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Abstract

Background: Few studies have compared anthropometric characteristics among national class athletes from different resistance training disciplines, such as Olympic Weightlifting (OL), Power Lifting (PL), and Bodybuilding (BB). **Objective:** The purpose of the current study was to determine if significant differences exist in the relationship between thigh muscle cross-sectional area and back squat strength among national class athletes from the sports of OL, PL, and BB. **Methods:** Fifteen national class athletes were assessed for back squat strength, mid-thigh circumference, and mid-thigh skinfold from which total thigh cross-sectional was estimated. A series of One-Way ANOVAs and Pearson Product Moment Correlations were used to compare groups and assess the relationship between variables. **Results:** The OL (200.18 $\pm$ 25.16kg) and PL (205.45 $\pm$ 17.28kg) groups were significantly stronger than the BB (160 $\pm$ 16.80 kg; $p \leq 0.05$) group. However, mid-thigh skinfold thickness ($p = 0.36$), mid-thigh circumference ($p = 0.87$), and estimated thigh cross-sectional area ($p = 0.34$) were not significantly different between groups. Thigh muscle cross-sectional area was weakly correlated to back squat strength in the OL ($r = .42$) and PL ($r = .12$) groups, but moderately correlated in the BB ($r = .70$) group. **Conclusion:** Thigh cross-sectional area was of relatively minor importance in determining back squat strength for the OL and PL groups, despite these groups being significantly stronger than the BB group. Specific training protocols will elicit different outcomes with regard to muscular hypertrophy that may or may not contribute to a functional increase in back squat strength. **Keywords:** hypertrophy, strength, resistance training, anthropometrics, power

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Introduction

Athletes engage in resistance training programs to gain strength and power with the intent of creating a positive transfer to performance in their respective sport. The sports of Olympic Weightlifting (OL) and Power Lifting (PL) are judged based on lifting performance; the snatch and clean and jerk for OL and the back squat, bench press, and deadlift for PL[1,2,3]. The resistance training programs performed by athletes from other sports may include each of these lifts and many variations. A third sport that is highly dependent on resistance training effectiveness is Bodybuilding (BB). However, in contrast to OL and PL, BB is judged subjectively based on aesthetics (e.g. muscle size, low body fat percentage, muscle symmetry), but resistance training is used as the primary tool to achieve an aesthetically pleasing physique[4].

Sports scientists have compared athletes from OL, PL, and BB to assess variations in muscular characteristics resulting from differences in the resistance training programs of each sport[1,2,5,6].

Prescriptive components from OL, PL, and even BB might be borrowed by athletes from non-lifting based sports to improve performance based on individual needs and objectives[7,8,9,10]. Variations in the mode, volume, intensity, movement velocity, rest interval between sets, and frequency of sessions stimulate different muscular adaptations that become evident over time. For example, PL and OL protocols typically incorporate heavier training loads than BB, but the training volume (load x sets x repetitions) is greater in BB. Although OL, PL, and BB use distinctly different training protocols, the use of the back squat exercise is commonly utilized by each group[7,8,9,10].

Few studies have examined the relationship between measures of muscle cross-sectional area and strength in national class athletes from the sports of OL, PL, and BB[1]. The belief that improvements in strength occur as a result of muscle hypertrophy is widely accepted[11]. For example, Ikai and Fukunaga[12] demonstrated that muscles with a larger cross-sectional area produce greater forces versus similar muscles with a smaller cross-sectional area. However, Maughan et al.[13] suggested that as cross-sectional area increases, the strength per cross-sectional area ratio decreases. The greater pennation angles in hypertrophied muscles might be responsible for decreased force transferred through a tendon[14].

