The Relationship Between Thigh Muscle Size and 1RM Squat Strength Among Bodybuilders, Powerlifters, and Olympic Weightlifters

James DiNaso

Eastern Illinois University

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Date
The Relationship Between Thigh Muscle Size and IRM Squat Strength

Among Bodybuilders, Powerlifters, and Olympic Weightlifters

(Title)

By

James DiNaso

Thesis

Submitted in partial fulfillment of the requirements for the degree of

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In the Graduate School, Eastern Illinois University

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I hereby recommend that this thesis be accepted as fulfilling this part of the graduate degree cited above

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The Relationship Between Thigh Muscle Size and 1RM Squat Strength Among
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Eastern Illinois University 2003
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Abstract

The purpose of this study was to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite bodybuilders, powerlifters, and Olympic weightlifters. Fifteen male subjects between the ages of 16 and 48 years participated in the study. All three subject groups, Olympic weightlifters (OWL, n=5), powerlifters (PL, n=5), and bodybuilders (BB, n=5), were highly trained and currently involved in competition training. All test subjects were of similar body weight and weighed between 76-96 kilograms. Measures of body weight, body composition (bioelectrical impedance), shoulder width, thigh circumference (proximal, distal, and mid-thigh), and thigh skinfold thickness were performed on all three subject groups. The barbell back squat exercise was used to measure one repetition maximum (1RM) squat strength. Stance width, bar placement, and squat depth were controlled so that all subjects performed the exercise in a similar manner. All measures of thigh size were compared to measures of 1RM squat strength. Comparisons among the groups were performed using ANOVA with significant omnibus results followed by Tukey's HSD post-hoc. Pearson Product Moment Correlations were performed to determine if a correlation existed between measures of thigh muscle size and 1RM squat strength. Statistical analysis showed no significant differences in thigh muscle area (TMA) (p=.44).
or for any measure of thigh circumference among the groups. The PL (205.45 ± 17.27 kg) and OWL (200.18 ± 25.16 kg) groups had significantly greater 1RM squat strength than the BB group (159.99 ± 16.82 kg). Significance was p=.01 and p=.02 for PL and OWL respectively. No significant difference in 1RM squat strength was found between the PL and OWL groups. The PL group (2.91 ± .34 kg/kg FFM) had significantly (p=.02) greater strength per kg fat free mass (FFM) than the BB group (2.15 ± .32 kg/kg FFM). No significant difference was found in strength per kg FFM between the OWL and BB groups or between the PL and OWL groups. The PL (.0904 ± .0099 kg/cm²) (p=.003) and OWL (.0831 ± .0119 kg/cm²) (p=.02) groups demonstrated significantly greater 1RM squat strength per unit TMA than the BB group (.0636 ± .0062 kg/cm²). No significant difference existed between the OWL and PL groups in strength per unit TMA. There was no significant correlation among the groups for any measure of thigh muscle size with any measure of strength. The correlation between mid-thigh circumference (MTC) and 1RM squat strength was r=.20. It was concluded that thigh size among highly trained BB, PL, and OWL of similar body weight was not significantly different. Powerlifters and OWL are significantly stronger than BB in the 1RM squat lift. Differences in strength among the groups were not due to differences in absolute muscle size. The relationship between muscle hypertrophy and strength is different in highly trained individuals than that of untrained or lessor-trained individuals.
Dedication

This thesis is dedicated to the loving memory of my grandfather, Charles "Chick" DiNaso and to my grandmother, Muriel "Gram" Halliday who both lived long and fulfilling lives in spite of facing incredible difficulties and great challenges.
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I would like to thank Dr. Brian Pritschet for the countless hours he has spent working with me on this study. He has certainly spent more time and energy talking with me and giving me guidance than what the department is paying him. He is not only my thesis advisor, but over the past three years has become a friend.

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CHAPTER I

INTRODUCTION

The belief that increases in strength occur as a result of muscle hypertrophy is widely accepted (Clark, 1973). Ikai and Fukunaga (1968) demonstrated that muscles with a larger cross-sectional area produce greater forces than similar muscles with a smaller cross-sectional area. However, Maughan, Watson, and Weir (1984) suggested that as cross-sectional area increases the strength per cross-sectional area ratio decreases. Greater pennation angles in hypertrophied muscles are responsible for smaller amounts of force produced in the tendon in response to a given level of force produced by a muscle (Maughan et al. 1984). Zatsiorsky (1995) suggested that there are different types of muscle hypertrophy which may influence muscular size and strength differently. Sarcoplasmic hypertrophy (increases in noncontractile proteins and sarcoplasm) may develop without significant increases in muscular strength (Zatsiorsky, 1995). Myofibrillar hypertrophy (increases in contractile proteins and the number of myofibrils) leads to an increase in muscular strength and size (Zatsiorsky, 1995).

Lesmes, Costill, Coyle, and Fink (1978) demonstrated that increases in muscular strength are not always accompanied by changes in muscle hypertrophy. Increases in muscular strength, in the absence of hypertrophy, have been attributed to neural adaptations occurring early in strength training programs. These neural factors include: an increased neural drive (Narici, Roi, Minetti, and Cerretelli, 1989), increased motor unit recruitment and synchronization (Lesmes et al., 1978), increased motor unit firing frequency (Komi, 1986), and inhibition of proprioceptors (Hakkinen and Komi, 1983). Improvements in muscle strength, due to hypertrophic factors, occur much later in
strength training programs when increases in cross-sectional area are significant (Hakkinen, Komi, and Tesch, 1981).

With a number of factors influencing muscular strength, muscle hypertrophy may not be the most important factor. More investigation is needed to determine the role of muscle hypertrophy in force development.

Increases in the strength and size of a muscle group occur as a result of an appropriate resistance training program. Individuals who engage in weight training often display high levels of muscle strength and hypertrophy. Highly trained Olympic weightlifters (OWL), powerlifters (PL), and bodybuilders (BB) display more muscle mass than the average person (Katch, Katch, Moffatt, and Gittleson, 1980). High levels of strength are also a common characteristic among these three groups (Hakkinen, Kauhanen, Komi, and Alen, 1986). These three groups represent the extremes in muscular strength and size.

Olympic weightlifters and PL train for the purpose of gaining strength to lift the heaviest possible weight in specific events (Katch, Katch, Moffatt, and Gittleson, 1980). Bodybuilders lift weights to achieve the highest degree of muscle hypertrophy. Powerlifters and OWL typically lift heavier loads than BB while the BB typically lift lighter loads. Different weight training protocols (number of sets and reps, loading schemes, speed of movement, recovery time, and frequency of exercise) are used among the three groups to achieve the desired training adaptation of strength or hypertrophy. Although OWL, PL, and BB use distinctly different training protocols, the use of the squat exercise is commonly utilized by each group (McBride, Triplett-McBride, Davie,
and Newton, 1999; Schwarzenegger and Dobbins, 1998). Few studies have been done comparing both the strength and size of specific muscle group(s) among OWL, PL, and BB. A comparison of muscular strength and size among the three groups is needed to better understand the role of muscle hypertrophy and its relationship to strength in highly trained individuals.

**Purpose of the Study**

The purpose of this study was to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite BB, PL, and OWL. Specifically, does the group with the greatest thigh size have the greatest 1RM squat strength?

It was hypothesized that the BB group would have the greatest thigh size and the lowest 1RM squat strength, while the OWL and PL groups would have the greatest 1RM squat strength but have a smaller thigh size than the BB group. Therefore, the PL and OWL groups would have greater 1RM squat strength per unit thigh muscle area (TMA).

**Limitations and Assumptions**

It was assumed that differences in thigh circumference measurements among the test subjects implied differences in hypertrophy of the thigh muscles. This assumption may be invalid due to differences in subcutaneous body fat, body weight, and genetic factors such as the total number of thigh muscle fibers present among the groups.

**Delimitations**

The test subjects were equal in terms of the success they had achieved in their specific sport (qualifying or competing at the national level) and were considered "elite". Only subjects weighing between 76-96 kilograms were used in the study.
Definitions

Muscle hypertrophy: an increase in the cross-sectional area of a muscle fiber in response to highly specific forms of stress

One Repetition Maximum: the ability to complete one maximal effort repetition of a given movement or exercise

Squat: an upper leg and hip exercise performed with a barbell resting on the shoulder, and a deep knee bend is performed; then the squatter returns to an erect standing position

Olympic Weightlifter: an athlete who competes to lift the most weight overhead; the two lifts contested are the snatch and the clean and jerk

Powerlifter: an athlete who competes to lift the most weight in three different lifts; the three contested lifts are the squat, bench press, and deadlift

Bodybuilder: an athlete who competes in physique contests where muscle size, muscle definition, and symmetry are judged

Significance of the Study

Few studies have examined the relationship between measures of muscle size and strength in highly trained BB, PL, and OWL at this level of ability. The present study was conducted to better understand the role of muscle hypertrophy and its relationship, if any, to strength in highly trained individuals.
CHAPTER II

REVIEW OF LITERATURE

The purpose of this study was to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite BB, PL, and OWL. Specifically, does the group with the greatest thigh size have the greatest 1RM squat strength?

This review of related literature was organized as follows: the relationship of cross-sectional area to muscular strength, assessment of muscle hypertrophy, neural factors influencing strength, and muscle architecture changes and the affect on strength.

The Relationship of Cross-sectional Area to Muscular Strength

It has been shown that a relationship exists between the cross-sectional size of a muscle and its ability to develop force. Studies have shown that the isometric force produced by human skeletal muscle is proportional to a muscle’s cross-sectional area (Ikai and Fukunaga, 1968; Maughan, Watson, and Weir, 1983).

A 1968 study by Ikai and Fukunaga investigated the relationship between muscle cross-sectional area and strength. Two hundred forty-five healthy persons participated. The subjects ranged in age between 12 and 30 years. Nine of the male subjects were highly trained university Judo athletes. Muscle strength and cross-sectional area of the biceps brachii and brachialis in 119 male subjects and 126 female subjects was measured at the elbow joint. In a seated position with the elbow joint flexed at 90°, each test subject contracted the elbow flexors isometrically against a cloth belt attached over the wrist. The belt was connected to a straingauge tensiometer, which measured each
maximal contraction. The highest value of three measurements was used as the
maximum strength of each subject.

Cross-sectional area was calculated using an ultrasonic measurement device.
Lying in a prone position, each subject's arm was extended to the bottom of a water tank.
While grasping a fixed handle at the bottom of the tank, an ultrasonic scanner took
images of each subject's upper arm for 30 seconds. An ultrasonic wave of 2.25-5
megacycle per second was used to get a clear image of bone, muscle, and subcutaneous
fat. Bakelite models were used to make a calibration curve to measure the size of the
tissues. Cross-sectional area was calculated in a flexed elbow position with maximal
contraction at the same joint angle as in the measurement of maximal strength. The axis
of rotation, the attachment site of the biceps brachii to the tuberositas radii, and the
resistance point were calculated using pictures created by x-ray photography.

Ikai and Fukunaga (1968) showed a positive relationship between cross-sectional
area and strength of the elbow flexors. This was observed in all subjects regardless of
training status, gender, or age. Differences in the strength per unit area was statistically
non-significant and did not differ by age or gender. In addition, there was no significant
difference between trained and untrained adult subjects. However, the individual
variation of the strength per unit area was distributed in a wide range from 4-8 kg per
cm². It was concluded from the results that muscle strength of the elbow flexors was
proportional to cross-sectional area. Furthermore, the strength per unit cross-sectional
area is the same regardless of age, gender, or training experience.

Ikai and Fukunaga (1968) could not explain the wide range of individual variation
in strength per unit cross-sectional area. The results from similar studies (Morris, 1948;
Hettinger, 1964) which used the muscle of cadavers show differences in cross-sectional area. To calculate cross-sectional area more accurately, Ikai and Fukunaga (1968) used living subjects and ultrasonography rather than calculations from cadavers. The wide range in individual strength per unit cross-sectional area suggests that the methods used by Ikai and Fukunaga (1968) may not be valid. Furthermore, significant differences between highly trained and untrained subjects were not found. The lack of any difference between highly trained and untrained subjects implies that cross-sectional area is the limiting factor in muscular strength. However, only 9 of the 245 subjects were considered highly trained. An investigation with less variability between the number of highly trained to untrained subjects may be necessary before conclusions can be drawn on the relationship between muscle size and strength.

Twenty-five males and 25 females between the ages of 20 and 38 years participated in a study by Maughan, Watson, and Weir (1983). Some subjects engaged in regular physical activity whereas others were sedentary. However, none of the subjects were considered to be highly trained. The maximum isometric force of the knee extensor muscles was measured on both legs of all test subjects. The subject's back was supported in an upright position and the back of the knee was positioned at the front edge of a chair. With the knee held at a right angle, a strap was positioned around the lower leg proximal to the malleoli. A wire attached the strap to a steel plate fixed to the rear of the chair, which measured knee extensor force via four strain gauges. Each subject was allowed three attempts to produce a maximum contraction and the highest value was recorded as the maximum strength of each leg. Unlike the study conducted by Ikai and Fukunaga (1968), computed tomography was used rather than ultrasonography to measure cross-
sectional area of the knee extensor muscles in test subjects. Computed tomography has been shown to have a higher degree of resolution than ultrasonography (Ferrucci, 1979). The results of the study by Maughan, et al. (1983) demonstrated a significant positive correlation between muscle strength and cross-sectional area in both male (r=.59; P<.10) and female (r=.51; P<.01) groups. These results were similar to the results of Ikai and Fukunaga (1968). However, contrary to Ikai and Fukunaga (1968), the ratio of strength to cross-sectional area had a tendency to be greater in males than females, but the difference was not statistically significant. The authors concluded that muscle strength is related to cross-sectional area with a possible tendency for males to have a higher ratio of strength per unit cross-sectional area.

The results and conclusions of the previous studies imply that exercise induced changes in muscular strength, by people who engage in resistance training, are proportional to increases in muscle hypertrophy. Hence, muscles with a large cross-sectional area should be capable of producing more force than muscles with a smaller cross-sectional area.

A study by Narici, Roi, Minetti, and Cerretelli (1989) concluded that hypertrophy produced by strength training accounted for 40% of the increase in force while the remaining 60% seems to be associated with increases in neural drive and possible changes in muscle architecture. Four male test subjects between the ages of 23 and 34 years participated in the study. None of the subjects were highly trained or engaged in any type of competitive exercise. The subjects trained for 60 days followed by a detraining period of 40 days. Training consisted of six sets of 10 maximal isokinetic knee extensions at an angular velocity of 2.09 rad·s⁻¹ performed four times a week. The
training was unilateral with only the dominant leg being trained. At the beginning of the study and on every 20th day of training and detraining, quadriceps strength, cross-sectional area, and neural activation were measured. Using an isokinetic dynamometer, with the subject’s pelvis and trunk secured to a chair, the best of five trials was recorded as the maximal isometric contraction. Quadriceps cross-sectional area was measured using nuclear magnetic resonance imaging. Cross-sectional area measurements were performed on the quadriceps as a whole and individually on all four of the quadriceps muscles. Neural activation was assessed by electromyography of the vastus lateralis muscle.

