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ORIGINAL ARTICLE

Effect of range of motion in heavy load squatting on muscle and tendon adaptations

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Abstract Manipulating joint range of motion during squat training may have differential effects on adaptations to strength training with implications for sports and rehabilitation. Consequently, the purpose of this study was to compare the effects of squat training with a short vs. a long range of motion. Male students ($n = 17$) were randomly assigned to 12 weeks of progressive squat training (repetition matched, repetition maximum sets) performed as either a) deep squat (0–120° of knee flexion); $n = 8$ (DS) or (b) shallow squat (0–60 of knee flexion); $n = 9$ (SS). Strength (1 RM and isometric strength), jump performance, muscle architecture and cross-sectional area (CSA) of the thigh muscles, as well as CSA and collagen synthesis in the patellar tendon, were assessed before and after the intervention. The DS group increased 1 RM in both the SS and DS with $\sim 20 \pm 3$ %, while the SS group achieved a 36 ± 4 % increase in the SS, and 9 ± 2 % in the DS ($P < 0.05$). However, the main finding was that DS training resulted in superior increases in front thigh muscle CSA (4–7 %) compared to SS training, whereas no differences were observed in patellar tendon CSA. In parallel with the larger increase in front thigh muscle CSA, a superior increase in isometric knee extension strength at 75° (6 ± 2 %) and 105° (8 ± 1 %) knee flexion, and squat-jump performance (15 ± 3 %) were observed in the DS group compared to the SS group. Training deep squats elicited favourable adaptations on knee extensor muscle size and function compared to training shallow squats.

Keywords Resistance training · Hypertrophy · Patellar tendon · Jumping performance

Abbreviations

CV	Coefficient of variation
CJ	Counter movement jump
CSA	Cross-sectional area
DS	Deep squat
DEXA	Dual energy X-ray absorption
LBM	Lean body mass
MRI	Magnetic resonance imaging
r	Pearson correlation coefficient
PINP	Procollagen type 1 N-propeptide
RM	Repetition maximum
SEC	Series elastic component
SS	Shallow squat
SJ	Squat jump
SD	Standard deviation
SE	Standard error
SSC	Stretch shortening cycle

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Introduction

Strength training is associated with improvements in muscle strength through adaptations in neural control (Aagaard et al. 2002; Del Balso and Cafarelli 2007), muscle cross-sectional area (CSA) (Wickiewicz et al. 1984; Kawakami et al. 1995; Aagaard et al. 2001), muscle architecture (Blazevich et al. 2003; Aagaard et al. 2001; Alegre et al. 2006), fibre-type transformation (Andersen and Aagaard 2000) and alterations in the length–force characteristics (Abe et al. 2000). Furthermore, muscular adaptations appear to be dependent on loading parameters, volume of exercise, velocity of exercise, and movement intent of the exercises used in training (Hakkinen et al. 1985; Thepaut-Mathieu et al. 1988; Weir et al. 1994; Rimmer 2000; Blazevich et al. 2003; Lockie et al. 2003; Markovic et al. 2007).

Improved muscle strength increases the forces distributed from the muscles through the tendons (Kannus 2000) and increases the stress on the connective tissue within the muscle, as well as on the tendons in series with the muscles. It is thus likely that the biomechanical properties of the connective tissue are influenced by the force-generating capacity of the muscles, although little research has been conducted to address this (Kongsgaard et al. 2007; Couppe et al. 2008).

Exercise has been shown to increase the turnover of tissue within tendons both acutely and as a result of a prolonged training intervention (Langberg et al. 1999, 2000; Miller et al. 2005; Kongsgaard et al. 2007; Langberg et al. 2007). Animal studies show that exercise improves the physical properties of tendons, e.g. maximal tensile strength (Elliott 1965; Woo et al. 1981), and newly published data indicate that this also is the case in humans (Haraldsson et al. 2005; Kongsgaard et al. 2007; Couppe et al. 2008).

Strength training utilizing the squat exercise can be performed in various ways, among those being a full range deep squat (DS) or a limited range shallow squat (SS). To our knowledge, only one study has explored the effect of squat training at different joint angles (Weiss 2000). Hypothetically adaptations to squat training performed using full- or limited range of motion could lead to differential adaptations, with implications for, e.g. power sport performance or during preventative rehabilitation programs against certain musculotendinous injuries.

