Low-load Slow Movement Squat Training Increases Muscle Size and Strength but Not Power

Abstract

We tested a hypothesis that low-load squat training with slow movement and tonic force generation (LST) would increase muscle size and strength but not necessarily power. Healthy young men were assigned to LST [50% one-repetition maximum (1-RM) load, 3 s for lowering/lifting without pause: n=9] or low-load normal speed (LN: 50% 1-RM load, 1 s for lowering/lifting with 1 s pause; n=7) groups. Both groups underwent an 8-week squat training program (10 repetitions/set, 3 sets/day, and 3 days/week) using the assigned methods. Before and after the intervention, quadriceps femoris muscle thickness, maximal torque during isometric hip extension and knee extension, 1-RM squat, lifting power from squatting position and rate of electromyography rise (RER) in knee extensors during the task, leg extension power and vertical jump height were measured. After the intervention, the LN group showed no changes in all the variables. The LST group significantly (P < 0.05) increased muscle thickness (6–10%), isometric hip extension torque (18%) and 1-RM squat (10%), but not isometric knee extension torque, lifting power and RER, leg extension power and vertical jump height. These results suggest that LST can increase muscle size and task-related strength, but has little effect on power production during dynamic explosive movements.

Introduction

Resistance training has been popular not only among athletes but also in a wide spectrum of individuals, regardless of sex or age, because of its beneficial impact on sports performance and quality of life [4,10]. In general, using high-load resistance training (>70% one-repetition maximum (1-RM)) has been regarded as optimal for gaining muscular size and strength [4]. However, such a training regimen is not always recommended for, or favored by, some individuals due to the high level of mechanical stress and potential risk of injuries [20]. In addition, a marked increase in systolic blood pressure (up to 250 mmHg) has been reported to occur during high-load resistance training for large muscle groups [16], which is strongly associated with the risk of exercise-related accidents, including death from cardiovascular as well as noncardiovascular causes, especially in elderly populations [15,19]. Therefore, developing a resistance training regimen that can produce substantial gains in strength with much reduced mechanical stress is to be considered [27].

As an approach to the training regimen mentioned above, Tanimoto and Ishii [27] reported that relatively low-load (~50% 1-RM) resistance training with slow movement and tonic force generation (3 s for lowering and lifting actions without a relaxing or pause phase, designated as LST) in knee extension caused significant increases in muscle thickness (~6–10%), isometric hip extension torque (18%) and 1-RM squat (10%), but not isometric knee extension torque, lifting power and RER, leg extension power and vertical jump height. These results suggest that LST can increase muscle size and task-related strength, but has little effect on power production during dynamic explosive movements.

Keywords
- movement speed
- task-specificity
- explosive power
- rate of electromyography rise
important neuromuscular function in various physical activities and also contributes to reducing the incidence of falling or slipping, especially in elderly populations [2]. Tanimoto et al. [26] also observed that a 13-week LST program in the leg muscles changed muscle activation and force generation patterns during dynamic (cycling) movements to be more tonic. This suggests that LST may have unfavorable effects on dynamic power production, since more instantaneous (i.e., less tonic) muscle activation is important for achieving high power [1], especially during dynamic explosive movements. Additionally, Kanehisa and Miyashita [18] reported that slow speed resistance training had little effect on power production during high-speed movements. Considering these factors, it is possible that LST would increase muscle size and strength, but not necessarily power during dynamic explosive movements due to the task-specific adaptation to the training modality (i.e., slow speed and tonic force generation). The purpose of this study was therefore to examine the effect of LST on muscle size and function, with the specific emphasis on explosive power production during whole-body or multi-joint dynamic movements. We hypothesized that LST would increase muscle size and strength but have little, if any, effect on power production during dynamic explosive movements.

Methods

Subjects

16 healthy young men voluntarily participated in this study. The subjects were randomly assigned to either LST (n=9) or low-load normal speed (LN: n=7) group. The means and standard deviations (SDs) of age, body height and body weight were 22.2 ± 2.1 years, 175.0 ± 7.2 cm and 71.6 ± 5.8 kg for the LST group, and 22.5 ± 0.5 years, 169.4 ± 4.7 cm and 68.7 ± 5.2 kg for the LN group, respectively. The subjects were habitually active, but none were involved in any type of exercise program (≥ 30 min/day, ≥ 2 days/week). None had experienced a systematic resist

pose, procedures and possible risks involved in the study, and provided written informed consent.