The results of the study showed that the isometric maximal strength of the trained leg increased significantly at an average rate of 0.32% per day during the training period. The total strength increase in the trained leg was 20.8% when compared to pre-training levels. Strength of the untrained leg increased after the 60-day training period, however, it was not statistically significant. Strength in the trained leg decreased during the 40-day detraining period similar to the rate of strength increase during training. No significant changes in cross-sectional area were found in the untrained leg during training or detraining. Cross-sectional area of the trained leg increased significantly. Individually each of the quadriceps muscles hypertrophied to a different degree. The total combined increase of the quadriceps cross-sectional area was 8.5%. During detraining, cross-sectional area of the trained leg decreased with a similar time course to that of training. An increase of 42.4% was found in peak electromyographic activity during isometric contraction of the trained leg after training. In the untrained leg, the increase in
electromyographic activity was statistically non-significant. During detraining, the changes in electromyographic activity were similar to those of training.

These results led Narici et al. (1989) to conclude that factors other than hypertrophy were responsible for increases in strength. There was a disproportionate increase in isometric maximal voluntary contraction of 20.8% compared to an increase of 8.5% in total cross-sectional area. Narici et al. (1989) expected results similar to Ikai and Fukunaga (1968) which demonstrated increases in strength proportional to that of cross-sectional area. Changes in muscle architecture and an increased neural drive, evident by the increase in electromyographic activity, were suggested as possible explanations for the difference in the strength to cross-sectional area ratio.

Most of the subjects in each of the studies by Ikai and Fukunaga (1968), Maughan et al. (1983), and Narici et al. (1989), were not highly trained. All of the test subjects performed isometric maximum voluntary contractions to measure strength and to promote hypertrophy. It is unclear if studies using relatively untrained subjects, performing isometric contractions, have any correlation to highly trained OWL, PL, and BB, who use isotonic contractions in their training protocols.

Assessment of Muscle Hypertrophy

Some studies show that hypertrophy induced by resistance training, is due to an increase in the myofibrillar material of the individual muscle fibers (Goldspink, 1964; Helander, 1961). The study authored by Helander (1961) used animals in two series of experiments to show what effects exercise and inactivity had on sarcoplasmic and myofibrillar protein volume. The first series of experiments were performed on 48 guinea pigs divided into three groups of 16. All animals were healthy and of similar
weight. The animals were fed a normal diet and came from the same breeder. Group 1 was used as the control group and was kept in a large, roofless cage (300 cm x 75 cm wide). Group 2 was the exercise group and was kept in the same size cage as Group 1. This group was exercised six days per week on a motorized belt moving at a constant velocity for a distance of 1000 meters with two, 10 minute pauses. Group 3 was restricted in activity and was kept in small cages (22 cm high and 35 cm x 24 cm wide) which only held three animals each. The experimental period for the guinea pigs lasted four months.

The second series of experiments were performed on 25 healthy rabbits that were divided into four groups. Group 1 was the control group whose activity was not restricted. This group of 10 rabbits was sacrificed at the beginning of the experiment. Group 2 consisted of 6 rabbits that were kept for six months without restriction of activity. The five rabbits in Group 3 were kept for six months in small cages (35 cm high and 35 cm x 70 cm wide) with one third of the floor space occupied by food and containers. The fourth group of 4 rabbits was kept in the same type of cages as Group 2 for three years.

At the end of the experiments, all of the animals were sacrificed. The calf muscles of the guinea pigs were removed as well as the quadriceps femoris muscles of the rabbits. A portion of each specimen was set aside to determine water content. Sarcoplasmic and myofibrillar proteins were extracted using an exhaustive and complex extraction process. The results showed that among the three groups of guinea pigs there were no appreciable differences in sarcoplasmic proteins, stroma proteins, and non-protein nitrogen. The exercise group however, showed a significantly higher content of
myofibrillar protein than the other two groups. The weight of both calf muscles was higher for the exercise group (Group 2) but the difference was not statistically significant.

The results of the series of experiments involving the rabbits were inconclusive based on statistical evaluation. This was likely due to the small number of animals used as test subjects. However, although statistically insignificant, the total nitrogen content and the proportions of stroma protein and non-protein nitrogen were unaltered in all groups of rabbits. The rabbits in Groups 1 and 2 had a myofibrillar protein content that was more than twice as large as the sarcoplasmic protein content. Group 4 had approximately equal proportions and Group 3 occupied an intermediate position. Helander concluded that exercise in guinea pigs increases the amount of myofibrillar protein in skeletal muscle. It was also concluded that the composition of muscle cells varies within wide limits. It was suggested that exercise seems likely to cause muscle hypertrophy and a concurrent increase in myofibrillar protein content. Both of these changes might enhance the contractile strength of the muscles whereas restricted activity decreases myofibrillar density and increases the proportion of sarcoplasmic protein.

Goldspink (1964) drew similar conclusions based on the results of a 25-day experiment involving mice. Sixteen healthy female mice from the same strain were used in the experiment. The mice were of similar body weight and were divided into four equal groups. The first group received 3.5 grams of food per day and was made to exercise. The second group, a control group, did not exercise but received 3.5 grams of food per day. The third group exercised and received 5 grams of food per day. The fourth group, a control group, received 5 grams of food per day and no exercise. An apparatus was developed to exercise the mice which consisted of a pulley over which a
cord was placed with a weight at one end and a food cube at the other. The cord was pushed through the cube so that a short length hung below the food. In order to obtain the food, the mouse had to pull down the cord against the weight. The axle of the pulley was connected to a lever, which left a record on a rotating drum each time the animal pulled down the cord. An equation was used to calculate the amount of work the mouse performed which took into account the distance that the weight was pulled, the number of pulls, and the weight pulled. The mice were kept in identical cages with the exception of the cages that housed the exercising groups. These cages were fitted with the pulley apparatus. The amount of exercise performed was controlled so that each animal in the exercising groups did approximately the same amount of work. At the end of the experimental period, a histological procedure was used to determine the diameter of the fibers of the biceps brachii muscle of each mouse. The diameter of 100 fibers from each muscle was measured using an ocular micrometer eyepiece. A photomicrograph was used to create images for the purpose of observing sarcoplasm and myofibrillar number.

The results of the study showed the exercise groups exhibited a more pronounced distribution of large phase fibers normally seen in mice of heavier body weight. The muscles of the control group showed a much smaller percentage of large phase fibers especially the group receiving 3.5 grams of food per day. The exercised mice tended to gain more weight than the control group. The muscles of the exercised mice had a greater muscle fiber diameter with increases in fiber diameters almost the same among the exercise groups receiving 3.5 and 5 grams of food per day. An increase in the number of myofibrils in the hypertrophied fibers was observed and a linear relationship
between muscle fiber diameter and myofibrillar number was shown. In contrast, the small phase fibers demonstrated a greater abundance of sarcoplasm.

It was concluded that hypertrophy following muscular exercise in mice is due to an increase in the diameter of only some of the fibers. The author concluded that the actual number of myofibrils per fiber increased with the increase in muscle fiber diameter where Helander (1961) showed an increase in myofibrillar protein volume. Another conclusion, which is in agreement with the study done by Helander (1961), is that the weights of exercised muscles are not greater than the muscles of the control groups even though the fibers of the exercised muscles are larger in girth. Goldspink (1964) suggested that the hypertrophied muscle fibers developed at the expense of extracellular components (sarcoplasm). This was also shown by Helander (1961).

Hypertrophy associated with increases in myofibrillar protein volume and myofibril number in human subjects is not supported by the data of MacDougall, Sale, Elder, and Sutton (1982). A group of five elite bodybuilders and two international caliber powerlifters (Group 1) were compared to a control group of five untrained subjects (Group 2). The untrained subjects participated in a heavy resistance training program of the elbow extensor muscles for a period of six months. Six of the seven BB and PL currently were using or had previously used anabolic steroids, while none of the control group had used steroids. Two needle biopsies were taken from the long head of the triceps brachii of each test subject. In the control group, biopsies pre and post the six month training period were taken. One biopsy was prepared for electron microscopy and stereologically analyzed. The second biopsy was stained and photographed under a light microscope after being frozen in isopentane. Elbow extension strength was measured
using a dynamometer at a joint angular velocity of $30^\circ \cdot s^{-1}$ (0.524 rad·s$^{-1}$). Arm girth was measured using a spring-loaded tape at the largest point of circumference in the relaxed extended position.

The results of the study showed elbow extension strength and arm girth were significantly greater in Group 1 compared to Group 2. However, there were not any significant differences between the two groups in mean cross-sectional area of fast twitch or slow twitch fibers or in percentage of fiber type. The stereological analysis showed myofibrillar volume density was significantly lower and sarcoplasmic volume density significantly higher in the elite group than in the post-trained controls. Although there was an increase in the absolute amount of contractile protein per fiber, the relative volume density decreased. Morphometric analysis revealed abnormalities in the muscle fibers of the BB and PL group. These included enlarged sarcoplasm "spaces", extremely atrophied fibers of both types, and a proliferation of fatty tissue. Other abnormalities were centrally located nuclei, which were also found in the post-trained controls, although their incidence was much lower than in the BB and PL group.

MacDougall et al. (1982) concluded from these results that elite BB and PL might possess a greater total number of muscle fibers than normal groups. This was suggested due to no significant difference in fiber area or percentage fiber type between the controls and the elite group. It was also concluded that extreme hypertrophy, through heavy resistance training, results in an increase in sarcoplasmic volume density and a parallel decrease in myofibrillar volume density. The authors of this study suggested that sarcoplasm increases might be due to an increase in muscle glycogen content, which occurs in response to heavy resistance training. Another possibility suggested was an
increase in collagen that surrounds individual muscle fiber (endomysial connective tissue) which varies considerably between muscle types (Kovanen, Suominen, and Heikkinen, 1980). A third possibility was the use of anabolic steroids by the elite group. This could have caused an excess fluid content resulting in a larger sarcoplasm volume density. It was also concluded that elite BB and PL have a high incidence of abnormal muscle fibers, but it was unclear if these abnormalities were due to anabolic steroid use or chronic training.

Some limitations in the study by MacDougall et al. (1982) included a low subject number. Only seven elite BB and PL were used as subjects. Only two PL participated in the study and were part of the same test group (Group 1) as the BB. Competitive BB and PL train for distinctly different purposes and utilize very different resistance training protocols (Katch et al. 1980). It may not be appropriate to include PL and BB in the same test group and make comparisons with other groups without taking into account the differences between PL and BB.

It was unclear as to what types of resistance training protocols were used with the control group, nor was information given about the BB and PL training programs. The training programs and protocols may have influenced the resulting physiological adaptations found in all the test groups especially the elite group, which demonstrated abnormalities.

Zatsiorsky (1995) differentiates between two types of muscle hypertrophy. Sarcoplasmic hypertrophy is characterized by an increase in noncontractile proteins and sarcoplasm. The filament area density decreases while the cross-sectional area of the muscle fiber increases. This occurs without a concurrent, significant increase in muscle strength. Myofibrillar hypertrophy is characterized by an increase in contractile proteins
and the number of myofibrils. Filament density increases and the increase in cross-sectional area is associated with increased muscular strength (Zatsiorsky, 1995). Zatsiorsky (1995) points out that sarcoplasmic hypertrophy typically occurs in BB and myofibrillar hypertrophy is seen in elite OWL, if the training program is designed properly (Figure 1). This is in agreement with the study by MacDougal et al. (1982) in which it was demonstrated that BB had less contractile protein per fiber area than a control group.

The study by MacDougal et al. (1982) and explanations by Zatsiorsky (1995) provide evidence to suggest that different physiological adaptations are responsible for resistance training induced hypertrophy of skeletal muscle. The specificity of resistance training protocols may influence not only the type of muscle hypertrophy, but also the degree of increases in force production associated with increases in cross-sectional area. Bodybuilding training protocols, which aim solely to increase cross-sectional area, are responsible for increases in non-contractile proteins and connective tissues. This may have a negative impact on the force production of hypertrophied muscles. Komi (1986) suggests that muscle power, and strength is not necessarily synonymous with hypertrophy. He states:

The degree of hypertrophy is not only dependent on the type of strength/power training used, but that its occurrence may follow the effects of motor input, and that the proceeding influence of motor unit activation could be the necessary condition for the hypertrophic myofibrillar changes (Komi, 1986, p. 515-516).

Neural factors may account for early gains in strength from high intensity training and an increasing contribution from hypertrophic factors gradually occurs over time. The
Figure 1  Comparison of Sarcoplasmic and Myofibrillar Hypertrophy

Untrained Muscle Fiber

Sarcoplasmic Hypertrophy

Myofibrillar Hypertrophy

Adapted from *Science and Practice of Strength Training*, by B.M. Zatiorsky, 1995.
sequence of events leading to increases in strength is shown in Figure 2. According to Komi (1986), hypertrophy is a delayed process and the magnitude of the resulting hypertrophy is largely dependent on the intensity and duration of the training stimulus.

**Neural Factors Influencing Strength**

A study by Lesmes, Costill, Coyle, and Fink (1978) demonstrated increases in strength could occur without measurable increases in muscle hypertrophy. Lesmes et al. (1978) investigated the effects of high intensity training on knee extensor and flexor muscles of five healthy male volunteers. All five test subjects were of similar age, weight, and height. Knee extensor and flexor muscles were tested using an isokinetic dynamometer. Subjects were seated and strapped at the chest, thigh, and hip to help localize contraction of the targeted muscle groups. A lever was connected to the tibia at the ankle, and maximal knee extensions and flexions were performed from 90° to full knee extension. Three isokinetic tests were performed before and after the training period. Maximal voluntary contractions of each leg during knee extension and knee flexion were measured. Knee extension strength was tested on a separate day from knee flexion strength. A second test measured the total work output of each leg at three different settings of 180, 60, and again at 180°·s⁻¹ for a 6-second and 30-second work bout. A third test, which measured fatigue, was performed on a separate day. This test consisted of 60 seconds of all-out repeated flexion and extension. Work output was recorded every 10 seconds. Thigh girth was measured along with thigh skinfold thickness and leg volume. Leg volume was determined by water displacement.
Figure 2  Events Leading to Muscle Strength Increases

High Intensity Strength Training

Increased Synchronization of Motor Units
Increased Motor Unit Activity

Increases in Muscular Strength

Muscle Hypertrophy

Adapted from How important is neural drive for strength and power development in human skeletal muscle? by P.V. Komi, 1986, *Biochemistry of Exercise* VI.
The test subjects trained four times a week for seven weeks. Two days of training were followed by a rest day until four workouts were completed. Each training session consisted of maximal extensions and flexions of the knee at a constant velocity of 180°·s⁻¹. One leg was trained with 10 bouts of 6-second sets with 114 seconds recovery time between bouts. The other leg was trained with two bouts of 30-second sets with 20 minutes of recovery time between bouts. The rationale for selecting 6 and 30-second sets was to selectively emphasize both the ATP-cp and glycolytic metabolic systems.