Theoretically, in maximal lifts the forces on the knee extensors and patellar tendon are the same in both the DS and SS even though the SS can be performed with substantially more load (Fig. 1). This is because the external moment arm is approximately twice as long when the femur is parallel to the ground (DS) compared to a limited range of motion of 60° of knee flexion (SS). Thus, assuming that the force on the muscle–tendon system is the same in both ranges of motion, the only difference is the length at which the working muscles contract.

However, changes in the patellar tendon moment arm with increasing knee angles also need to be considered, as the moment arm of the knee extensor muscles is described by the moment arm of the patellar tendon. Peak values for the patellar tendon moment arm are estimated to be near 45° of knee flexion (Krevolin et al. 2004). Interestingly, at 90° of knee flexion the patellar tendon moment arm seems to decrease by approximately 50 %, and most likely continues to decrease with increasing knee angles (Krevolin et al. 2004). Assuming this to be true, the DS would thus elicit higher tendon and muscles forces compared to the SS, and hypothetically be a catalyst for patellar tendon hypertrophy and collagen synthesis. This hypothesis is supported by findings reported by Tsaopoulos et al. (2006).

The purpose of this randomised study was therefore to explore whether the DS and SS exercise had a differential effect on specific adaptations in the front thigh muscles and patellar tendon, as well as on jump performance. It was hypothesized that SS training would be superior in eliciting increased strength in the SS. In contrast, DS training would

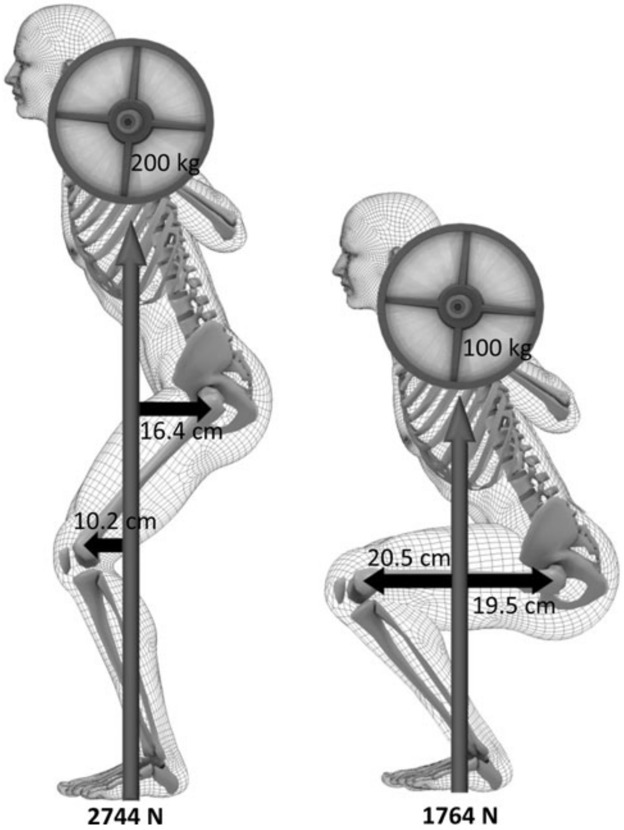

Fig. 1 Illustration of the deepest position in the SS (*left*) and DS exercise (*right*). The external moment arms indicated are estimated from an average subject with regard to lifting technique and height (180 cm). The ground reaction forces represent a body mass of 80 kg and an external load of 200 kg in the SS, and 100 kg in the DS

be superior in increasing strength in the DS and front thigh muscle CSA as well as increasing patellar tendon CSA and collagen synthesis. Furthermore, it was hypothesized that these superior muscle and tendon adaptations with DS training would translate into a more positive effect on jumping performance compared to the SS.

Materials and methods

Subjects

It was calculated that ten subjects in each training group would give a statistical power of 90 %. Normally, the drop-out rate in training interventions is around 10–20 %. Therefore, twenty-four males were recruited for the study (Table 1). All subjects were sports science students. If they had been squat training more than once weekly during the preceding 6 months, or if they were engaged in strength or power sports, they were excluded from the study. During the intervention, subjects were requested not to participate in endurance sports more than three times per week, or to engage in strength training of the lower extremities. After a 1-week familiarization period, subjects were tested and paired according to their initial DS strength. From each pair one subject was drawn, by envelope, into either the DS or SS group with the other member of the pair allotted to the opposite group. Four subjects withdrew preceding training. This left 20 subjects, where an additional two subjects withdrew due to illness and injury. Training attendance was set at ≥80 %, and one additional subject was excluded due to a lack of attendance. This left 17 subjects with nine in the SS group, and eight in the DS group.