Furthermore, Zatsiorsky[10] suggested that different types of muscle hypertrophy may influence strength such that an observable increase in size may or may not be accompanied by an increase in strength. For example, sarcoplasmic hypertrophy (increases in noncontractile structural proteins and sarcoplasm) may develop without significant increases in strength[10]. However, myofibrillar hypertrophy (increases in contractile proteins and the number of myofibrils) does lead to an increase in strength[10]. Lesmes et al.[15] demonstrated that increases in muscular strength are not always accompanied by changes in hypertrophy. Increases in muscular strength, in the absence of hypertrophy, have been attributed to neural adaptations such as increased neural drive[16], increased motor unit recruitment and synchronization[15], increased motor unit firing frequency[17], and decreased antagonist co-activation and agonist inhibition[18].

With a number of factors influencing muscular strength, hypertrophy might be of relatively minor importance in determining strength performance[1,2,5,6]. More investigation is clearly needed from a practical standpoint to determine the role of muscle hypertrophy in strength performance. Therefore, the purpose of the current study was to determine if significant differences exist in the relationship between thigh muscle cross-sectional area and back squat strength among national class athletes from the sports of OL, PL, and BB. We hypothesized that the BB group would have the greatest thigh muscle cross-sectional area and the lowest 1-RM back squat strength, while the OL and PL groups would have the greatest 1-RM back squat strength, but a smaller thigh muscle cross-sectional area versus the BB group.

Methods

Subjects

Fifteen men were recruited to participate in the current study (see Table 1 for descriptive characteristics). The subject pool only included lifters that competed in the 75-96 kg body mass range to allow more meaningful comparisons between thigh cross-sectional area and squat strength. This study was unique because all subjects in the OL (OL, n=5), PL (PL, n=5), and BB (BB, n=5) groups were considered national class athletes in their respective sports, based upon having qualified or competed at the national level in an officially sanctioned competition within the previous twelve months. The subjects from each discipline (with the exception of one subject in the PL group), were competing in organizations that enforced a strict drug testing policy. Key highlights of the subject sample included two professional subjects in the BB group, one of which had recently competed in the *Mr. Universe* competition. Two subjects in the PL group had placed first at national competitions and one subject in the PL group was ranked second nationally in his weight class. The OL group included one subject with international experience (Jr. World Championships) who was ranked third nationally in his weight class. Two of the OL subjects had placed second in national level competitions.

Table 1: Descriptive mean comparison (±SD), effect size, and power

	BB	PL	OL	Effect size	Power
Height (cm)	172.72 (3.59)	172.21 (3.77)	176.28 (5.85)	0.17	0.21
Body mass (kg)	83.64 (5.47)	87.92 (8.66)	85.74 (7.60)	0.07	0.10
Age (Yrs)	40.00 (7.31)	33.20 (6.38)	19.40** (2.97)	0.73	0.99
Body fat (%)	10.95 (2.49)	19.02 (6.57)	14.86 (5.96)	0.30	0.38
Mid-thigh skinfold (mm)	12.73 (4.42)	17.79 (6.26)	15.53 (5.25)	0.16	0.20
Mid-thigh circumference (cm)	60.56 (3.44)	59.47 (1.83)	60.48 (4.85)	0.20	0.07
1-RM back squat (kg)	160.00* (16.82)	205.45 (17.28)	200.18 (25.16)	0.56	0.88
Relative strength (1-RM back squat/body mass)	1.92 (.26)	2.37 (.43)	2.34 (.28)	0.32	0.46
Estimated thigh muscle cross-sectional area (cm^2)	175.82 (14.60)	160.17 (10.90)	169.60 (21.27)	0.17	0.21

Note. ** $p \leq 0.01$ versus PL and BB groups; *$p \leq 0.05$ versus OL and PL groups.

Prior to testing, subjects were given a detailed description of the study and the risks of participation both verbally and in writing. Subjects then gave their voluntary informed consent. The procedures followed were in accordance with the institutional ethical research guidelines and with the Helsinki Declaration of 1975, as revised in 2008. Subjects were also asked to complete a competition training questionnaire and a health history form. Exclusion criteria for participation included a history of hypertension, orthopaedic injuries to the hip, knee, and/or low back, or chronic low back pain.