The results of the study demonstrated the training programs did not produce any significant changes in thigh girth, skinfold thickness, or thigh volume in either trained leg (Lesmes et al., 1978). A significant increase in isometric knee extension strength after the seven-week training program was observed in both the 6-second and 30-second trained legs. The increase in strength was not different between training protocols (6-second or 30-second) and no significant differences in strength were noted between the two legs. These results appear to confirm Komi’s (1986) suggestion that neural factors may account for early gains in strength training. The work output of both legs increased significantly. No differences were observed between the legs trained at a velocity of 60 degrees per second. However, at 180°·s⁻¹, the 30-second trained leg increased its work output by 27% which was significantly greater than the 18% increase in the six-second trained legs. Both legs were able to perform significantly more work after the training period ended. No difference was observed in work capacity in either leg except during the final 10 seconds of the 60-second fatigue test. Work output of the 30-second trained leg was significantly greater than the 6-second trained leg during this last 10 seconds.
Lesmes et al. (1978) concluded isokinetic training could increase muscular strength and work capacity of muscle. It was also concluded that increases in strength are possible with very short duration isokinetic training. The authors of the study suggested that increases in muscular strength, in the absence of hypertrophy, were due to other muscular or neuromuscular adaptations. It was speculated that increases in muscle fiber recruitment and a more synchronous firing of motor units could have been responsible.

The test subjects for this study trained for seven weeks and for only 60 seconds per day, four days each week. Training periods longer in duration might be necessary to see a statistically significant increase in muscle hypertrophy from high intensity strength training. It was also unclear if the five test subjects were untrained or experienced exercisers.

A study by Hakkinen, Komi, and Tesh (1981) used subjects who trained over a 16-week period to study the effect high intensity training had on the leg extensor muscles. The subjects were 24 males between the ages of 20-30 years and of similar height and weight. The experimental group was made up of 14 subjects who weight trained for their own conditioning purposes. No one in the experimental group participated in competitive lifting. The control group of 10 subjects was physically active but had no experience with weight training. The experimental group trained for 16 weeks followed by a detraining period of eight weeks. A training program of dynamic squat exercises using a barbell was performed three times per week. One to six repetitions per set were performed concentrically. One to two repetitions, lasting three to four seconds, were performed eccentrically. Seventy-five percent of the total muscle contractions performed were concentric with the other 25% being eccentric. The training program
followed a progressive loading scheme. Weekly increases in intensity progressed from 80 to 100% concentrically and 100 to 120% eccentrically. These percentages were based on the subjects’ 1RM in the barbell squat exercise. The number of lifts increased weekly from 16 to 22 per exercise. Light concentric exercises for the trunk, arms, and legs were included to prevent injury and make the training more interesting for the test subjects.

The experimental group was tested on seven identical occasions every four weeks before, during, and after the 24-week period. The control group was tested only at the beginning and the end of the study. Testing to measure functional strength, maximal isometric strength, and force-time parameters were performed along with anthropometric measurements and muscle biopsies. The barbell squat was used as a functional performance test of maximal force. The subject raised up from a full squat position with a barbell resting on the shoulders with no preliminary counter movement. The control group was not tested in the barbell squat for safety reasons due to their inexperience with weight training. Isometric strength was measured bilaterally using an electromechanical dynamometer. Each subject performed three maximal isometric contractions at the maximally produced rate of force development. This was done to measure force-time along with isometric strength. The force of each contraction was recorded on magnetic tape and analyzed with a computer. Relative and absolute measurements were calculated in the force-time analysis. In the relative scale, the times needed to increase force from 10, to 30, 60, and 90% were calculated. In the absolute scale, calculations were performed from the force level of 100 Newtons to 500, 1000, and 2000 Newtons. A vertical jump test was used to measure force-time under dynamic conditions. A squat jump, from a static position with the knees flexed at 90 degrees, was performed on a
force platform. Each jump was recorded on magnetic tape and a computer analysis revealed the maximum height from the flight time. Skinfold measurements using the same method as Durnin and Rahaman (1967) were used to calculate body fat and fat free mass. Thigh girth was measured while the subject was in a seated position with the thigh muscles relaxed. The proximal, medial, and distal thigh was measured using a measuring tape. Needle biopsies of the vastus lateralis were obtained for histochemical staining to classify fast twitch and slow twitch fibers. For the calculation of fiber area and the fast twitch to slow twitch area ratio, 10 fast twitch and 10 slow twitch fibers were selected from the same area of the muscle. The cell area for both fiber types was determined by a computer from an image off a digital board reflected by a microscope. Muscle enzyme activity of myokinase and creatine kinase of freeze-dried muscle tissue were determined using a fluorometric coupled reaction of nicotinamide adenine dinucleotide and nicotinamide adenine dinucleotide phosphate.

The results of the study demonstrated that the experimental group gained significantly in weight, fat-free weight, and thigh girth. Changes in body fat percentage were not significant. During the eight-week detraining period, thigh girth and body weight decreased non-significantly while percentage of body fat increased. In the control group percent body fat increased, fat free weight decreased, and thigh girth remained the same between the first and last tests. Performance in the barbell squat lift improved significantly by 25.5% from 117.5 to 147.1 kg by the end of the training period. This increase was very small (1.2%) during the last four weeks of training. During detraining the squat performance decreased by 11.6% to an average of 131.8 kg. Isometric leg extension force increased during the 16 weeks of training by 21%. This increase
occurred mainly during the first eight weeks with a slight improvement during the last eight weeks of training. Isometric strength decreased by 12% during detraining. The control group demonstrated no change in maximal isometric force between tests. The time to reach certain force levels was reduced through the 12th week of training using the absolute scale. At both high and low force levels, the subjects were able to reach specific force in significantly shorter times post-training as compared with pre-training. There was no change in the force time curve during this 12-week period in the relative scale. Times to reach absolute and relative force levels, at the 16th week of training, increased compared to the values after 12 weeks. The change in the relative scale was significant at this time. The tendency towards a reduction in the times to reach different low force levels occurred mostly during the first four weeks of detraining.

The control group demonstrated no change in the force-time curve between pre and post testing. Vertical jump heights improved 9.6% after the 16-week training period from 28.9 cm to 31.7 cm. Vertical jump performance increased gradually over the first 12 weeks and then decrease slightly during the last four weeks of training. After detraining, vertical jump height showed a non-significant decrease. There was no change in vertical jump performance in the control group. The cross-sectional area of fast twitch fibers increased significantly with smaller increases in slow twitch fibers over the first eight weeks of training. The greatest increase in cross-sectional area, in both types of fibers, occurred during the last eight weeks of training. However, the ratio of slow twitch to fast twitch fibers was unchanged. The cross-sectional area of fast twitch fibers decreased more than the cross-sectional area of slow twitch fibers during detraining. No changes occurred in the fiber characteristics of the control group pre and post
measurements. No changes in myokinase and creatine kinase occurred during training, however, creatine kinase activity increased during detraining.

Hakkinen et al. (1981) concluded that a high intensity strength training program of combined concentric and eccentric muscle exercises results in significant gains in maximal muscle strength and force-time parameters of the leg extensor muscles. Near maximal gains in force occur over the first eight to 12 weeks of training with smaller gains occurring over the last four to eight weeks of a 16 week training program. Improvements in the rate of force production early in the training program were related to selective hypertrophy of fast twitch fibers. Hakkinen et al. (1981) speculated that improvements in the capabilities of fast twitch motor units may have also contributed to the rate of force production. It was suggested that these adaptations were responsible for improvements in the force-time curve and vertical jumping ability. There was a significant reduction in the rate of force production after 12 weeks. The authors suggested that the specificity of the training program (the slow speed of the eccentric contractions) and the enlargement of slow twitch fibers during the last eight weeks of training may have been responsible for this reduction in the rate of force. Hypertrophy occurred mainly during the last eight weeks of training after significant improvement in muscle strength. Hakkinen et al. (1981) concluded that training periods greater than eight weeks are necessary for significant muscle hypertrophy to occur. This is in agreement with Lesmes et al. (1978) who demonstrated that increases in strength during a seven-week training program occurred without measurable increases in cross-sectional area.

The concept of specificity of strength training was strongly supported by the authors. Concentric contractions may have contributed to the reduction in the rate of
force development, although Hakkinen et al. (1981) made no mention of it in the study. This may have been a contributing factor especially since the concentric training loads were progressively increased each week from 80% to 100% of the subject's 1RM. Progressive loading in the higher percentages would have greatly reduced the speed of the ascent during the concentric phase of the barbell squat exercise. Thus, it seems logical that both slow eccentric as well as slow concentric contractions (specificity of training, i.e. slow contraction speed) might have had a negative effect on the force-time curve and vertical jump performance. A relative improvement of 25.5% in squat strength during the first 12 weeks of training suggests that the experimental group may not have been highly trained in the squat exercise. This initial improvement in strength might have been due to a motor learning of the unfamiliar exercise (barbell squat). It is unclear if the conclusions drawn by Lesmes et al. (1978) and Hakkinen et al. (1981) have any value to highly trained competitive OWL, PL, and BB.

Hakkinen, Kauhanen, Komi, and Alen (1986) compared neuromuscular performance capacities between OWL, PL, and BB. A total of 18 highly trained male subjects volunteered for the study. Seven OWL, 4 PL, and 7 BB, all with a training and competition background of several years, participated in the study. The subjects were Finnish national and near-national level competitors. It was unclear how old the test subjects were.

Measurements of weight, height, percent body fat, and fat-free weight were performed on all test subjects. Skinfold thickness measurements were used to calculate (Durnin and Rahaman, 1967) percent body fat and fat-free weight. An electromechanical
dynamometer was used to measure maximal bilateral isometric force of the leg extensor muscles. Force-time and relaxation time parameters of the leg extensors were also measured. The force of each isometric contraction was recorded on magnetic tape and analyzed by computer. In the force-time analysis, relative and absolute measurements were calculated. The times to increase force from 10% to 30, 60, and 90% were calculated for the relative scale. In the absolute scale, calculations were performed from a force level of 100 Newtons to 500, 1500, and 2500 Newtons. The relaxation-time curve was analyzed in the relaxation phase of the contraction. The times needed to relax the force from 85% to 60, 30, and 10% were calculated. Dynamic maximal force was measured by testing the subjects with various jumps and a barbell squat lift.

The squat was performed with the subjects bending their knees, with a loaded barbell resting on the shoulder, to a full squat position and then standing erect. All vertical jumps were performed on a force platform and recorded on magnetic tape. Jumping heights were calculated from the flight times measured by the force signal. A squat jump, without a counter movement, was performed from a semi-squat position. The test subjects’ hands remained on their hips throughout the entire jump. Loaded squat jumps were performed with a barbell resting on the shoulders. Loads of 20, 40, 60, 80, and 100 kg were used. Drop jumps performed from heights of 20, 40, 60, 80, and 100 cm onto the force platform with subsequent jumps upward were also performed. The best dropping height and the height of rise of the best drop jump were calculated. The dropping height that gave the highest performance was recorded as the best drop jump.

Anthropometric measurements revealed the body weight of the test subjects ranged from 56 to 100 kg. The range of body weight among the groups was: OWL 56–
100 kg, PL 82.5–100 kg, and BB 80–100 kg. These differences were not statistically significant. The body fat levels of the OWL and BB were significantly lower than the PL group. The estimated body fat among the groups was: OWL 12%, BB 13.4%, and PL 19.9%. No differences of statistical significance were found in maximal isometric force among the groups. However, maximal isometric force per body weight was greater in the OWL group. The results show a mean value in maximal isometric force of 60.1 kg for OWL, 50.7 kg for PL, and 49.3 kg for BB. In the barbell squat lift, the PL group demonstrated dynamic strength of 207.5 kg compared to 186.4 kg for the OWL, and 183 kg for the BB group. However, the differences in squat strength among the three groups were statistically non-significant. Dynamic strength per body weight of the OWL was greater than the PL and the BB in the squat exercise. The times of isometric force production, in the relative and absolute scale, were shorter in both the OWL and BB groups compared to that of the PL. No statistically significant differences in the times of relaxation were demonstrated among the three groups. Loaded squat jumping heights were highest for OWL at all loads and lowest for the PL group especially at 20 and 40 kg. Jumping heights did not differ among groups. Drop jumping heights of OWL were statistically significant compared to the PL group from dropping heights of 60, 80, and 100 cm, and from the BB group at 100 cm. The best drop jump of 41.1 cm (mean value) performed by the OWL group was significantly higher than those of the other groups. The BB group demonstrated a better drop jumping ability of 33.9 cm as compared to 30.7 cm of the PL group.

A significant positive correlation existed between the average time to produce 60% force, of maximum isometric contraction, with the average relaxation time from 85-
10% among the PL and BB groups. Vertical jumping height in the squat jump also correlated significantly, although the relationship was negative, with the time to increase isometric force to 1500 Newtons among the PL and BB groups. Both of the corresponding correlations were insignificant in the OWL group.

Hakkinen et al. (1986) concluded that elite OWL, PL, and BB have similar levels of absolute strength, but OWL have greater isometric and dynamic strength per body weight than PL and BB. The authors speculated that a greater capacity for maximal voluntary neural activation of the working motor units produced higher values for strength per unit muscle mass in OWL. Hakkinen et al. (1986) thought this might be a plausible explanation based on the demonstration of increases in maximum electromyographic activity of trained muscles during controlled strength training (Hakkinen and Komi, 1983). Although statistically non-significant, the authors implied that specificity of training and testing might have been responsible for the higher absolute value in the barbell squat lift, demonstrated by the PL group. Hakkinen et al. (1986) reasoned that because the training of PL involves high intensity slow contraction velocity exercises, adaptations of the neuromuscular system to produce a slower rate of force might take place. Changes in the firing frequencies and/or recruitment patterns of the motor units were suggested as possible reasons for a slower rate of force development in the PL group. Specificity of training was also suggested as a possible explanation for the higher performances by the OWL group in the dynamic strength tests. The training of OWL involves barbell exercises and various jumping drills in which eccentric contractions are rapidly followed by concentric contractions. The authors reasoned that this type of training influenced the superior performance of the OWL group in the drop
jumping tests. It was concluded that OWL have a higher capacity to utilize stored elastic energy than PL and BB. However, the authors emphasized that drop jumping results of OWL were inferior to those of higher jumpers in other studies and that pure strength training alone does not cause any changes in the elastic properties of muscle. The lack of differences between the OWL and BB groups in the rate of isometric force production and the tendency for shorter relaxation times of BB was unexpected. A faster rate of force development in the OWL group was expected since the training of OWL involves high contraction velocities. Hakkinen et al. (1986) speculated that the short rate of isometric force production and relaxation times was due to the BB special competition training. This training involves isometric contractions and relaxation without external loads in order to control the body during competitions (posing). The authors acknowledged that no muscle biopsy samples were taken and that muscle fiber composition may have influenced the observed times in the rate of isometric force production as well as vertical jump ability.