Training

Both groups engaged in strength training, three times per week for 12 weeks. Each session started with a 10-min general warm-up, followed by a specialized warm-up consisting of 1–3 submaximal squats (shallow or deep according to training group). Both groups performed barbell squat free weight exercises. The SS group performed the squat from complete knee extension (0°) to 60° of knee flexion, and back to extended knee, while the DS group performed a full range of motion squat, with the femur parallel to the floor in the lowest position (120° of knee flexion) (Fig. 1). Both squat variations were executed with an eccentric phase lasting 2–4 s followed by a maximal effort in the concentric phase with the subjects' feet staying on the ground. The training program was periodized, and loads progressively increased during the 12 weeks (Table 2). All training sessions were supervised to ensure correct range of motion and safety. The study complied with the Declaration of Helsinki and was approved by the Regional Ethics Committee of Southern Norway.

Table 1 Pretest characteristics of subjects in the SS group and in the DS group (mean ± SD)

	Shallow squat group ($n = 9$)	Deep squat group ($n = 8$)
Age (years)	23 ± 3	25 ± 6
Weight (kg)	80 ± 15	79 ± 6
Height (cm)	178 ± 6	181 ± 5
Peak torque (Nm) (isometric at 105°)	241 ± 66	242 ± 29
Jump height (cm) (squat jump)	33.9 ± 3.6	32.8 ± 3.3
Muscle CSA (cm^2) (front thigh)	95.6 ± 14.1	95.2 ± 7.3
Tendon CSA (mm^2) (middle part)	162 ± 9	166 ± 12

Testing procedures

Microdialysis and ultrasonography were carried out during the familiarization week, while the remainder of the pretests were carried out the following week. All tests were carried out at pre-intervention and after 12 weeks. Testers were blinded in regard to training group.

1 RM strength

All subjects were tested using 1 RM for both the DS and SS after a general and specialized warm-up consisting of a series of 10–6–3–1 repetitions, without subjects reaching fatigue. Based on the last sub-maximal series of 1 repetition, a plausible load was chosen. Hereafter, loads were increased with a minimum of 5 or 10 kg and a maximum of 15 or 30 kg, for DS and SS, respectively, until the subjects failed to lift the load with correct technique.

Isometric strength

Isometric strength of the knee extensors on the right leg was measured in a dynamometer (Technogym REV 9000, Gambettola, Italy) at knee angles of 40°, 75° and 105° (full knee extension at 0°). After a specific warm-up with four isokinetic knee extensions with increasing intensity, two maximal contractions of 5 s were performed at each knee angle with a 30 s rest between attempts. Peak torque at each knee angle was used for analysis (coefficient of variation (CV) <5 %).

Cross-sectional area (CSA)

The CSA of the front thigh muscles [m. sartorius and quadriceps (and adductors in the most proximal sections)],

Table 2 Periodization and progression of strength training

Week	Monday	Wednesday	Friday
1	Familiarization	Familiarization	Familiarization
2	Pretesting	Pretesting	Pretesting
3	3 × 10 RM	3 × 8 (submax)[a]	4 × 5 RM
4	3 × 10 RM	3 × 10 (submax)	4 × 5 RM
5	3 × 10 RM	3 × 8 (submax)	4 × 5 RM
6	3 × 10 RM	3 × 10 (submax)	4 × 5 RM
7	3 × 10 RM	3 × 8 (submax)	4 × 5 RM
8	3 × 10 RM	3 × 10 (submax)	4 × 5 RM
9	3 × 6 RM	3 × 8 (submax)	5 × 3 RM
10	3 × 6 RM	3 × 10 (submax)	5 × 3 RM
11	3 × 6 RM	3 × 8 (submax)	5 × 3 RM
12	3 × 6 RM	3 × 10 (submax)	5 × 3 RM
13	3 × 6 RM	3 × 8 (submax)	5 × 3 RM
14	3 × 6 RM	3 × 10 (submax)	5 × 3 RM
15	Posttesting	Posttesting	Posttesting

[a] Eight reps with a 12–13 RM load

back thigh muscles (hamstrings) and the patellar tendon were obtained using magnetic resonance imaging [(MRI), GE Signa 1.5 Tesla EchoSpeed, GE Medical Systems, Milwaukee, WI]. A total of nine slices were analysed for muscle CSA from both legs. The first slice was placed 10 cm proximal to the lateral femoral epicondyle and was defined as the most distal slice. The remaining eight slices were then placed proximally to this reference point with 10 mm between each slice. To measure the CSA of the patellar tendon seven slices per leg were taken. The first slice was placed 5 mm distal to the tibial plateau (reference point). The second slice was placed on the tibial plateau, and the remaining slices were taken proximal to the tibial plateau with 5 mm between each slice.