Anthropometric measurements

Anthropometric measures were performed to assess body mass, body composition, mid-thigh circumference, and mid-thigh skinfold thickness. All measures were made prior to the 1RM back squat testing. A fibreglass tape measure (OHJI, Japan) was used for the mid-thigh circumference measurement in centimetres (cm) as described by Lohman et al.[19]. Mid-thigh skinfold thickness was assessed in millimetres (mm) using a Slim Guide calliper (Creative Health Products, Plymouth, Michigan). Body mass in kilograms (kg) was assessed using a calibrated Health-O-Meter professional scale (Model 160, Big Foot 11). The percentage body fat was estimated via bioelectrical impedance (OMRON,-HBF-301 Vernon Hills, IL).

Total thigh muscle cross-sectional area was subsequently estimated using an equation (see below) established by Housh et al.[20] for acute assessment and more recently tested by DeFreitas et al.[21] for long-term assessment of changes in muscle cross-sectional area. DeFreitas et al.[21] confirmed that the Housh et al.[20] equation was a reliable measurement ($r = 0.961$) with acceptable accuracy relative to a lab based pQCT scanner.

Total Thigh Muscle Cross-Sectional Area (TMA) = (4.68 x midthigh circumference in cm) – (2.09 x anterior thigh skinfold in mm) – 80.99.

Back squat 1-RM assessment

The assessment of a 1-RM back squat was performed using a standard 7-foot Olympic bar and metal Olympic weight plates with safety collars. The number and intensity of warm-up sets was controlled using procedures adapted from Fleck and Kraemer[7] for finding a 1-RM starting weight and included the following steps: (1) the first warm-up set was performed for 10 repetitions at 50% of an estimated 1-RM, (2) after a one minute rest interval, a second warm-up set for one repetition was performed at 70% of an estimated 1-RM, (3) after another one minute rest interval, a final warm-up set was performed for one repetition at 90% of an estimated 1-RM, (4) after a two minute of rest interval, a 1-RM was attempted, (5) if that attempt was successful, subjects were asked if they could attempt another 1-RM with an additional load of 1% to 5%; if they chose to do so, a five minute rest interval was instituted prior to the next 1-RM attempt. Step number five was repeated until subjects indicated that they could not make another attempt or until subjects failed in an attempt.

All squat testing was performed inside a *power rack* with the safety pins adjusted to ensure the necessary squat depth. With reference to stance width, the following criteria were adopted from McBride et al.[2]: (1) an anthropometer was used to measure each subject's biacromial width; this value was recorded and used to set limits for each subject's widest possible squat stance; the widest allowable squat stance was 15cm wider than each subject's biacromial width, (2) subjects were permitted as narrow a stance as they desired, (3) squat stance limits were marked with tape on the floor where the 1-RM squat was to be performed. Additionally, bar placement was required to be between the 7th cervical vertebra and the superior angle of the scapula. Squat depth was required to be the position at which the tops of the thighs at the hip joint were lower than the tops of the knees. All subjects were required to squat to this depth with an unloaded barbell to become familiar with the necessary depth prior to 1-RM testing, and an audible cue was given when the appropriate squatting depth was reached. Any squat that did not meet the criteria for depth was disqualified. The use of any artificial means of support such as supportive suits and knee wraps were strictly forbidden. However, to minimise the possibility of low back injury, subjects were allowed to use a weight belt if desired. The width of the belt was standardized and could not exceed 10cm. It should be noted that every subject chose to wear a weight belt while performing the 1RM attempt. All anthropometric and strength measurements were performed by the same investigator. No external motivation (e.g. verbal encouragement) was given during 1RM testing.