Lighter lifters demonstrate greater levels of relative strength and lower levels of absolute strength when compared to heavier lifters. This is evidenced by the higher strength ratings, based on formula, by lighter weight class lifters when compared to the heavier weight class lifters in elite OWL and PL competitions. This was demonstrated in the study by Hakkinen et al. (1986) as the OWL group had the lightest body weight and the greatest isometric and dynamic strength (barbell squat lift) per body weight than the PL and BB groups. Although differences in body weight were statistically insignificant in the study, there was a 24 kg difference between the lightest OWL and BB. Similarly, there was a 26.5 kg difference between the lightest OWL and PL. A range in bodyweight
of 56-100 kg represents a 44 kg difference between the lightest and heaviest test subjects. A study designed with less variability in body weight may have greater significance statistically and practically when comparing strength among OWL, PL, and BB. It was unclear whether the testing criteria for stance width and bar placement was standardized for dynamic strength testing in the barbell squat lift and loaded squat jumps. It has been demonstrated that stance width and bar placement has an affect on muscle activity (McCaw and Melrose, 1998) and the ability to lift heavier loads (O’Shea, 1985). Possible differences in stance width and bar placement may have influenced the results of these two tests.

A similar study by McBride, Triplett-McBride, Davie, and Newton (1999) compared strength and power characteristics between OWL, PL, and sprinters. Twenty-eight male subjects between the ages of 18 and 32 years participated in the study. All the subjects were highly trained and competitive at the national level with the exception of the control group. The control group of 8 subjects did not have any prior experience with resistance training and consisted of moderately active individuals. The 6 OWL, 8 PL, and 6 sprinters were not currently, or in the previous year, taking performance enhancing drugs.

All testing for a subject was performed on a single day. Testing included anthropometric measurements of height, weight, and body fat. The equation by Jackson and Pollock (1977) was used to estimate percent body fat from skinfold measures. Vertical jump, 1RM squat test, and loaded jump squats were measured. A recovery period of 10 minutes between each of the three tests was allotted. Stance width and bar placement was standardized for 1RM squat testing and jump squats. Bar placement was
required to be between the superior portion of the scapula and the seventh cervical vertebra. The stance width was constrained to within 15 cm of the lateral portion of the subject’s deltoid. Outward rotation of the foot of no more than 30° was allowed. The distance between the heels of the feet and the bar could not be more than 8 cm in front or behind the bar. No stance criteria were established for the vertical jump tests. Vertical jump testing was performed with a counter movement executed to a knee angle of 90°.

Two warm-up trials were performed using body weight before attempting a jump of maximum height. The test jumps were performed in randomized order with each subject performing three trials at a given load. Maximum jumps using body weight and loads of 20 and 40 kg were measured. Loading was achieved by the test subject holding dumbbells in each hand. One-minute recovery time was allowed between each jump and two minutes recovery time allowed between the various loads. One repetition maximum testing was performed using a Smith machine. The Smith machine utilizes a barbell fixed to metal guides, which direct upward and downward movements. Warm-up trials using 30, 50, 70, and 90% of an estimated 1RM were performed. The estimated 1RM was based on the test subject’s own estimation or 2-2.5 times the subject’s own body weight. The load was then increased to determine a 1RM for the Smith machine squat. Three to four maximal efforts were used in this determination. Each subject flexed the knee to an angle of 90° which was marked by adjustable stoppers. An audible cue was given to the test subject at 90° knee flexion to move the bar upward to the starting position. Three to five minutes recovery time was allowed between 1RM attempts. Jump squats of 30, 60, and 90% of the 1RM were performed with the Smith machine. Two warm-up trials with the unloaded bar were performed before attempting a loaded jump.
Each subject flexed the knee to an angle of 90°, which was marked by adjustable stoppers, just as in the 1RM Testing. An audible cue was given to the test subject at this point. The subject immediately jumped forcefully upward as fast as possible with the feet leaving the surface of the floor. The best trial was used for comparisons based on proper technique and maximal height. Two trials were performed at each given load. Two minutes recovery time was allowed between jumps and three minutes recovery time was allowed between the loads. A force plate, mounted below the subject's feet, was used to record ground reaction forces during the vertical jumps and jump squats. A position transducer, attached to the Smith machine bar, recorded bar displacement during jump squat performances. Biomechanical analyses were performed by a computer to determine peak force, peak velocity, peak power output, and jump height of both the vertical jump and jump squat tests.

The results of the testing demonstrated no significant differences among the groups in body weight or percent body fat. The sprinters were significantly taller than the OWL and PL groups. The control group was significantly taller than the OWL group. One repetition maximum squat strength was significantly different between the groups. The OWL group demonstrated a maximal squat of 243.9 kg compared to 225.5 kg of the PL group, 204.3 kg of the sprinter group, and 161.3 kg of the control group. The differences in squat strength between the OWL and PL groups were statistically non-significant. However, the OWL group was significantly higher in squat strength than the sprinter group. The OWL, PL, and sprinter groups were significantly higher in squat strength than the control group. Peak force in the vertical jump was significantly higher in the OWL and sprinter groups compared to the control group for all three load
conditions. The PL group was significantly higher in peak force for the 20 and 40-kg load conditions compared to the control group. A significant difference in peak force between the OWL and PL groups for the body weight load condition was demonstrated. The OWL group demonstrated significantly higher peak force compared to the PL and sprinter groups for the 20 and 40-kg load conditions. Peak velocity was significantly higher for the OWL and sprinter groups than the PL and control groups for all load conditions. The PL group was higher than the control group in peak velocity in the 40-kg load condition only. Peak power was significantly higher in the OWL, PL, and sprinter groups for all load conditions compared to the control group. The OWL group was significantly higher in peak power for all load conditions compared to the PL group. Peak power was significantly higher in the OWL group compared to the sprinter group in the 20-kg load condition. Jump height was significantly higher in the OWL and sprinter groups for all three load conditions compared to the PL and control groups. The PL group was significantly higher in jump height in the 20 and 40-kg load conditions compared to the control group.

Peak force in the jump squat was higher for all three load conditions in the OWL, PL, and sprinter groups compared to the controls. Peak force was significantly higher in the OWL group compared to the PL group in the 30 and 60% load conditions. Peak force was also higher in the 60 and 90% load conditions in the OWL group compared to the sprinter group. No statistically significant differences in peak velocity were demonstrated between any of the groups for any load conditions. The OWL group demonstrated the highest peak power in the 30% load condition compared to the PL, sprinter, and control groups. Jump height was significantly higher in the sprint group in
the 30% load condition compared to all the other groups. In the 60% load condition, jump height of the OWL, sprinters, and control groups were significantly higher than the PL group. At 90%, the jump height of the sprinter group was significantly higher than the OWL and PL groups. Jump height at 90% load condition was significantly higher in the control group compared to the PL group.

McBride, Triplett-McBride, Davie, and Newton (1999) concluded that differences exist in strength, power, and physical performance measurements between OWL, PL, sprinters, and moderately active controls. The poor performances of the PL group in tests of power and explosive performance compared to the OWL and sprinter group was not surprising. The authors reasoned that the high force, low velocity training of the PL group does not produce significant gains in power. The PL group performed significantly lower than the control group in the jump squat at the 90% load condition. This suggests that initiating a high force, low velocity exercise in an explosive manner is not a sufficient stimulus for improvements in muscle power, movement velocity, or jump height. The lack of significant difference between the PL and sprinter group in the 1RM Smith machine squat was surprising to the authors. It was suggested that the PL group may have been disadvantaged using the Smith machine rather than a free weight barbell squat to test 1RM leg strength. Significantly higher peak velocities, power outputs, and jump heights by the OWL group compared to the PL group led the authors to conclude that OWL are both forceful and powerful. It was suggested that training specificity of the OWL group (high force, high velocity) was responsible for the differences among the two groups. The OWL group produced significantly higher peak forces than the sprinter group during jumping movements. However, the higher jumping heights of the sprinter
group compared to the OWL group were similar to the results of other studies comparing jumping performances of the two groups. The higher jumping heights of the sprinter group, in spite of the significantly lower peak force measurements when compared to the OWL group, led McBride et al. (1999) to conclude that the OWL group was able to utilize maximal strength at high velocities and thus produce the highest power outputs. Sprinters, however, use low force, high velocity training (sprinting and plyometric training). This results in the ability of sprinters to generate high velocities and jump heights but does not allow the use of high levels of strength and high velocities simultaneously. The authors concluded that various divisions in power exist as demonstrated by the performances of the various groups. Resistance training should be adapted to meet specific demands of high force, low velocity (strength); high force, high velocity (strength, power); or low force, high velocity (performance, power).

McBride et al. (1999) demonstrated that OWL and PL had similar levels of strength in the 1RM squat exercise. The use of a Smith machine rather than a barbell to test 1RM leg strength could have influenced the performance of the PL group. The authors acknowledged this. The more upright position and restriction of forward lean, in the Smith machine squat, inhibits greater use of the lower back, gluteus, and hamstring muscles. Joint angles of the hip and knee in this position are similar to the type of squat technique that OWL and BB perform in training (Figure 3).

**Muscle Architecture Changes and the Affect on Strength**

Another factor that might influence muscular strength is muscle architecture. Maughan, Watson, and Weir (1984) suggested that the internal architecture of the quadriceps muscle group affects maximum isometric force production. As mentioned
Figure 3  Comparison of Different Squat Techniques

High-Bar Squat Used by Olympic Weightlifters and Bodybuilders

Low-Bar Squat Used by Powerlifters

earlier in this chapter, the conclusions of a study by Narici et al. (1989) led its authors to suspect that part of the disproportionate increases in maximal voluntary contraction compared to cross-sectional area was due to possible changes in muscle architecture.

Forty-three male subjects participated in the study by Maughan et al. (1984). The control group consisted of 35 subjects who were not engaged in any exercise training program. The strength trained group consisted of 8 highly trained individuals. The strength trained group had engaged in strenuous weight training three times per week for at least two years. The training experience of the group ranged between 2-12 years. None of the strength-trained group participated in competitive weightlifting events. All the test subjects were between the ages of 22-34 years.

Height, weight, percent body fat, and lean body mass were measured in all the test subjects. Skinfold thickness measurements were used to calculate percent body fat (Durnin and Ramahan, 1967) and lean body mass. Maximal voluntary isometric force of the knee extensor muscles was measured using an apparatus described by Maughan et al. (1983) previously reviewed in this chapter. Isometric force was measured separately for each leg. All the test subjects were allowed three attempts to produce a maximum contraction. Further attempts were allowed if significant differences between the two best efforts existed after three contractions. Only the measurements of the stronger leg were used to calculate strength values. Computed tomography was used to measure cross-sectional area of the rectus femoris, vastus lateralis, vastus intermedius, and vastus medialis.

The results demonstrated no significant difference between the trained group and control group for age, height, or body fat. The trained group was heavier and had a
greater lean body mass than the control group. The right leg was stronger than the left leg in 5 of the 8 trained subjects and 26 of the 35 controls. Strength differences between the legs were small with the exception of four test subjects. Three of these subjects had previous or current injuries that influenced the ability to generate high forces, with a particular limb, during the testing. Another test subject had a left leg significantly weaker than the right leg. This difference could not be accounted for through an examination of the subject’s history. The mean difference in strength between the stronger and weaker legs was 9.4% in the untrained group and 10% in the trained group with the exception of the four subjects previously described. Cross-sectional area differences between the weaker and stronger legs were 2.8% in the control group and 4.8% in the trained group. Knee extensor strength in the trained group was greater than the control group. The mean maximal isometric force for the trained group was 992 Newtons compared to 742 Newtons of the controls. The ratio of strength to body weight and strength to lean body mass was greater in the trained group compared to the untrained group. A significant relationship was shown to exist between muscle strength and lean body mass in both groups. A significantly greater cross-sectional area of the knee extensor muscles was observed in the trained group of 104.1 cm² compared to 81.6 cm² of the controls. In both groups, the weaker leg had a significantly smaller cross-sectional area than the stronger leg. The mean ratio of strength to cross-sectional area in the trained group was 9.53 compared to 9.20 in the control group. This ratio was not statistically different between the two groups. Muscle strength in the untrained subjects was significantly correlated with muscle cross-sectional area.
Maughan et al. (1984) concluded that as the cross-sectional area of muscle increases, the ratio of strength to cross-sectional area has a tendency to decrease. The control group demonstrated this inverse relationship in the study. The ratio of strength to cross-sectional area was not significantly different between the trained and the untrained groups. The authors suggested that the internal architecture of the four knee extensor muscles was responsible for the decrease in the ratio of strength to cross-sectional area. Three of the vasti muscles are uni-pennate and the rectus femoris is bi-pennate. The forces developed, in the individual fibers of these muscles, act at an angle to the long axis of the muscle. Increases in the angle of pennation (as is the case in hypertrophied pennate muscle) would produce a smaller force in the tendon in response to a given level of force produced by the muscle (Figure 4). Maximal isometric strength and cross-sectional area was greater in the trained group compared to the untrained group. The authors suggested that it would be logical to assume that the strength-trained subjects would have lower levels of strength per unit of cross-sectional area than the untrained control group. This led the authors of the study to speculate that the strength-trained subjects were able to somehow compensate for the decrease in strength to cross-sectional area ratio. An increased neural drive and an increased density of contractile proteins in the muscles were suggested as possible explanations for the greater strength demonstrated by the trained group.

An increase in the density of contractile proteins, as a plausible explanation of compensatory strength in hypertrophied muscles, was not supported by MacDougall et al. (1982). Myofibrillar protein densities were lower in BB than a resistance trained control group.
A study by Kawakami, Abe, and Fukunaga (1993) suggested muscle hypertrophy accompanied an increase in muscle fiber pennation angles. Thirty-two male test subjects between the ages of 18-28 years old volunteered for the study. The subjects included untrained university students, moderately active subjects, and highly trained BB. Upper arm circumferences of the subjects ranged from 24.8 cm to 40.5 cm. Muscle thickness and muscle fiber pennation angels of the triceps brachii were measured in vivo using an ultrasonogram. Muscle thickness measurements have been shown to correlate highly with muscle cross-sectional area (Martinson and Stokes, 1991) and were used to represent muscle size in the study. The test subjects stood with the arms relaxed in the extended position. Starting at the lateral epicondyle of the humerus, muscle thickness was measured in a cross-sectional plane at a site 40% of the distance from the lateral epicondyle to the acromion process of the scapula. The long and medial heads of the triceps brachii were included in the measurement. The distance from the adipose tissue-muscle interface to the muscle-bone interface represented muscle thickness. Muscle fiber pennation angles were measured at the same site as the muscle thickness measurements only this time parallel to the long head of the triceps. The test subject extended the elbow to allow the tester to visually confirm the muscle belly of the long head. The angles between the echoes of the aponeurosis and echoes from the interspaces among the fascicles were measured and represented pennation angles. Eleven of the 32 subjects were randomly selected and tested twice for measurement reproducibility. To validate muscle thickness and pennation angles, ultrasound measurements were performed on the triceps of three cadavers. Manual measurements were also performed
Figure 4  Pennation Angle Differences in Hypertrophied and Non-Hypertrophied Muscle Fiber

Untrained Uni-Pennate Muscle Fibers

Trained Uni-Pennate Muscle Fibers

by dissection of the cadavers' triceps. Two persons testing blindly performed both of
these measurements. Upper arm circumferences were also measured in all 32-test
subjects.