A line was manually drawn along the perimeter of the muscle bellies and the tendon on each slice, and the CSA was automatically generated in the software (OsiriX 3.9.3, Pixmeo, Bernex, Switzerland).

Lean body mass (LBM)

LBM of the legs and body composition were measured using Dual energy X-ray absorption [(DEXA), Lunar Prodigy densitometer, GE Medical Systems, Madison, WI]. Subjects were requested not to eat or drink during the 2 h preceding the scanning and to eat identical meals at identical times at both pre and post test.

Muscle architecture

Using ultrasound imaging (Toshiba Sonolayer Just Vision 400) pennation angle and muscle thickness of the right m. vastus lateralis were measured. Ultrasound was performed with subjects relaxed and lying in supine with the knees fully extended. Using a point midway between the greater trochanter and the lateral condyle, isolated muscle thickness and pennation angle were measured in vivo using the ultrasonograph, and pictures were stored and blinded. Muscle thickness was determined by measuring the distance between the superficial and deep aponeurosis whereas the pennation angle was defined as the angle between the fascicle and the deep aponeurosis (Alegre et al. 2006). Five measurements were taken. The highest and lowest values were withdrawn, and a mean value was determined from the three remaining measurements. Reliability measurements were not conducted in the present trial; however, CV of 3 % for muscle thickness and 5 % for pennation angle has hence been performed utilizing same analysis procedures and ultrasonograph technicians. The posttest was performed 1 day after a submaximal training session during the last training week.

Collagen synthesis in the patellar tendon

Pretest microdialysis was performed, with no exercise or testing done during the preceding 2 days (Langberg et al. 1999). The post sampling was executed the day after the last training session (16–28 h after exercise). On each leg, one microdialysis catheter, custom-made in the laboratory, was placed in front of the patellar tendon before and after the intervention. The active part of the membrane was 30-mm long covering the width of the patellar tendon. The sterilized (ETO) fibres were all high molecular mass cut-off fibres (3,000 kDa, membrane length 30 mm, catheter outer diameter 0.05 mm). In vivo recovery was determined using labelled glucose (Glucose D-[3-^{3}H]), 250 μCi in 2.5 ml ethanol/water (9:1), as no radioactively labelled procollagen type 1 N-propetide (PINP) was commercially available. The catheters were perfused (CMA 100) at a rate of 2 μl/min. After the microdialysis catheters had been positioned, the subjects rested for at least 90 min before starting the sampling (4 h), to ensure that the insertion trauma was minimized (Langberg et al. 1999). The samples were immediately frozen at −80 °C until analyses were done. Collagen synthesis was analysed as the peritendinous concentration of PINP in the microdialysis samples by a sandwich ELISA (Christensen et al. 2008). The dialysate samples were diluted: 1:9, 1:10 or 1:20 before the analysis, based on previous analysis of the sample. The detection level was 41 pg/ml and the intra-assay variation (CV) of 4.9 % at 4.2 ng/ml. All the samples from the same subject were analysed on the same ELISA plate.

Jump performance

Squat jumps (SJ) and counter movement jumps (CMJ) were performed on a forceplate (SG–9, Advanced

Mechanical Technologies, Newton, MA, USA) and low-pass filtered at 1,050 Hz. SJ were performed with no counter-movement from a knee angle of 90° with hands fixed at the hip. The CMJ started from a standing position with the hands fixed at the hip. Jump height was calculated from the impulse during takeoff. At each test, the subjects did three to six jumps, and the best result was used for analysis (CV < 5 %).

Statistical methods

A per-protocol analysis was applied, thus all results are based on the 17 subjects who completed the training intervention. Means, standard deviations (SD) and standard errors (SE) were calculated, and all values are presented as means and standard errors unless otherwise noted. The paired *t* test was performed to assess changes over time within each training group, whereas the un-paired *t* test was performed to assess the statistical significance of between-group differences. Pearson's correlation coefficient (*r*) was used to calculate SS and DS collapsed variables. Significance was set at 5 % ($P \leq 0.05$).

Results

The pretest characteristics of the subjects are presented in Table 1 with no between-group differences.