Statistical analyses

Descriptives (mean $\pm$ SD) for the following variables: height (cm), body mass (kg), age (yrs), body fat (%), mid-thigh skinfold (mm), mid-thigh circumference (cm), 1RM back squat strength (kg), relative strength (1-RM back squat/body mass) and estimated thigh cross-sectional area (cm^2) were calculated and statistically compared between groups using a series of One-Way ANOVAs; Eta square effect sizes (η^2) and observed power ($1 - \beta$) were also calculated. Levene's tests were computed for each of the variables to check for equality of variances. None of the Levene's tests computed were significant, suggesting no evidence for unequal variance. In the case of significant Main Effects, follow-up comparisons were made using Scheffe post hocs to control for type I error. Pearson Product Moment Correlations for each group independently (i.e. OL, PL, BB) were calculated to assess the relationship between the following variables: mid-thigh circumference (cm), 1RM back squat (kg), relative strength, and estimated thigh cross-sectional area (cm^2). The significance of all comparisons and correlations was based on an alpha level of $p \leq 0.05$. Statistical analysis was conducted via use of SPSS version 16 (SPSS Inc., Chicago, IL) (see Table 2).

Table 2: Pearson-product moment correlations across selected variables

		Squat	Relative strength	Cross-sectional area
Bodybuilders	Thigh circumference	.33	-.08	.82
	Squat		.88*	.70
	Relative strength			.30
Power lifters	Thigh circumference	-.55	-.74	.11
	Squat		.94*	.12
	Relative strength			.24
Olympic lifters	Thigh circumference	.73	.26	.88*
	Squat		.75	.42
	Relative strength			.06

Note. * $p \leq 0.05$.

Results

The main effects for age ($F_{2,12} = 16.05$; $p \leq 0.01$) and 1-RM back squat strength were significant ($F_{2,12} = 7.63$; $p \leq 0.01$). Follow-up post hoc comparisons for age indicated that the OL group (19.4 $\pm$ 2.96 yrs) was significantly younger than the BB (40 $\pm$ 7.31yrs) and PL (33.2 $\pm$ 6.38yrs) groups ($p \leq 0.01$). Follow-up post hoc comparisons for 1-RM back squat strength indicated that the OL (200.18 $\pm$ 25.16kg) and PL (205.45 $\pm$ 17.28kg) groups were significantly stronger than the BB (160 $\pm$ 16.80 kg) group ($p \leq 0.05$). The main effects for height ($p = 0.34$), body mass ($p = 0.67$), body fat percentage ($p = 0.14$), mid-thigh skinfold thickness ($p = 0.36$), relative strength ($p = 0.10$), mid-thigh circumference ($p = 0.87$), and estimated thigh cross-sectional area ($p = 0.34$) were not significantly different between groups (see Table 1).

Significant correlations were found between the 1-RM back squat strength and relative strength (1-RM/body mass) for the PL ($r = 0.94$) and BB ($r = 0.88$) groups ($p \leq 0.05$). For the OL group, a significant correlation was found between the thigh circumference and cross-sectional area ($r = 0.88$; $p \leq 0.05$); while this relationship approached significance for the BB group ($r = 0.82$; $p = 0.09$). Other notable correlations that approached significance included the 1-RM back squat strength and cross-sectional area for the BB group ($r = 0.70$; $p = 0.19$); the thigh circumference and relative strength for the PL group ($r = -0.74$; $p = 0.15$); and the 1-RM back squat strength and relative strength ($r = 0.75$; $p = 0.15$) and 1-RM back squat strength and thigh circumference ($r = 0.73$; $p = 0.16$) for the OL group.

Discussion

The purpose of the current study was to determine if significant differences exist in the relationship between thigh muscle cross-sectional area and back squat strength among national class athletes from the sports of OL, PL, and BB. These authors hypothesised that the BB group would have the greatest thigh muscle cross-sectional area and the lowest 1-RM back squat strength, while the OL and PL groups would have the greatest 1-RM back squat strength, but a smaller thigh muscle cross-sectional area versus the BB group. This current study's hypothesis was partially supported in that the OL and PL groups demonstrated significantly greater back squat strength versus the BB group. However, this hypothesis was also partially rejected in that the thigh muscle cross-sectional area was not significantly different between groups.