The results of the study demonstrated the test subjects' arm circumferences
ranged from 28.4 to 40.5 cm. In vivo measurements of muscle thickness of the 32 test
subjects ranged from 28-61 mm. In vivo measurements of pennation angles ranged from
15-53° for the long head and 9-26° for the medial head. No significant difference in
muscle thickness or pennation angle measurements existed between the measurements of
the 11 randomly selected subjects for re-testing and the first measurement values.
Significant relationships existed between muscle thickness and upper arm mass and
between muscle thickness and body mass. Muscle thickness in the human cadavers
ranged from 12-21 mm and pennation angles from 9-16°. The pennation angles of the
long head of the triceps in cadavers were similar to the 32 test subjects. Ultrasonic
measurements differed from manual measurements by 0-1 mm for muscle thickness and
0-1° for pennation angles. Muscle fiber thickness and pennation angles were greater in
BB when compared to the other test subjects. A muscle thickness of 46 mm and
pennation angles of 33° (long head) and 19° (medial head) in the BB compared to a
muscle thickness of 26 mm and pennation angles of 15° (long head) and 11° (medial
head) in the other test subjects were statistically significant. Similar results were
demonstrated when muscle thickness was normalized for upper arm length. In BB, the
fascicles were arranged curvilinearly whereas in the most other subjects the fascicles
were arranged linearly. This tendency was observed, especially in the long head, where
muscle fiber pennation angles were steeper where the fascicles attached to the aponeurosis.

Kawakami et al. (1993) concluded that muscle thickness measurements could be used to estimate muscle size and the degree of muscle hypertrophy. Ultrasonography can be used to measure muscle thickness and pennation angles with measurement errors of <1 mm and <1°. The authors suggested that muscle hypertrophy in the triceps brachii of BB involves an increase in fiber pennation angles. This was demonstrated in the curvilinear arrangements of hypertrophied muscle fibers of BB arising from the aponeurosis at steeper angles. Greater pennation angles would result in more contractile material attached to a larger area of the tendon. It was speculated that this would not significantly increase anatomical cross-sectional area. This would make the relationship between cross-sectional area and muscle force different from the relationship in muscles with linear pennation. Kawakami et al. (1993) suggested that this might explain the differences between cross-sectional area and strength per unit cross-sectional area demonstrated by Maughan et al. (1984).

A more recent study by Kawakami, Abe, Kuno, and Fukunaga (1995) examined the effects of a resistance-training program on muscle architecture. Five physically active male subjects accustomed to weight training volunteered for the study. All of the test subjects were right handed and were between the ages of 25-32 years.

The subjects participated in a 16-week resistance training program of the elbow extensor muscles. The training was unilateral with the left arm being trained three days each week. The untrained right arm served as the control. Five sets of eight repetitions were performed at 80% of the subjects’ 1RM in the French Press exercise. Execution of
the exercise was performed while standing. The forearm was moved upward then
downward, concentrically and eccentrically, with a dumbbell held in the left hand. The
left upper arm was held upright, in a static position, to minimize shoulder movement.

Prior to training, a 1RM was established. Every two weeks another measurement of 1RM
was performed to adjust the training load. Muscle thickness and pennation angles of the
triceps brachii was measured using the same technique described previously in this
chapter by Kawakami et al. (1993). Anatomical cross-sectional area was measured by
magnetic resonance imaging before and after training. The cross-sectional images of the
triceps brachii were outlined, traced, and then digitized on a computer. Muscle volume
and physiological cross-sectional area was then determined. Physiological cross-
sectional area was described as the total cross-sectional area of all the muscle fibers at
right angles to their long axes. Maximal voluntary isometric, concentric and eccentric
strength of the elbow flexors were measured before and after training using an isokinetic
dynamometer. In order to isolate the targeted muscles, the subject performed the testing
seated on an adjustable chair with support for the back, elbow, shoulders, and hips.
Elbow extensions were performed with the arm supported in the horizontal plane on a
padded table. The order of the measurements was randomized and one-minute recovery
was allowed between trials. The best of two to three trials was used as the maximal value
of isometric torque. Concentric and eccentric torque was measured at velocities of 30,
90, and 180°·s⁻¹. All torque was recorded on a strip recorder. Determination of specific
tension was achieved by dividing torque output by the moment arm of the triceps brachii
muscles. Corrections for differences in forearm length and the force acting on the tendon
were estimated. The tendon force was then divided by the physiological cross-sectional area to determine specific tension.

The results of the study showed cross-sectional area of the trained arm increased significantly in the middle portion of the muscle, but remained unchanged near the proximal and distal ends. No significant changes in cross-sectional area were observed in the control arm. A significant relationship existed between muscle thickness and fiber pennation angles. Muscle thickness and pennation angles increased significantly after training in the trained arm. No differences of statistical significance were observed in the control arm. Muscle volume and physiological cross-sectional area increased significantly in the trained arm with no differences observed in the right arm. Increases in isometric and isokinetic torque of the elbow extensors significantly increased in the trained arm at all velocities. Significant changes in trained arm in relative strength of 16% isometrically, 20-32% concentrically, and 15-16% eccentrically were observed. There was not a significant relationship between relative changes in torque and cross-sectional area, muscle volume, or physiological cross-sectional area. No significant changes occurred in specific tension in the control arm. Significant changes in the trained arm were observed especially in isometric and eccentric contraction.

Kawakami et al. (1995) concluded that muscle hypertrophy does not occur equally throughout the entire length of the muscle. This was evident by the increase in cross-sectional area in the middle portion of the muscle. A positive correlation between muscle thickness and fiber angles was in agreement with an earlier study (Kawakami et al., 1993). The authors concluded that the training program resulted in increases in the muscle thickness and fascicle angles of the triceps brachii. The results imply that muscle
hypertrophy, in pennate muscle, increases the angle of pennation. This change in muscle architecture increases physiological cross-sectional area resulting in more contractile material attached to the tendon. This may decrease efficiency of the muscle to transmit force to the tendon. This decrease in efficiency is due to the change in the line of pull of the muscle. The authors reasoned that the highly hypertrophied muscles of BB might have a negative effect on force production resulting in a lower force capacity than less hypertrophied muscles.

In pennate muscle, there is a disparity between the direction of the force generated by the muscle fibers and the tendon transmitting the force to the bones (Alexander and Vernon, 1975). It was suggested by Kawakami et al. (1995) that the force capabilities of hypertrophied muscles might be smaller than less hypertrophied muscles. Narici (1999) suggests that even small changes in the length of pennate muscle may result in a reduction in the amount of force the muscle can develop. These changes (hypertrophic) affect the length-tension relationship of the muscle fiber.

Summary

A comprehensive review of the literature suggests physiological, neurological, and architectural factors as well as the specificity of resistance training programs influence muscle strength and size. There is some disagreement among the studies on whether or not cross-sectional area is proportional to strength. The general consensus seems to be that cross-sectional area influences muscular strength, but it might be only one of many factors. The strength per unit cross-sectional area may be different in hypertrophied muscles than untrained muscles. The type of muscle hypertrophy is a factor in the force generation capabilities of muscle. Depending on the resistance training
protocol, increases in non-contractile proteins and semi-fluid plasma can cause increases in cross-sectional area without significant increases in strength. In contrast, certain training protocols increase contractile proteins and myofilament density and are associated with increases in muscular strength. Neurological factors such as an increased neural drive, a more synchronous firing of motor units, increased motor unit activity, and inhibitory mechanisms seem to precede muscular hypertrophy and are associated with gains in strength early in resistance training programs. Hypertrophy occurs after significant neurological adaptations over longer training periods of greater than 8-weeks. Muscle architecture also plays an important role in force development. The degree of pennation angles affects the amount of force generated and transmitted to the tendon. Hypertrophied muscles change pennation angles and may have a negative affect on muscle strength.

Studies comparing 1RM squat strength among OWL, PL, and BB demonstrate similar levels of absolute strength. However, it is difficult to draw real-world comparisons of strength among the groups because of the great variability in body weight among the test subjects and the use of different testing criteria and equipment in each study.
CHAPTER III

METHODS

The purpose of this study was to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite BB, PL, and OWL. Specifically, does the group with the greatest thigh size have the greatest 1RM squat strength?

Subjects

The subjects recruited for this study were competitive male Olympic weightlifters, powerlifters, and bodybuilders between the ages of 16 and 48 years. All subjects were currently involved in competition training in each of their respective disciplines. All three subject groups, Olympic weightlifters (OWL, n=5), powerlifters (PL, n=5), and bodybuilders (BB, n=5), had qualified or competed at the national level in an officially sanctioned competition within the past twelve months prior to participation in the study. All test subjects were required to have a body weight between 76-96 kilograms. A range of 20 kilograms body weight was chosen for the following reasons: it allowed BB, PL, and OWL to participate from different weight classes within each sport but at similar body weights and it controlled for variability in body weight among the subjects. The ranges of the weight classes for each particular sport, from which subjects were chosen, are as follows: BB 70.11-90 kg, PL 75-89.88 kg, and OWL 77-94 kg.

Prior to testing, subjects completed a comprehensive questionnaire including an informed consent (Appendix A), a competition training questionnaire (Appendix B), and a health history form (Appendix C) which included questions on past training injuries, orthopedic problems, surgeries, and cardiovascular health. Exclusion criteria for
participation in the testing included a history of hypertension, orthopedic injuries to the hip, knee, and low back, and chronic low back pain. Other exclusionary criteria included those individuals who indicated on the competition and training questionnaire that they did not use the barbell back squat exercise as part of their regular training. Subjects were chosen based upon being competitive at the national level in order to compare athletes who were equal in terms of the success each group had achieved in their specific sport. All subjects chosen for participation were informed of pre-test instructions. Subjects were informed as to the anthropometric procedures for measurements and the 1RM squat test, including equipment usage, warm-up, stance width, and squatting depth.

**Measurements**

Anthropometric measures were performed to assess body weight, body composition, shoulder width, proximal, distal, and mid-thigh circumference, and mid-thigh skinfold thickness. All of these measures were taken prior to the 1RM squat testing. Thigh circumference measurements of the proximal, distal, and mid-thigh were taken using the technique described by Lohman, Roche, and Martorell (1988). All measures were performed while the subject was standing. An OHJI (Japan) 150-cm fiberglass tape measure was used to take the measurements. Circumference sites were: immediately distal to the gluteal furrow (proximal thigh), midway between the midpoint of the inguinal crease and proximal border of the patella (mid-thigh), and proximal to the femoral epicondyles (distal thigh). Measurement sites were marked with a marking pencil. To help reduce investigator bias, the three different thigh circumference sites were measured in succession, then the cycle was repeated three times using the average of the scores at each site as the final measurement value. If one measure varied from the others
by more than 0.5 cm, an additional measure was taken and the outlier was omitted. Thigh circumference measurement values were recorded to the nearest 0.1 cm. Thigh circumference measurement error has been reported to be as little as ± 0.2 cm (Katch, and Katch, 1980) and ± 0.5 cm (Lohman et al., 1988).

Thigh skinfold thickness was measured at the same site as the mid-thigh circumference located at the midline of the anterior aspect of the thigh, midway between the inguinal crease and the proximal border of the patella. A SlimGuide skinfold caliper (Creative Health Products, Plymouth, Michigan) was used to measure skinfold thickness. Thigh skinfold thickness was taken using the technique described by Lohman et al., (1988). The subject's body weight was shifted to the leg opposite the side of measurement. The thickness of the vertical fold was measured with the subject's foot flat on the floor, the knee slightly flexed, and the leg relaxed. Three different non-successive measurements were taken with the average of the three measurements being used as the final measurement value. According to Katch and Katch (1980), test-retest reproducibility of skinfold scores is usually above \( r = 0.85 \) as long as the same site is not measured in succession. In order to achieve a high degree of reliability, thigh skinfold measurements were taken in between each successive cycle of thigh circumference measurements. Body weight (BW) was measured using a Health-O-Meter professional scale (Model 160, Big Foot 11) which was calibrated before each measurement session. Body composition was estimated by bioelectrical impedance (OMRON, HBF-301 Vernon Hills, IL). Percent body fat (% fat) estimates were used to calculate fat free mass (FFM) using the following equation where:

\[
\text{FFM} = \text{BW} - (\text{BW} \times \text{fractional \% body fat})
\]
Thigh muscle area (TMA) was estimated using the equation adapted from Lohman et al. (1988).

\[
TMA = \frac{[MTC - (\pi \times MTS)]^2}{4 \pi}
\]

where: \(MTC\) = mid-thigh circumference in cm; \(MTS\) = mid-thigh skinfold in cm

Squat Strength

The measurement of 1RM squat strength was performed using a standard 7-foot Olympic bar with standard metal Olympic weight plates and safety collars. Test subjects were allowed as much time as they needed to properly warm-up before performing a 1RM squat attempt. All squat testing was performed inside a power rack with the safety pins adjusted for the subjects' height and depth of squat. Self-selection in stance width and bar placement was allowed. However, the following criteria adopted from McBride, Triplett-McBride, Davie, and Newton (1999) were applied. An anthropometer was used to measure each subject's shoulder width. The measurement value was the distance between the lateral portion of the deltoids. This value was recorded and used to set the limits for the subject's widest possible squat stance. The widest allowable squat stance was 15 cm wider than the measurement value of the test subject's shoulder width. Subjects were permitted as narrow a stance as they desired. The squat stance limits were marked with masking tape on the floor where the 1RM squat testing was to be performed. Bar placement was required to be between the 7th cervical vertebra and the superior angle of the scapula. Squatting depth had to be parallel or lower which was described as the position in which “...the top surface of the legs at the hip joint are lower than the top of the knees” (U.S.A. Powerlifting, 1998, p.8). All subjects were required to squat into this position with an unloaded barbell to become familiar with the necessary squatting depth.
prior to 1RM testing. If the subject desired, an audible cue was given when the appropriate squatting depth was reached during 1RM testing. Subjects were allowed to squat lower than parallel if they chose. Any squat that did not meet the criteria for depth was disqualified. One repetition maximum squat strength values were used to calculate strength per unit TMA using the following equation:

\[
\frac{\text{1RM squat strength}}{\text{TMA}}
\]

The process for finding the 1RM starting weight was adapted from the procedures described by Fleck and Kraemer (1996). Loading percentages were based on each test subject’s estimated 1RM in the squat exercise as indicated on the competition and training questionnaire that the subject filled out prior to testing. A set of five to ten repetitions using 50% of the estimated 1RM was performed first. After two minutes rest, 70% of the estimated 1RM was performed for one repetition. One repetition at 90% of the estimated 1RM was then performed after two minutes of rest. After one more rest period of four minutes, 100% of the estimated 1RM was attempted. If the estimated 100% attempt failed, the lifter rested four to five minutes and took another attempt using 5% less weight. If that attempt failed, 90% of the estimated 1RM was used as the 1RM. If the estimated 100% attempt was successful and the test subject wished to continue, a mandatory rest period of four to five minutes was allotted. Another squat using 1-5% more weight was attempted. This process continued until the test subject performed a true 1RM squat or informed the tester that he wanted to terminate testing. The heaviest weight lifted was recorded as the final 1RM squat. The use of any artificial means of support such as supportive suits and knee wraps were forbidden during the test. However, to minimize the possibility of low back injury, test subjects were allowed to
use a weight belt if they desired. The width of the belt was standardized and could not exceed 4 inches.