Strength

Both training groups increased 1 RM when tested in the SS and DS (Fig. 2). For the DS group, an increase of ~20 ± 3 % was observed in both squat ranges ($P < 0.05$), while the SS group achieved a 36 ± 4 % increase in the SS and 9 ± 2 % in the DS ($P < 0.05$). The SS group increased 1 RM in the SS more than the DS group, and the DS group increased 1 RM in the DS more than the SS group ($P < 0.05$). Maximal isometric knee extensor torque increased in the DS group at knee angles of 75° (6 ± 2 %) and 105° (8 ± 1 %) ($P < 0.05$). At 105°, the increased torque in the DS group was larger than in the SS group (8 ± 1 vs. 0 ± 5 %, respectively) ($P < 0.05$) (Fig. 3).

Thigh muscle CSA

The three most distal slices were a mix of muscle and tendon tissue (especially in the tallest subjects) and were therefore not analysed. The muscle CSA of the front thigh was increased at all measured sites in the DS group (4–7 %), while increases at the two most proximal sites were observed in the SS group ($P < 0.05$) (Fig. 4, upper panel). The change in muscle CSA at all measured sites was greater in the DS group ($P < 0.05$). The muscle CSA of the back thigh was increased at the second most proximal site in the DS group ($P < 0.05$) (Fig. 4, lower panel).

Lean body mass

LBM of the legs increased by 2.0 ± 0.8 % ($P < 0.05$) in the DS group while no increase was observed in the SS group (1.5 ± 0.9 %) (Fig. 5). The DS group achieved increases in body mass 1.7 ± 0.6 kg (2.2 ± 0.6 %) ($P < 0.05$) and total LBM 1.2 ± 0.4 kg (1.8 ± 0.8 %) ($P < 0.05$). No changes in body mass were detected in the SS group. There were no differences between training groups in body composition, and no changes in fat percent for either group.

Muscle architecture

No changes in muscle thickness were observed in either training group. However, increases in pennation angle were observed for both the SS and DS group (23 ± 5 and 22 ± 6 %) ($P < 0.05$), respectively. There were no differences between groups for changes in muscle thickness or pennation angle (Table 3).

Tendon CSA and collagen synthesis

We found no changes in the CSA of the patellar tendon at any of the measured sites in any group. Collagen synthesis, indicated by the PINP content measured with microdialysis, did not increase after training in either group.

Jump height

CMJ height increased by 7 ± 4 % in the SS group and 13 ± 2 % in the DS group ($P < 0.05$) (Fig. 6). SJ height

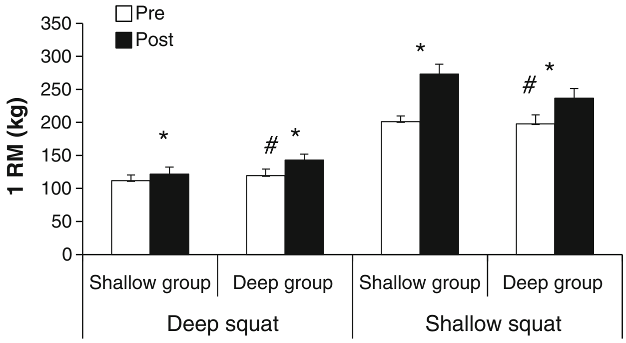

Fig. 2 One repetition maximum (1 RM) in the DS and SS exercise measured pre and post intervention. *Asterisk* significant change from pretest, *hash* significant difference between groups from pre to posttest

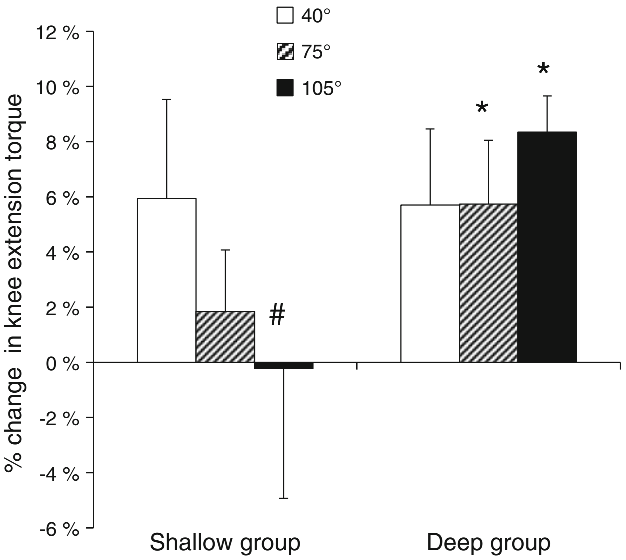

Fig. 3 Change in isometric knee-extension peak torque measured at knee angles of 40°, 75° and 105° (0° is full extension). *Asterisk* significant change from pretest, *hash* significant difference between groups from pre to posttest

