide an estimate of the changes in muscle mass which is one of the most important biological parameters for powerlifting performance. Furthermore, measurement of the quadriceps CSA in powerlifters may also provide valid estimates of the muscle mass and SQ performance changes.

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