All measurements were performed by the same investigator. The level of external motivation was controlled so that all subjects were tested under similar conditions, without encouragement or cheering, when lifting in the presence of their peers.

**Data Analysis**

Descriptive statistics (mean ± SD) for all variables within groups were calculated. Comparisons among the three groups for differences in the descriptive characteristics and dependent variables were performed using ANOVA with significant omnibus results followed up with Tukey's HSD post-hoc. To determine if a correlation existed between thigh muscle size and 1RM squat strength, Pearson Product Moment Correlations were performed. The criteria for statistical significance were set at an α level of 0.05.
The purpose of this study was to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite bodybuilders (BB), powerlifters (PL), and Olympic weightlifters (OWL). Specifically, does the group with the greatest thigh size have the greatest 1RM squat strength? Male BB, PL, and OWL were compared because few studies have examined the relationship between muscle hypertrophy and strength in elite resistance trained individuals. It was hypothesized that the BB group would have the greatest thigh size and lowest 1RM squat strength, while the OWL and PL groups would have the greatest 1RM squat strength but have a smaller thigh size than the BB group. Therefore, the PL and OWL groups would have greater 1RM squat strength per unit thigh muscle area (TMA). Descriptive statistics (mean ± SD) were calculated for all variables by group. Group means were compared using ANOVA with significant omnibus tests followed up with Tukey's HSD post-hoc. An α level of p<.05 was chosen for significance.

RESULTS

Descriptive Characteristics of Subjects

Fifteen males between the ages of 16-48 years participated in the study. The subjects were highly trained and considered to be elite athletes based upon the following criteria: having qualified or competed at the national level within the past twelve months prior to participation in the study. All subjects, with the exception of one subject in the PL group, competed in organizations that tested for anabolic steroids. Thirteen of the fifteen subjects had competed at the national level or higher. The BB group included two
professionals with one having competitive experience at the international level (Mr. Universe Competition). Another BB subject had placed first in his weight class at a national competition. Two subjects in the PL group placed first at national competitions and one of the PL subjects was the second ranked lifter nationally in his weight class. The OWL group included one subject with international experience (Jr. World Championships) who was currently ranked third nationally in his weight class. Two of the OWL subjects placed as high as second in national competitions.

Statistical analysis (ANOVA) revealed a significant difference in age between the BB (40.0 ± 7.31 years) and OWL (19.40 ± 2.96 years) groups (p=.00). A significant difference in age was also found between the PL (33.20 ± 6.37 years) and OWL groups (p=.00). Differences in age between the BB and PL groups were non-significant (p=.20). No differences in height (p=.30) or body weight (BW) (p=.67) were found among the groups (Table 1).

**Body Composition**

Percent body fat was measured by Bioelectrical Impedance Analysis. The inability to obtain valid data for one subject in the BB group resulted in the body composition analysis of only four of the five BB subjects. No significant differences in percent body fat were found among the groups (p=.13). Body fat values were 10.95 ± 2.49 %, 19.02 ± 6.57 %, and 14.86 ± 5.95 %, for BB, PL, and OWL respectively. Furthermore, there were no significant differences in thigh skinfold measures among the groups (p=.36). Statistical analysis revealed no significant differences in fat-free mass among the groups (p=.54). Table 2 shows the group means for body fat percentage, fat free mass (FFM), and mid-thigh skinfold (MTS) measurements.
Table 1  Descriptive Characteristics of Subjects for BB, PL, and OWL Groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>BB</th>
<th>PL</th>
<th>OWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>172.59 (3.60)</td>
<td>171.95 (3.76)</td>
<td>176.27 (5.84)</td>
</tr>
<tr>
<td>Range</td>
<td>32.0 - 48.0</td>
<td>27.0 - 43.0</td>
<td>16.0 - 24.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>83.63 (5.44)</td>
<td>87.86 (8.62)</td>
<td>85.72 (7.60)</td>
</tr>
<tr>
<td>Range</td>
<td>77.72 - 90.45</td>
<td>75.0 - 95.45</td>
<td>76.36 - 95.9</td>
</tr>
</tbody>
</table>
Table 2  Comparison of Body Composition Among BB, PL, and OWL

<table>
<thead>
<tr>
<th>Variable</th>
<th>BB</th>
<th>PL</th>
<th>OWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body fat (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>10.95 (2.49)</td>
<td>19.02 (6.57)</td>
<td>14.86 (5.95)</td>
</tr>
<tr>
<td>Range</td>
<td>8.0 - 14.0</td>
<td>10.0 - 27.0</td>
<td>10.0 - 22.0</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>72.92 (3.58)</td>
<td>70.73 (3.07)</td>
<td>72.66 (3.13)</td>
</tr>
<tr>
<td>Range</td>
<td>68.70 - 76.19</td>
<td>67.58 - 75.79</td>
<td>68.11 - 75.76</td>
</tr>
<tr>
<td>MTS (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>12.73 (4.42)</td>
<td>17.79 (6.26)</td>
<td>15.53 (5.24)</td>
</tr>
<tr>
<td>Range</td>
<td>8.0 - 19.66</td>
<td>7.30 - 23.0</td>
<td>9.33 - 22.0</td>
</tr>
</tbody>
</table>
Muscle Size

There were no significant differences among the groups for proximal (p=.85), distal (p=.60), and mid-thigh (p=.86) circumference measures (Table 3). Thigh muscle area (TMA) cm$^2$ was not significantly different (p=.44) among the BB (2518.53 ± 282.43), PL (2282.42 ± 148.58), and OWL (2440.95 ± 388.49) groups (Figure 5).

Muscle Strength

The PL (p=.01) and OWL (p=.02) groups had significantly greater 1RM squat strength than the BB group (Figure 6). No significant differences in squat strength were found between the PL and OWL groups (p=.91). Dynamic strength was calculated by dividing 1RM squat strength by BW (kg). Dynamic strength values were 1.92 ± 0.26 kg/kg BW, 2.37 ± .43, and 2.34 ± .27 for BB, PL, and OWL respectively of which no statistically significant differences were found among the groups (p=.09). However, when 1RM squat strength was divided by fat free mass (FFM), a significant difference existed between the BB (2.15 ± .32 kg/kg FFM) and PL (2.91 ± .34 kg/kg FFM) groups (p=.02). No significant difference among the BB group and OWL (2.76 ± .40 kg/kg FFM) group was found (p=.07) or between the PL and OWL groups (p=.79).

Strength per Unit TMA

One repetition maximum squat strength per unit TMA was significantly different between the BB group and the PL and OWL groups. The PL (.0904 ± .0099 kg/cm$^2$) (p=.003) and OWL (.0831 ± .0119 kg/cm$^2$) (p=.02) groups were significantly stronger per unit area than the BB group (.0636 ± .0062 kg/cm$^2$) (Figure 7). No significant difference (p=.48) between the PL and OWL groups were found.
Table 3  Comparison of Thigh Circumferences Among BB, PL, and OWL

<table>
<thead>
<tr>
<th>Variable</th>
<th>BB</th>
<th>PL</th>
<th>OWL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proximal thigh (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>62.55 (3.18)</td>
<td>63.44 (2.46)</td>
<td>63.77 (4.54)</td>
</tr>
<tr>
<td>Range</td>
<td>60.0 - 67.90</td>
<td>60.0 - 66.55</td>
<td>57.30 - 69.10</td>
</tr>
<tr>
<td>Distal thigh (cm)</td>
<td>Mean (± SD)</td>
<td>50.80 (4.97)</td>
<td>50.47 (2.91)</td>
</tr>
<tr>
<td>Range</td>
<td>42.40 - 55.06</td>
<td>48.0 - 54.65</td>
<td>44.56 - 54.20</td>
</tr>
<tr>
<td>Mid-thigh (cm)</td>
<td>Mean (± SD)</td>
<td>60.56 (3.44)</td>
<td>59.47 (1.82)</td>
</tr>
<tr>
<td>Range</td>
<td>57.16 - 65.80</td>
<td>57.35 - 61.36</td>
<td>54.73 - 66.55</td>
</tr>
</tbody>
</table>
Figure 5  Comparison of Thigh Muscle Area (cm²) Among BB, PL, and OWL

![Bar chart showing comparison of thigh muscle area among BB, PL, and OWL groups.]

- BB: 2518.53 cm²
- PL: 2262.42 cm²
- OWL: 2440.95 cm²
Figure 6 1RM Squat Strength Among BB, PL, and OWL

![Bar graph showing 1RM Squat Strength among groups BB, PL, and OWL. The graph indicates that the PL group has the highest 1RM strength at 205.45 kg, followed by BB at 159.99 kg and OWL at 200.18 kg.]
Figure 7 1RM Squat Strength per Unit TMA (cm²)
Correlation between Muscle Size and 1RM Squat Strength

Pearson Product Moment Correlations were calculated to determine if a correlation existed between measures of muscle size and measures of muscle strength. There were no significant correlations for any measure of thigh muscle size with any measure of strength (Table 4).

Summary

In summary, no significant differences were found among the groups for any measure of thigh muscle size including proximal, distal, and MTC measures. However, a significant difference in strength was found between the BB group and the PL and OWL groups. The PL and OWL groups were significantly stronger in 1RM squat strength than the BB group. A significant difference was found between the BB group and the PL group in 1RM squat strength/FFM. One repetition maximum squat strength per unit TMA was significantly greater in the PL and OWL groups compared to the BB group. No significant correlation existed between any measure of thigh muscle size and measures of 1RM squat strength in these elite resistance trained athletes.
Table 4  Pearson Product Moment Correlations and Significance \( r(p) \) Between Muscle Size and 1RM Squat Strength Among BB, PL, and OWL

<table>
<thead>
<tr>
<th>Variable</th>
<th>1RM</th>
<th>1RM/BW</th>
<th>1RM/FFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>.20 (.47)</td>
<td>- .12 (.66)</td>
<td>.21 (.45)</td>
</tr>
<tr>
<td>TMA</td>
<td>.06 (.81)</td>
<td>- .08 (.77)</td>
<td>.09 (.74)</td>
</tr>
</tbody>
</table>
DISCUSSION

Comparisons with the Literature

It appears that few studies have compared differences between elite BB, PL, and OWL. Katch et al. (1980) examined anthropometric differences among the groups. Fahey, Akka, and Rolph (1975) examined body composition and VO2 max differences. Hakkinen et al. (1986) compared performance capabilities in strength, power, and force-time parameters. The subjects in all three studies were considered elite and similar in ability to the subjects who participated in the present study.

Subjects in the present study are similar in height, weight, and body fat to subjects from studies by Katch et al. (1980) and Fahey et al. (1975). Mean body fat percentages of subjects in the present study were comparable to data from Hakkinen et al. (1986). Table 5 shows comparative data for age, height, weight, and body fat between subjects in the present study and those from samples in the literature. The mean ages for all three-subject groups in the present investigation were different from those of Katch et al. (1980) and Fahey et al. (1975). However, only 2 subjects were included in the BB group and 3 subjects in the PL group in the study by Fahey et al. (1975). In the present study all subjects in the BB group and 4 of the 5 subjects in the PL group competed in organizations that tested for anabolic steroids. Since most of the BB and PL subjects may have been steroid free and trained naturally, it may have taken a longer period of time to achieve the results necessary to compete at an elite level. The use of steroids by younger subjects among the other studies may explain the greater mean age of the BB and PL groups in the present study. Eleven percent of the BB group and forty six percent of the
Table 5  Comparative Data on BB, PL, and OWL mean (± SD)

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Body Fat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Present Study</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB</td>
<td>5</td>
<td>40.00 (7.31)</td>
<td>172.59 (3.60)</td>
<td>83.63 (5.44)</td>
<td>10.95 (2.49)</td>
</tr>
<tr>
<td>PL</td>
<td>5</td>
<td>33.20 (6.37)</td>
<td>171.95 (3.76)</td>
<td>87.86 (8.62)</td>
<td>19.02 (6.57)</td>
</tr>
<tr>
<td>OWL</td>
<td>5</td>
<td>19.40 (2.96)</td>
<td>176.27 (5.84)</td>
<td>85.72 (7.60)</td>
<td>14.86 (5.95)</td>
</tr>
<tr>
<td><strong>Hakkinen et al. 1986</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BB</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>13.40 (3.90)</td>
</tr>
<tr>
<td>PL</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>19.90 (5.40)</td>
</tr>
<tr>
<td>OWL</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>12.00 (4.50)</td>
</tr>
<tr>
<td><strong>Katch et al. 1980</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB</td>
<td>18</td>
<td>27.80 (1.80)</td>
<td>177.10 (1.10)</td>
<td>82.40 (1.00)</td>
<td>9.30 (0.75)</td>
</tr>
<tr>
<td>PL</td>
<td>13</td>
<td>24.80 (1.60)</td>
<td>173.50 (2.80)</td>
<td>80.80 (3.20)</td>
<td>9.10 (1.20)</td>
</tr>
<tr>
<td>OWL</td>
<td>8</td>
<td>25.30 (1.80)</td>
<td>173.90 (1.80)</td>
<td>76.50 (3.70)</td>
<td>10.80 (0.85)</td>
</tr>
<tr>
<td><strong>Fahey et al. 1975</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB</td>
<td>2</td>
<td>29.00 (7.10)</td>
<td>172.40 (3.10)</td>
<td>83.10 (6.20)</td>
<td>8.40 (3.90)</td>
</tr>
<tr>
<td>PL</td>
<td>3</td>
<td>26.30 (4.20)</td>
<td>176.10 (2.90)</td>
<td>92.00 (9.20)</td>
<td>15.60 (3.00)</td>
</tr>
<tr>
<td>OWL</td>
<td>11</td>
<td>25.30 (4.60)</td>
<td>177.10 (6.70)</td>
<td>88.20 (12.10)</td>
<td>12.20 (3.80)</td>
</tr>
</tbody>
</table>
PL group reported anabolic steroid use in the study by Katch et al. (1980). It was unclear if the subjects in the study by Fahey et al. (1975) used anabolic steroids.