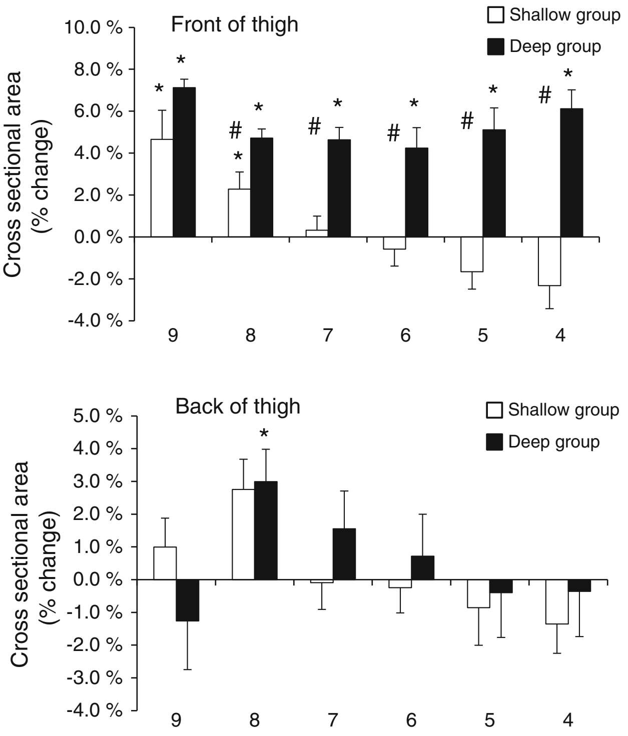

Fig. 4 Change in front thigh muscle CSA (*upper panel*) and back thigh (*lower panel*). *Asterisk* significant change from pretest (Section 9 was the most proximal), *hash* significant difference between groups from pre to posttest

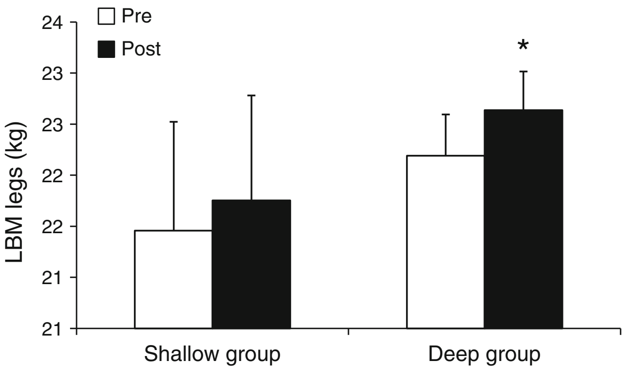

Fig. 5 Leg lean body mass (LBM) pre and post intervention. *Asterisk* significant change from pretest

increased in the DS group (15 ± 3 %) ($P < 0.05$) and was greater than in the SS group ($P < 0.05$).

Correlations

Front thigh muscle CSA/LBM legs and strength

Correlations between muscle CSA of the front thigh and 1 RM DS strength were detected at both pretest and posttest, whereas correlations between muscle CSA of the front thigh and 1 RM SS strength only were observed at pretest (Table 4). No correlations were detected between isometric knee extension strength and front thigh muscle CSA. However, correlations between isometric knee extension strength at both 75° and 105° and LBM of the legs were found at pretest.

Muscle strength and architecture

Correlations between isometric strength at 105° and pennation angle were found at pretest (Table 4).

Front thigh muscle CSA and patellar tendon CSA

No correlations between front thigh muscle CSA and patellar tendon CSA were observed. However, at pretest, a correlation was found between the mean patellar tendon CSA and LBM of the legs. Furthermore, there was a correlation between mid-patellar tendon CSA and maximal isometric knee extensor strength at 105° (Table 4).