A key finding of the current study was that the OL group was significantly younger versus the PL and BB groups. In addition to differences in resistance exercise prescription, a younger chronological age can impact the responsiveness of the nervous system and the extent of increases in characteristics such rate of force development and movement velocity that are important for success in OL[22]. Therefore, in the current study, the significantly greater back squat strength for OL group versus the BB group was likely due to greater neurological plasticity in part based on a younger age.

Another key finding of the current study was that the highest overall correlation ($r = .94$) was found between the back squat absolute and relative strength for the PL group; a finding that reflects the specificity of the back squat being required for PL competition and perhaps the greater frequency of performing this lift with near maximal loads by these athletes[1,2,3,5]. Furthermore, a strong correlation was evident for the BB group between the back squat strength and thigh cross-sectional area. These findings indicate that strength performance for BB might depend more on peripherally mediated adaptations as in muscular hypertrophy. Conversely, strength performance for PL and OL might depend more on centrally mediated adaptations in the ability to maximally synchronize motor unit recruitment[1,2,5,6,15,16,17,18].

The three sports (OL, PL, BB) involve fundamentally different resistance exercise protocols, but with the common use of the back squat exercise in various phases. However, the intensity of loads utilised and the volume completed per training session (load x sets x repetitions) are key differences between OL, PL, and BB. Different levels of intensity and volume produce different functional adaptations that result in a blend of hypertrophy and neurological adaptations over time, but one may take precedence based on the emphasis of specific prescriptive variables[4,7,9,10].

Generally speaking, neurological adaptations precede hypertrophic adaptations early in resistance training programs and are responsible for the initial strength gains in untrained and lesser-trained subjects[15,16]. However, years of training may involve additional neural adaptations that further increase strength performance. This may explain the weak correlations between the back squat strength and thigh cross-sectional area for the OL and PL athletes in the current study. Muscle size correlates with strength across a continuum of training level (e.g. untrained, recreationally trained, highly trained); within a group of highly trained individuals, other characteristics might take precedence, which may weaken the strength to muscle size relationship[1,2,5,6,15,16,17,18].

Improvements in neuromuscular activation, such as an increased nerve (motor neuron) discharge to the agonist muscles[23] and a higher capacity for maximal voluntary activation of the working motor units[1] have been suggested as adaptations that occur to a greater degree in OL and PL athletes. According to O'Shea[9], high intensity weight training protocols, as practiced for OL and PL, cause morphological and physiological changes in the nervous system. These changes include increases in the size of the axon, the number of functional synapses, the size of the neuromuscular junction, and the enhancement of multiple fibre summation. Collectively, these adaptations enhance neuromuscular efficiency, optimising the expression of strength and power.

The performance of high force and high velocity movements like the snatch and clean and jerk (and variations) are rarely, if ever, performed during BB training[4]. Furthermore, BB training typically incorporates lower resistance versus PL training for pressing and deadlift exercises[1,4,7,9,10]. This is done to increase the volume of work in an attempt to stimulate anabolic signalling pathways that enhance muscle protein synthesis. The resistance training programs for BB tend to include more single joint exercises (often on machines) that are less technical and stimulate smaller muscle groups, to promote muscle symmetry over the entire body[1,4,7,9,10].

In contrast to the findings of the current study, Hakkinen et al.[1] found that back squat strength was not significantly different between OL, PL, and BB athletes; a possible explanation being that Hakkinen et al.[1] utilized athletes over a wider range of body mass (56-100kg) versus the current study (75-96 kg). The narrower range of body mass in the current study augments the conclusion that strength performance might be more reliant on factors other than muscle cross-sectional area, especially in advanced lifters. This point is further highlighted by the finding in the current study that body mass, body fat percentage, mid-thigh circumference, and thigh cross-sectional area were not significantly different between groups. Similar to the current study, McBride et al.[2] compared back squat strength between OL and PL athletes as well as sprinters and a control group; body mass was 85.3 ± 9.5kg and 78.2 ± 3.7kg for OL and PL groups, which were similar body mass values of 85.74 ± 7.60 and 87.92 ± 8.66 for the OL and PL groups of the current study, respectively. Also, consistent with the current study, McBride et al.[2] reported no significant differences in back squat strength between OL and PL groups.