Results from the present study show the OWL group was significantly younger (19.40 ± 2.96 years) than the BB group (40.0 ± 7.31 years). A former weightlifting coach of the year, international team coach, and United States Weightlifting board of directors member states, "Success in the sport of Olympic weightlifting is dependent largely upon speed, technique, and flexibility, more so than powerlifting. Absolute strength can increase with age up into the 30's and 40's, but speed and flexibility diminishes as people age" (M. Schnorf, personal communication 2003). This may explain why the OWL group was younger than the other two groups.

It was hypothesized that the BB group would have the greatest thigh size since BB specifically train for the purpose of increasing muscle size. However, the results revealed no statistically significant differences in proximal, distal, MTC measures among the groups. These results concur with the findings of Katch et al. (1980) who found MTC measures were 59.60 ± 0.47 cm, 60.70 ± 1.20, and 59.40 ± 1.60, for BB, PL, and OWL respectively. Comparative data on MTC measures are shown in Table 6. The present study found no significant differences in TMA among the groups. It is possible that the limited number of subjects in the present study was not a large enough sample to adequately represent the populations and test the hypotheses. However, the subjects used in the present study are not markedly different from the subjects of other studies using a greater number of BB, PL, and OWL as test subjects (Table 5 and 6). Therefore, it is speculated that there might be an upper limit in the capacity for thigh muscle hypertrophy in highly trained BB, PL, and OWL of similar BW regardless of the different training
Table 6  Comparative Data on Mid-Thigh Circumference Measure of BB, PL, and OWL mean (±SD)

<table>
<thead>
<tr>
<th>Study</th>
<th>BB</th>
<th>PL</th>
<th>OWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Study</td>
<td>60.56 (3.44)</td>
<td>59.47 (1.82)</td>
<td>60.48 (4.84)</td>
</tr>
<tr>
<td>Katch et al. (1980)</td>
<td>59.60 (0.47)</td>
<td>60.70 (1.20)</td>
<td>59.40 (1.60)</td>
</tr>
</tbody>
</table>
protocols used by each group. Katch et al. (1980) found proportional differences between the three groups are slight and concluded that anthropometric differences between BB, PL, and OWL occurred only for the shoulders, chest, forearms, and bicep girths.

Results from the present study show the PL (205.45 ± 17.27 kg) and OWL (200.18 ± 25.16 kg) groups had significantly greater 1RM squats than the BB (159.99 ± 16.82 kg) group. These results differ from the findings of Hakkinen et al. (1986) who found no statistically significant differences in 1RM squat strength among BB (183.0 ± 23.60 kg), PL (207.50 ± 34.30 kg), and OWL (186.40 ± 42.50 kg). A plausible explanation for this is the greater range in BW in the subjects of the study by Hakkinen et al. (1986). The range in BW among the subjects involved in the present study was 76 - 96 kg. The range in BW, among the subjects in the study by Hakkinen et al. (1986), was 56 - 100 kg. Comparing subjects with a greater range in BW, like the groups in the study by Hakkinen et al. (1986), may be less likely to demonstrate statistical difference in 1RM squat strength among BB, PL, and OWL. However, the value for 1RM squat strength among the groups may not represent other BB, PL, and OWL athletes.

McBride et al. (1999) compared 1RM squat strength among PL, OWL, sprinters, and a control group. Body weight values were 85.3 ± 9.5 kg and 78.2 ± 3.7 kg for OWL and PL respectively and similar to the subjects in the present study and to those in Hakkinen et al. (1986). No significant difference in 1RM squat strength was found among the OWL (243.90 ± 12.8 kg) and PL (225.50 ± 10.8 kg) groups. This agreed with the findings of the present study and the study by Hakkinen et al. (1986) where, in absolute terms, the PL group was the strongest as demonstrated by the largest 1RM squat
values. This was not the case in the study by McBride et al. (1999), which used a Smith machine to measure 1RM squat strength. The present study and the study by Hakkinen et al. (1986) used a barbell to test 1RM squat strength. McBride et al. (1999) acknowledged that the use of a Smith machine, rather than a barbell, could have influenced the performance of the PL group. The more upright position and restriction of forward lean, in the Smith machine squat, inhibit greater use of the lower back, gluteal, and hamstring muscles. Joint angles at the hip and knee in this position are similar to the type of squat technique that OWL perform in training (Wretenberg, Feng, and Arborelius, 1996). The use of a Smith machine might have improved the performance of the OWL group, although, no statistically significant difference between the groups were found. The present study adopted the stance width and bar placement criteria used by McBride et al. (1999). It was unclear if any criteria for stance width and bar placement was used by Hakkinen et al. (1986). Figure 8 compares data from the present study with the only other published data comparing 1RM squat strength between BB, PL, and OWL. Variables other than the actual strength of the subjects were more tightly controlled in the present study than in previous investigations (e.g. use of a barbell, stance width and bar placement criteria, lower variability in body weight, and highly elite test subjects).

The results of the present study show that the strength per unit TMA was significantly greater in the PL and OWL groups when compared to the BB group. Greater 1RM squat strength demonstrated by the PL and OWL groups with no significant difference in TMA among the groups may explain the difference in strength per unit TMA. Maughan et al. (1984) found the strength per unit cross-sectional area in the quadriceps of a trained group was not significantly different than an untrained group.
Figure 8  Mean 1RM Squat Strength Differences Among BB, PL, and OWL in the Literature Compared to the Present Study

![Bar chart showing 1RM Squat Strength for BB, PL, and OWL in the Literature Compared to the Present Study]
The trained subjects had a significantly greater cross-sectional area (p<.001) and demonstrated significantly greater (p<.001) strength than the untrained group. Maughan et al. (1984) concluded that an inverse relationship existed between the ratio of strength per unit cross-sectional area when comparing highly trained and untrained groups. The results of the present study suggest that the ratio of strength per unit cross-sectional area may be different when making comparisons among highly trained groups.

Specificity of Training

In the present study, the results of squat strength testing showed that the PL and OWL groups were stronger than the BB group. However, there was no significant difference in muscle size among the groups. It is well known that PL and OWL train for the purpose of gaining strength to lift the heaviest possible weight in specific events (Katch et al., 1980). Bodybuilders train to increase the size of muscle but are not concerned with functional strength improvements (Maughan et al., 1984). The three groups utilize different weight training protocols based on the specificity of training required for each sport. Two of the major differences between the training protocols of BB and those of PL and OWL are: 1) the intensity (% of 1RM used for each training set) and 2) the volume (number of sets and repetitions). Different levels of intensity and volume produce different functional adaptations in skeletal muscle. This was demonstrated by differences in 1RM squat strength among groups utilizing low, moderate, and high repetition weight training (Weiss, Coney, and Clark, 1999). It may be that in elite BB, PL, and OWL, the type of training has a greater influence on strength than it does on the absolute size of a muscle.
Neural Adaptations

It has been shown that hypertrophy is not solely responsible for increases in muscle strength among individuals who are not highly trained (Narici et al., 1989). Neurological adaptations precede hypertrophic adaptations early in resistance training programs and are responsible for initial strength gains by untrained and lessor-trained subjects (Lesmes et al., 1978; Sale 1988). It is obvious that initial neurological adaptations had occurred in the highly trained BB, PL, and OWL involved in the present study. This was demonstrated by the hypertrophied thighs, which were similar in all groups. The conclusion by MacDougal et al. (1982), that PL and BB have similar hypertrophic adaptations, suggest that other factors may be responsible for strength differences among the groups in the present study. In highly trained individuals, there might be a limited contribution of hypertrophic factors to muscle strength. In the elite, chronically trained athletes, further increases in strength may come from additional neural adaptations. This may explain why mid-thigh muscle size does not correlate with 1RM squat strength among subjects in the present study, while other studies have found a positive correlation between muscle cross-sectional area and strength using untrained and lessor-trained subjects (Ikai and Funkunaga, 1968; Maughan et al., 1984). Muscle size correlates with strength across the continuum of training level (i.e. untrained, beginners, recreationally trained, and lessor-trained individuals) but within a group of highly trained individuals other factors may be involved which could weaken the muscle size to strength correlation.

Improvements in neuromuscular efficiency, such as an increased nerve (motor neuron) discharge to the acting muscles (Ikai and Funkunaga, 1970) and a higher capacity
for maximal voluntary activation of the working motor units (Hakkinen et al., 1986) have been suggested as adaptations that occur to a greater degree in PL and OWL. These neural adaptations may be more pronounced due to the heavier loading schemes used by both PL and OWL, as part of their training protocols, and the explosive lifting done by OWL. According to O'Shea (1995), high intensity strength training protocols 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 fiber summation. O'Shea (1995) suggests that these adaptations enhance neuromuscular efficiency, optimizing the expression of strength and power. Only "athletic type strength training" elicits these highly specific adaptations (O'Shea, 1995). Athletic type strength training includes the performance of highly technical and complex exercises such as the snatch, clean and jerk, various squat exercises, deadlifts, and pressing movements. These exercises performed at high intensity levels, are characteristic of the type of training performed by PL and OWL. The performance of explosive movements like snatches and clean and jerks are rarely, if ever, performed by BB. Furthermore, BB use lower resistance than PL when performing pressing exercises and deadlifts. This is done in an attempt to increase the volume of work to stimulate muscle mass. Bodybuilders also include many single joint exercises that are less technical and stimulate smaller muscle groups, to develop muscle proportionally over the entire body. If these adaptations in the nervous system occur, as O'Shea suggests, it provides a plausible explanation for the difference in squat strength between the BB group and the PL and OWL groups. It seems probable that various
hypertrophic and neural factors contribute to the difference in strength among the highly trained BB, PL, and OWL in the present study.

**Selective Fiber Hypertrophy**

Higher volume/lower intensity training protocols used by BB might cause selective hypertrophy of slow twitch muscle fibers (Conroy and Earle, 1994). This corresponding hypertrophy may not contribute as much to high levels of strength. O'Shea (1995) has demonstrated by EMG analysis of the squat exercise, that fast twitch fiber recruitment is greatest with intensities of 90-100% of 1RM. Powerlifters and OWL typically use these high intensity levels as part of their regular training in an effort to gain strength. Selective hypertrophy of fast twitch fibers may occur in PL and OWL with little hypertrophy of slow twitch fibers (MacDougal, 1993). The difference in absolute thigh muscle size between the BB group, who may have primarily slow twitch fiber hypertrophy, and the PL and OWL groups with predominately fast twitch fiber hypertrophy might be negligible. This may explain why the PL and OWL groups were stronger than the BB group without any significant difference in thigh muscle size.

**Types of Muscle Hypertrophy**

Zatsiorsky (1995) suggests that BB training programs cause an increase in non-contractile proteins and sarcoplasm (sarcoplasmic hypertrophy). This produces an increase in muscle size but without a significant increase in strength. Zatsiorsky (1995) also suggests that the type of training performed by OWL causes an increase in contractile proteins and the number of myofibrils (myofibrillar hypertrophy) producing an increase in muscle size and strength. This may explain the difference in strength, without a significant difference in thigh size, between the BB group and the OWL group.
demonstrated in the present study. Cross-sectional myofilamental area, not the absolute cross-sectional area, would be a more accurate for calculating a muscles contractile strength (Helander, 1961). It should be noted that Zatsiorsky (1995) makes no mention if myofibrillar hypertrophy occurs in PL.

MacDougall et al. (1982) concluded that an increase in sarcoplasmic volume density and a parallel decrease in myofibrillar volume density occur in elite BB and PL. The methods used by MacDougall et al. (1982) included the analysis of muscle biopsies taken from each of the subjects. However, only two PL participated in the study and were included in the same test group as five BB. The conclusions were drawn from the results of the biopsies of the group as a whole (n=7). These results might reflect the physiological adaptations typical in BB but not PL. Furthermore, it was unclear if the two PL subjects had a decrease in myofibrillar volume compared to the BB in the group. A decrease in myofibrillar volume would have a negative effect on the muscle cell's ability to produce force. This would be a disadvantage to PL who train specifically to increase strength. If PL and BB have similar increases in non-contractile proteins, then it would be logical to conclude that the ensuing hypertrophy (sarcoplasmic hypertrophy) would be similar in BB and PL. This would be a possible explanation for the lack of differences in thigh size among the BB and PL groups in the present study. However, this does not explain the significant difference in squat strength between the two groups. In fact, the PL group had the greatest absolute 1RM squat strength of all three groups in the present study. If a decrease in myofibrillar volume does occur in PL, then factors other than hypertrophy might be responsible for the greater 1RM squat strength demonstrated by PL group.
Architectural Changes

Architectural changes in the hypertrophied muscles of the BB may explain the lower 1RM squat strength of the BB group. It has been demonstrated that muscle hypertrophy, in pennate muscle of BB, increases the angle of pennation (Kawakami et al., 1983). This may decrease the efficiency of the muscle to transmit force to the tendon in response to a given level of force produced by the muscle (Maughan et al., 1984; Kawakami et al., 1993). The decrease in efficiency is due to the change in line of pull of the muscle (Figure 4). It is unclear whether the hypertrophy demonstrated by PL and OWL has a similar or opposite effect on muscle fiber angle. The significant differences in squat strength among the groups in the present study imply that the hypertrophy demonstrated by PL and OWL does not negatively affect strength. It may be that the lower level of strength in the BB group occurs as a result of pennation angle changes due to increases in sarcoplasm. The PL and OWL groups may compensate for any changes in pennation angle with increases in the amount of contractile material and neural factors due to training.

Relative Strength per Kilogram FFM

One repetition maximum squat strength, when divided by FFM, was significantly different between the BB group and the PL group in the present study. Even though statistically there was no difference between the groups in percent body fat, the BB group had the lowest absolute body fat percentage and the PL group had the highest absolute body fat percentage. The PL group demonstrated significantly greater 1RM squat strength than the BB group. The PL group was also, in absolute terms, the strongest group in the present study. The significantly greater 1RM squat strength and the
difference in absolute body fat percentage, when compared to the BB group, might explain the significant difference in 1RM/FFM.

In summary, it appears that factors other than muscle size play a role in strength among different groups of elite resistance trained athletes. Specific training protocols may elicit different adaptations that increase muscle size but with different strength outcomes. Differences in strength may be due to neural factors, selective fiber hypertrophy, the type of muscle hypertrophy, and architectural changes in muscle.
CHAPTER V

SUMMARY AND CONCLUSIONS

This study was conducted to determine if a significant difference exists in the relationship between measures of muscle size and strength among elite BB, PL, and OWL. Specifically, does the group with the greatest thigh size have the greatest 1RM squat strength?