Jump height and muscle architecture/strength

A correlation was found between SJ height and isometric knee extensor strength at 105° both at pretest and posttest (Table 4). No correlations between jump performance and muscle architecture were observed. However, a negative

Table 3 Muscle architecture before and after training in the SS and DS group

	Shallow squat group		Deep squat group	
	Pre	Post	Pre	Post
Muscle thickness (cm)	2.47 ± 0.37	2.54 ± 0.33	2.51 ± 0.26	2.60 ± 0.32
Fasicle angle (°)	18.5 ± 3.0	22.6 ± 3.7*	18.6 ± 2.8	21.7 ± 2.0*

Pre and post values given as mean ± SD

* $P < 0.05$

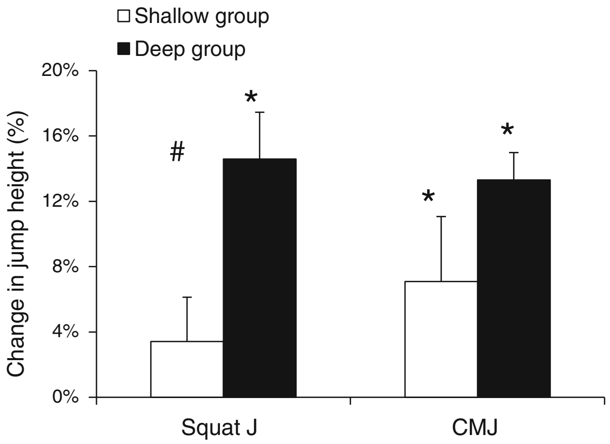

Fig. 6 Change in jump height in SJ and CMJ. *Asterisk* significant change from pretest, *hash* significant difference between groups from pre to posttest

Table 4 Correlation of selected outcomes at pre and posttest

Outcome	Outcome	Pretest (*r*)	Posttest Δ (*r*)
Isometric strength at 105°	Leg LBM	0.79*	0.29
Isometric strength at 75°	Leg LBM	0.75*	−0.03
1 RM deep squat	Front thigh muscle CSA	0.66*	0.53*
1 RM shallow squat	Front thigh muscle CSA	0.77*	−0.22
Mean patellar tendon CSA	Leg LBM	0.56*	0.11
Mid patellar tendon CSA	Isometric strength at 105°	0.60*	0.29
SJ height	Isometric strength at 105°	0.54*	0.55*
SJ height–CMJ height	Pennation angle	0.66*	
Isometric strength at 105°	Pennation angle	0.53*	0.06

* $P < 0.05$

correlation was found between pennation angle and the difference between the CMJ and SJ height.

Discussion

We found that 12 weeks of progressive heavy load squat training, regardless of range of motion, resulted in increases in 1 RM strength and pennation angle, as well as increases in CMJ height. However, only the DS group increased SJ height, LBM of the legs, isometric strength at 75° and 105°, and front thigh muscle CSA at all measured points. The SS group elicited front thigh muscle CSA increases only at the two most proximal sights.

Maximal muscle strength

In accordance with our hypothesis, the SS exercise elicited larger strength gains in the SS, while the DS exercise resulted in larger strength gains in the DS. It is, however, worth noting that DS training elicited similar results in both the DS and SS. In contrast, isometric knee extension strength measurements revealed no increases of strength in the SS group despite higher loads of training, whereas the DS group achieved increases at both 75° and 105° knee flexion. These results are similar to those reported by Weiss et al. (2000) who concluded that the DS was superior to the SS in regard to strength and squat performance.

In the SS group, the CSA of the front thigh muscles was increased only at the two most proximal sites. In conjunction, no isometric strength gains were found in the SS group, as well as no increases in leg LBM or in back thigh muscle CSA. This indicates that the increases in 1 RM strength observed in the SS group likely were due to neural adaptations and/or to muscular adaptations in muscles not analysed. The two most proximal sites included adductor muscles. Substantially higher loads were lifted by the SS group, and it seems reasonable to assume that this potentially resulted in an increased load on the adductor muscles, with hypertrophy to follow as well as favourable adaptations to other muscles working over the hip. Indeed, it is a study limitation that other muscles (e.g. hip extensors) were not measured, as these may have been affected differentially by the two squat training modes.