In the current study, the consistency in the procedures utilized to determine 1-RM back squat strength was critical to control for certain mechanical factors (e.g. bar and foot placement, range of movement) that could have afforded a lifting advantage. However, the degree of forward lean at the torso, a factor not assessed in the current study, affects thigh muscle recruitment. Joint moment forces are distributed more equally between the hip and knee joints when performing the back squat with a relatively upright torso[24]. Thus the ability to successfully ascend with the weight is dictated to a large extent by the ability to extend the knees with the quadriceps femoris, Conversely, performing the back squat with a greater forward lean at the torso increases hip flexion and creates a hip moment of force that can be twice the joint moment force as that of the knee[24]. This places much of the workload on the gluteus maximus and the lower back musculature. Thus the ability to successfully ascend with the weight in this case is dependent, to a large degree, on the ability to extend the hips, rather than the knees.

Variations in torso angle during the back squat further complicate the relationship between absolute strength and thigh muscle size due to the multiple joints involved and varying recruitment patterns. It is possible that either of the aforementioned back squat styles can produce impressive gains in total thigh muscle cross-sectional area; future research should assess differences in regional hypertrophy (i.e. quadriceps , gluteus maximus, hamstrings) based on long term practice of different torso angles during performance of the back squat.

The combination of lower intensity and higher volume characteristic of BB protocols may cause selective hypertrophy of slow twitch muscle fibres[25]. This corresponding hypertrophy may not contribute directly to high levels of strength. O'Shea[8] demonstrated that during the back squat exercise, fast twitch muscle fibre recruitment was greatest at 90-100% 1RM. OL and PL protocols typically involve these higher intensity levels and may stimulate selective hypertrophy of fast twitch fibres, with little hypertrophy of slow twitch fibres. Furthermore, Fry and colleagues[5,6] reported that PL and OL, when compared to controls, had greater cross-sectional areas of fast twitch type IIa fibres with no significant difference in slow twitch fibres. This may explain why, in the current study, the OL and PL groups were significantly stronger than the BB group without significant differences in thigh cross-sectional area.

Zatsiorsky[10] suggested that BB training programs cause an increase in non-contractile proteins and sarcoplasm (sarcoplasmic hypertrophy), producing an increase in muscle size but without a corresponding increase in strength. Zatsiorsky[10] also suggested that the type of training performed for OL causes an increase in contractile proteins and the number of myofibrils (myofibrillar hypertrophy), producing an increase in both muscle size and strength. This may also explain the significant difference in strength between the OL and PL groups versus the BB group of the current study, but without a significant difference in thigh cross-sectional area between groups.

It should be noted that the Housh et al.[20] equation used in the present investigation has been shown to consistently underestimate muscle CSA when compared to a more accurate imaging technique (DeFreitas et al.[21]). Therefore, the CSA values from this manuscript should not be compared with CSA values of other populations that were collected using other measurement methods. Nevertheless, the high reliability and sensitivity of the Housh et al.[20] equation provides an appropriate and easy comparison between OL, PL, and BB subjects.

It was concluded that thigh cross-sectional area was of relatively minor importance in determining back squat strength for the OL and PL groups, despite these groups being significantly stronger than the BB group. Specific training protocols will elicit different outcomes with regard to muscular hypertrophy that may or may not contribute to a functional increase in back squat strength. Differences in strength performance might be due to neurological factors, selective muscle fibre hypertrophy, mechanical factors, and the type of hypertrophy.

Conclusions
The results of this study have implications for strength and conditioning coaches when designing resistance training programs for highly trained athletes from other sports. A BB type program may not transfer well to dynamic sports performance because the increase in muscle size may not lead to a functional increase in strength. Conversely, training programs which focus primarily on developing maximal strength, similar to OL and PL may increase muscle size to a certain extent, with perhaps greater transferability to dynamic sports performance. These authors may tentatively conclude that the use of OL and PL type training programs may have a greater application for highly trained athletes from other sports.

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