It was hypothesized that the BB group would have the greatest thigh size and the lowest 1RM squat strength, while the OWL and PL groups would have the greatest 1RM squat strength but have a smaller thigh size than the BB group. Therefore, the PL and OWL groups would have greater 1RM squat strength per unit TMA. It was further believed that the relationship between muscle hypertrophy and strength might be different when highly trained groups were compared with each other rather than with untrained or lessor-trained groups.

Fifteen elite male BB, PL, and OWL (n=5 for each group) between the ages of 16-48 years were recruited for this study. All test subjects weighed between 76-96 kg. Anthropometric measures including body weight, body composition, shoulder width, thigh circumference, and thigh skinfold thickness were performed for all three subject groups. One repetition maximum squat strength was also measured and compared to measures of thigh size. All measurements were performed by the same investigator. Comparisons among the groups were performed using ANOVA with significance omnibus results followed by Tukey's HSD post-hoc. Pearson Product Moment Correlations were performed to determine if a relationship existed between measures of thigh muscle size and 1RM squat strength.
Summary of Findings

1. The mean age of the groups were 40.0 ± 7.31, 33.2 ± 6.37, and 19.4 ± 2.96 years for BB, PL, and OWL respectively. The physical characteristics of the subjects in this study, with the exception of age, compare favorably with those from similar populations in the literature. The mean age of the BB and PL groups was older than those reported in the literature. The mean age of the OWL group was younger than those reported in the literature.

2. There was no significant difference in TMA (p=.44) or for any measure of thigh size among the BB, PL, and OWL groups.

3. The PL (p=.01) and OWL (p=.02) groups had significantly greater 1RM squats than the BB group. The mean squat values of the groups were 205.45 ± 17.27 kg, 200.18 ± 25.16 kg, and 159.99 ± 16.82 kg for PL, OWL and BB respectively.

4. A significant difference (p=.02) existed between the BB (2.15 ± .32 kg/kg FFM) and PL (2.91 ± .34 kg/kg FFM) groups when 1RM squat strength was divided by FFM. The PL group had greater strength per kg FFM than the BB group. No significant difference was found between the OWL and BB groups or between the PL and OWL groups.

5. One repetition squat strength per unit TMA was significantly greater in the PL (p=.003) and OWL (p=.02) groups when compared with the BB group. The mean values of the groups were .0904 ± .0099 kg/cm², .0831 ± .0119 kg/cm², and .0636 ± .0062 kg/cm² for PL, OWL and BB respectively. No significant difference was found between the PL and OWL groups.
6. There was no significant correlation among the groups for any measure of thigh muscle size with any measure of strength. The correlation between MTC and 1RM squat strength was $r=.20$.

The hypothesis, that the BB group would have the greatest thigh size and the lowest 1RM squat strength while the OWL and PL groups would have the greatest 1RM squat strength but have a smaller thigh size than the BB group, was not supported as the BB group had a thigh size similar to the other groups. However, the hypothesis that the PL and OWL groups would have greater 1RM squat strength per unit TMA was supported. The fact that significant differences in thigh strength were found between the BB group and PL and OWL groups while showing no significant difference in thigh size supports the premise that factors other than muscle size are important in strength development.

**Conclusions**

From the results of this study, the following conclusions were drawn:

1. Thigh size among highly trained BB, PL, and OWL of similar body weight was not significantly different.
2. Powerlifters and OWL are significantly stronger than BB in the 1RM squat lift.
3. Differences in strength among the groups were not due to differences in absolute muscle size.
4. There was no correlation between thigh muscle size and 1RM squat strength among elite BB, PL, and OWL, of similar body weight.
5. The ratio of 1RM squat strength per unit TMA was different among the three groups. The PL and OWL groups had a greater 1RM squat strength per unit TMA compared with the BB group. Therefore, it was concluded that the relationship between muscle
hypertrophy and strength is different in highly trained individuals than that of untrained or lessor-trained individuals.

**Practical Application**

The results of this study have implications for strength and conditioning coaches and personal trainers who design resistance training programs for highly trained athletes. Highly trained athletes, who follow bodybuilding type training programs to increase muscle size, may not increase strength levels to the same degree as athletes who use other training protocols. Training programs which focus primarily on developing strength and power, like the programs PL and OWL perform, may increase size and to a greater degree strength. This may have a more functional carryover to athletic activities where greater levels of strength can improve athletic performance.

**Recommendations for Future Study**

More investigation is needed to understand the contribution of muscle hypertrophy to strength in highly trained individuals. Future study in this area should attempt to use subjects who are physically similar and of equal ability levels (in terms of the level of success each subject has achieved in their specific sport). In addition, it may be beneficial to use methods such as: MRI to measure hypertrophy, biopsies to measure physiological adaptations, and EMG analysis to measure neurological adaptations in muscle. These types of technologies might make it possible to more accurately measure any differences among groups. Finally, it would be useful to compare highly trained groups with groups of untrained controls who begin resistance training using different protocols. This would be helpful in comparing the relationship of hypertrophy to strength across the continuum of untrained, lessor-trained, and highly trained individuals.
References


APPENDIX A - Informed Consent
Informed Consent

This study is being done to evaluate the relationship between muscle strength and muscle size. The results will help to better understand how muscle size affects strength. The study involves taking anthropometric measurements of the proximal, distal, and mid-thigh. A tape measure will be used to measure thigh circumference and a skinfold caliper will be used to measure thigh skinfold thickness. Body fat will be measured using a hand held body fat analyzer. A scale will be used to measure body weight. An anthropometer will be used to measure shoulder width. Muscle strength will be measured by having the subject perform a maximal barbell back squat.

Subjects will be allowed as much time as needed to properly warm up and stretch before 1RM squat testing. All squatting will be done in a power rack with the safety pins adjusted for the subject’s height and squat depth. A wide or narrow stance width and a high or low bar placement may be used, however the stance width cannot be wider than 15 cm of the subject’s deltoid determined by measurement of the shoulder. Bar placement cannot be higher than the seventh cervical vertebra or lower than the top of the scapula. Squatting depth has to be parallel. A squat will be considered parallel when the surface of the hip joint is lower than the top of the knee joint. An audible cue of “parallel” will be given when the proper squat depth is reached. The subject can squat lower than parallel if he chooses. A subject can attempt as many 1RM squats as he chooses as long as each successful attempt is heavier than the previous attempt. If the subject feels he has given his maximum effort, the heaviest weight lifted will be recorded as the 1RM squat. The use of a supportive suit or knee wraps is forbidden during the test. A weight belt may be used but the width of the belt cannot exceed 4 inches.

It is the subject's responsibility to inform the administrator of any reason why he (the subject) should not participate in any and/or part of the test. The subject has the opportunity to withdraw from the test and ask questions at any time.

The test consists of maximal strength exercises which could cause serious physical injury. By signing this document, the test subject fully understands the inherent risks of injury and assumes full responsibility for any injuries that may hereafter occur arising out of or connected with participation in this study. The subject also voluntarily gives permission to use the data collected from this test for the study. Subjects’ names will be kept confidential and only the following data collected including type of athlete, age, height, body weight, thigh circumference measurements, thigh skinfold measurements, body fat measurements, shoulder width measurements, and 1 RM squat strength will be used in the study. Additional information from the questionnaire will be used for the test administrator’s purposes only.

Signature ____________________________________________ Subject

Signature ____________________________________________ Witness
APPENDIX B - Competition and Training Questionnaire
Competition and Training Questionnaire

1.) How tall are you?

2.) What is your current body weight?

3.) Have you ever competed in (circle the sport that applies) a: powerlifting  
    b: Olympic weightlifting  
    c: bodybuilding

4.) Was the competition a sanctioned event?

5.) Have you ever qualified or competed in a national level competition?
    If yes, list the competition(s) and the year(s) in which you competed.

How did you place in the competition(s)?

Was the competition(s) drug tested?

What weight class(es) did you compete in?

6.) Do you use the barbell back squat in your training program?

7.) What is your estimated 1 RM maximum in the barbell back squat exercise?

8.) What is your age?
APPENDIX C - Health History Form
Health History Form

The following questions are intended to obtain information about your health that will assist the tester in making relevant decisions regarding the study. Answer all the questions to the best of your knowledge. All information will remain confidential. Please circle either “Yes or No” to the following questions.

1.) YES NO Do you have increased or high blood pressure?

2.) YES NO Do you have increased or high blood cholesterol?

3.) YES NO Are you currently taking medication?
   If yes, what kind and for what purpose? __________________________
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-----------------------

4.) YES NO Do you suffer from any chronic illness?
   If yes, what kind? __________________________
-----------------------

5.) YES NO Are you under treatment of any kind for this illness?
   If yes, list the type of treatment(s): __________________________
-----------------------

6.) YES NO Do you have a history of breathing or lung problems?
   If yes, please explain: __________________________
-----------------------

7.) YES NO Have you ever had an episode of asthma, that is, severe wheezing, brought on by physically demanding activity or exercise?

8.) YES NO Do you smoke?
   If yes, how many cigarettes do you smoke each day? ______________
   How long have you been smoking?) __________________________

9.) YES NO Have you ever been diagnosed as having low bone density or osteoporosis?

10.) YES NO Have you ever had a stroke?

11.) YES NO Have you ever had a heart attack?

12.) YES NO Have you ever had heart surgery?
13.) YES NO Has a physician ever told you that you have a heart condition or heart problem?
If yes, please explain:

14.) YES NO Have you ever had surgery of any kind?
If yes, what kind?
How long ago?

15.) YES NO Do you suffer from any low back pain or back problems?
If yes, please explain:

16.) YES NO Do you have any orthopedic problems with joints such as hips, knees, ankles, shoulders, elbows, etc. that might be aggravated by exercise?
If yes, please explain:

17.) YES NO Do you have arthritis?
If yes, where do you have the most pain or discomfort?

18.) YES NO Have you ever been treated by a chiropractor?
If yes, for what purpose and how long ago?

I have answered the above questions to the best of my knowledge, accepting full responsibility for any inaccuracies that may affect my participation in the study.

Signature ____________________ Date ____________________

Witness ______________________ Date ____________________
Data Collection Information

Type of Athlete: ________________________

Height: _________________

Age: _________________

Body Weight: _________________

% Body Fat: _________________

Shoulder Width _________________

Thigh Length: _________________

Thigh Circumference: proximal thigh ______ ______ ______ ______

                        distal thigh ______ ______ ______ ______

                        mid-thigh ______ ______ ______ ______

Mid-thigh Skinfold Thickness: ______ ______ ______ ______

Estimated 1RM: _________________

50% Estimated 1RM: _________________

70% Estimated 1RM: _________________

90% Estimated 1RM: _________________

1RM Barbell Back Squat: _________________

Comments:
APPENDIX E - Raw Data
<table>
<thead>
<tr>
<th>Height</th>
<th>Weight</th>
<th>Age</th>
<th>% Body Fat</th>
<th>Mid-Thigh Skinfold</th>
<th>Proximal Thigh</th>
<th>Distal Thigh</th>
<th>Mid-Thigh</th>
<th>1RM Squat</th>
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<tbody>
<tr>
<td><strong>Bodybuilders</strong></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5'8&quot; (172.72 cm)</td>
<td>199 lbs (90.45 kg)</td>
<td>46 yrs</td>
<td>NA</td>
<td>12.7 mm</td>
<td>67.9 cm</td>
<td>53.4 cm</td>
<td>65.8 cm</td>
<td>385 lbs (175 kg)</td>
</tr>
<tr>
<td>5'8&quot; (172.72 cm)</td>
<td>180 lbs (81.81 kg)</td>
<td>41 yrs</td>
<td>7.6%</td>
<td>8 mm</td>
<td>60 cm</td>
<td>50.5 cm</td>
<td>57.16 cm</td>
<td>335 lbs (152.27 kg)</td>
</tr>
<tr>
<td>5'7 3/4&quot; (172.08 cm)</td>
<td>171 lbs (77.72 kg)</td>
<td>33 yrs</td>
<td>11.6%</td>
<td>13.33 mm</td>
<td>61.73 cm</td>
<td>55.06 cm</td>
<td>61.1 cm</td>
<td>375 lbs (170.45 kg)</td>
</tr>
<tr>
<td>5'10&quot; (177.8 cm)</td>
<td>194 lbs (88.18 kg)</td>
<td>32 yrs</td>
<td>13.6%</td>
<td>19.66 mm</td>
<td>62.76 cm</td>
<td>52.65 cm</td>
<td>61 cm</td>
<td>295 lbs (134.09 kg)</td>
</tr>
<tr>
<td>5'6&quot; (167.64 cm)</td>
<td>176 lbs (80 kg)</td>
<td>48 yrs</td>
<td>11%</td>
<td>10 mm</td>
<td>60.36 cm</td>
<td>42.4 cm</td>
<td>57.75 cm</td>
<td>370 lbs (168.18 kg)</td>
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<tr>
<td><strong>Powerlifters</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5'7&quot; (170.18 cm)</td>
<td>165 lbs (75 kg)</td>
<td>27 yrs</td>
<td>9.9%</td>
<td>7.3 mm</td>
<td>60 cm</td>
<td>48 cm</td>
<td>57.7 cm</td>
<td>500 lbs (227.27 kg)</td>
</tr>
<tr>
<td>5'8&quot; (172.72 cm)</td>
<td>209 lbs (95 kg)</td>
<td>43 yrs</td>
<td>26.7%</td>
<td>21.33 mm</td>
<td>66.55 cm</td>
<td>54.65 cm</td>
<td>61.36 cm</td>
<td>425 lbs (193.18 kg)</td>
</tr>
<tr>
<td>5'10&quot; (177.8 cm)</td>
<td>184 lbs (83.63 kg)</td>
<td>28 yrs</td>
<td>15.2%</td>
<td>20.33 mm</td>
<td>63.2 cm</td>
<td>49.45 cm</td>
<td>57.35 cm</td>
<td>455 lbs (206.81 kg)</td>
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<tr>
<td>5'6&quot; (167.64 cm)</td>
<td>198½ lbs (90.22 kg)</td>
<td>34 yrs</td>
<td>22.7%</td>
<td>23 mm</td>
<td>64.85 cm</td>
<td>52.25 cm</td>
<td>60.7 cm</td>
<td>475 lbs (215.90 kg)</td>
</tr>
<tr>
<td>5'7½&quot; (171.45 cm)</td>
<td>210 lbs (95.45 kg)</td>
<td>34 yrs</td>
<td>20.6%</td>
<td>17 mm</td>
<td>62.6 cm</td>
<td>48 cm</td>
<td>60.26 cm</td>
<td>405 lbs (184.09 kg)</td>
</tr>
</tbody>
</table>