The DS group increased front thigh muscle CSA at all measured sites in accordance with our hypothesis. These findings are supported by the increases of leg LBM, and increases in both isometric and 1 RM strength in the DS group as well as pre and posttest correlations between 1 RM strength and front thigh CSA. Estimations of the external moment arms in the DS and SS showed that in the deepest position the external moment arm was approximately twice as long in the DS as in the SS (Fig. 1). This difference in external moment arm corresponded with the observed doubling of external load that could be lifted in the SS compared to the DS exercise. However, the patellar tendon moment arm is reduced when knee flexion is above 60° (deepest position in the SS) (Krevolin et al. 2004). Consequently, although the knee joint torque was similar in the deepest positions, the muscle force (and tendon force) working in the DS was probably 50–100 % higher than in the SS training due to the 25–50 % shorter patellar tendon moment arm in this position (Krevolin et al. 2004). Furthermore, when body mass is taken into consideration, the difference in muscle and tendon force between the two conditions may have been even larger. The greater hypertrophy observed in the extensor muscles in the DS group may therefore partly be explained by the larger muscle force developed in the DS training.

Muscle architecture

Both training groups achieved increases in muscle thickness and pennation angle of the m. vastus lateralis. There were no differences between groups, indicating no differential muscle architecture adaptations in response to the two different ranges of motion. As stated above, front thigh muscle CSA increases were larger in the DS than in the SS group, indicating that other muscle bellies could have been more affected by DS training than the m. vastus lateralis.

In the present study, a correlation between pennation angle and isometric strength at 105° was observed at pretest, and though no posttest correlation was found, it is reasonable to assume that the increases in pennation angle in both training groups may have had a positive influence on the observed strength development.

Patellar tendon properties

We had expected to find increases of patellar tendon CSA and collagen synthesis as a result of the squat training. However, neither group elicited gains in patellar tendon CSA or collagen synthesis. At pretest, correlations were found between the patellar tendon CSA and leg LBM and strength consistent with previous studies that have shown a relationship between muscle strength/size and patellar CSA (Elliott 1965; Kongsgaard et al. 2007). However, no change in patellar tendon CSA was observed in either group despite the increase in strength and CSA of the adjacent muscle, nor was any correlations found. Though not expected, these results are in accordance with several resistance training studies that have shown that increases in strength were not accompanied by increases in tendon CSA (Reeves et al. 2003; Kubo et al. 2007; Seynnes et al. 2009). Rather, a markedly altered elastic modulus was found in these studies, implying a change in the composition of the tendon structure instead of the size. However, in the present study no changes in collagen synthesis were observed which may indicate that 12 weeks of single-mode squat training is not sufficient time to generate a detectable change in patellar tendon CSA, nor collagen synthesis, in well trained subjects. Future studies are warranted to better understand the coordinated response of muscle and tendon as this knowledge could be of significant value in preventing overuse injuries of the tendon.

Jump height

CMJ height increased in both groups, however, only the DS group achieved gains in the SJ. As summarized by Earp et al. (2010), CMJ is a movement that involves a stretch shortening cycle (SSC) that allows the body to store and redirect energy through an eccentric movement quickly followed by a concentric movement. Due to the SSC, more force and power can be generated during the concentric phase of the jump, than if no eccentric phase was involved. This is seen when comparing the CMJ height to the SJ height.

We found no correlations between front thigh muscle CSA or strength gains and CMJ jump height in the present study. However, improvements in jumping performance could be caused by changes in muscle CSA only in variable individual combinations with changes in pennation angle, as these two variables are governing factors for the training-induced change in physiological CSA, and hence muscle force. As the SJ lacks the eccentric phase, and therefore the benefits of the SSC, the SJ is more dependent on maximal muscle strength. In the present study, we observed no between-group differences in CMJ height. In contrast, the DS group was superior to the SS group in the SJ. In addition, increases in isometric strength were largest in the DS group and a correlation both at pre and posttest were found between SJ height and isometric strength at 105°. Thus, the increases in strength achieved by the DS group, could account for the superior SJ performance. This positive relationship between increases in SJ height and strength underlines that increases in isolated muscle strength are beneficial for jump performance despite the increase in LBM and body mass due to muscle hypertrophy.

Conclusion

In conclusion, we found that 12 weeks of heavy load DS training was superior to the SS in regard to increases in front thigh muscle CSA and leg LBM, with no changes in patellar tendon CSA. Parallel with these adaptations, superior changes in isometric knee extension strength and SJ performance were observed with DS training. In both groups, increases in 1 RM squat strength and CMJ height were observed. We suggest that larger muscle–tendon forces over the knee joint, more internal (patellar tendon) work produced, and longer muscle length of the knee extensors during the DS compared to the SS exercise were the main explanations for the superior adaptations observed with DS training in this study. Adaptations in muscles involved in hip extension and stabilization were not measured in this study, and possible favourable adaptations with SS training in these areas can therefore not be ruled out.

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