Training program

Both groups underwent a parallel squat training program with 50% 1-RM load, 10 repetitions/set, 3 sets/day, 3 days/week, for 8 weeks using the following methods; LST: 3-s lowering and 3-s lifting without a pause phase, LN: 1-s lowering and 1-s lifting with 1-s pause phase [26]. Subjects in each group repeated the movement at approximately constant speed and frequency with the aid of a metronome. A rest period of 1 min was taken between the sets. For the first and second week of the training period, the exercise load (50% 1-RM) was based on the 1-RM for each subject measured at the pre-training measurement (explained in the 1-RM squat section below in detail). 1-RM squat was measured at the start of the third week and at every 2 weeks thereafter (i.e., at the start of the first session of the third, fifth and seventh weeks), and the exercise load (50% 1-RM) was adjusted for each subject on the basis of the measured 1-RM value. In the training sessions, that included a 1-RM measure-

ment, a rest period of at least 10 min was set before starting the prescribed exercise tasks (LST or LN).

Measurements

Before and after the training intervention, the following variables were measured.

Muscle thickness

Muscle thickness of the 4 muscles composing the quadriceps femoris of the right side was measured by a B-mode ultrasound (Prosound af6; Aloka, Tokyo, Japan) with a linear scanner. The measurement sites were 30, 50 and 70% of the femur (the distance from the great trochanter to articular cleft between the femur and tibia condyles) for the rectus femoris (RF) and the vastus intermedius (VI), and 50% for the vastus lateralis (VL) and the vastus medialis (VM). During the measurements, the subjects stood upright with their arms and legs relaxed extended position (i.e., the anatomical position). In accordance with a procedure described in an earlier study [3], the measurement sites were precisely located and marked at the anterior surface of the femur length. A transducer with a 7.5 MHz scanning head was placed perpendicular to the underlying muscle and bone tissues. The scanning head was coated with water-soluble transmission gel, which provided acoustic contact without depressing the dermal surface. The obtained cross-sectional ultrasonographic images were printed out by an echo copier. The muscle thickness was measured as the distance between the fat-muscle tissue and muscle-bone interfaces (for the VI, between bone and its superficial aponeurosis).

Isometric torque

Torque during maximal voluntary isometric hip extension and knee extension of the right leg was measured using an isokinetic dynamometer (Biodex system2; Biodex Medical Systems, NY, USA). In the hip extension torque measurements, the subjects lay supine on an adjustable seat, and the torso was held tightly in the seat (Fig. 1a). The hip extension/flexion attachment was set and isometric hip extension torque was measured at 90° (full extension: 0°) of the hip joint with the knee joint kept at 90° (full extension: 0°). In the knee extension torque measurements, the subjects sat on the seat with support for the back and hips, and the hip joint was kept at 90° (full extension: 0°) (Fig. 1b). The torso was held tightly in the seat. The knee extension/flexion attachment was set and isometric knee extension torque was measured at 90° of the knee joint. After a sufficient period of warm-up, the subjects were asked to perform maximal isometric hip extension and knee extension twice for each task. Additional trials were performed if the difference in the peak torque of the 2 trials in each task was more than 10%. A rest period of more than 2 min was taken between trials. In each task, the highest value of the peak torque was selected for analysis.

1-RM squat

1-RM parallel squat was measured with the same bar and weight plates used in the training regimen (Fig. 1c). As a warm-up, the subjects performed squat several times with the load 80% of the body weight. Subsequently, 5–10 kg weight plates were gradually added with at least 2-min interval between trials, and the maximal load lifted was determined as 1-RM.

Lifting power and rate of electromyography rise

Maximal lifting power from squatting position was measured using a custom-made lifting power measurement device (Fig. 1d). In this system, the bar was connected to the platform with the slings, and the load on the bar was adjusted on-line. From a parallel squatting position, the subjects tried to lift (stand up against) the bar on the shoulder as fast as possible, with the load 100% of the body weight (e.g., a 70 kg person lifted a 70 kg load). From lifting velocity data measured by an accelerometer set in the platform, maximal lifting power was calculated by the following equation.

\[
\text{Power (W)} = m \times v \times g
\]

where \( m \) is body weight (kg) of each subject (i.e., lifting load), \( v \) is peak lifting velocity (m/s), and \( g \) is gravitational acceleration (9.8 m/s²). After a sufficient warm-up and practice, the subjects performed the task twice with an interval of at least 30 s. Additional trials were performed if the difference in the maximal power of the 2 trials was more than 10%. The highest value of the peak power was selected for analysis.

During the task, surface electromyograms (EMGs) were recorded from the RF, VL, and VM muscles using a bipolar configuration. The bipolar Ag-AgCl electrodes (diameter, 8 mm; interelectrode distance, 20 mm) were placed over the bellies of those muscles after the skin surface was shaved, rubbed with sandpaper and cleaned with alcohol. All electrode positions were carefully measured in each subject to ensure identical pre- and post-training recording sites. The electrodes were connected to a differential amplifier (gain × 1000, Common-mode rejection ratio > 80 dB, input impedance > 100 MΩ, model MEG-6100; Nihon-Kohden, Tokyo, Japan) having a bandwidth of 5–1000 Hz. The EMG and lifting velocity data were synchronized and obtained at a sampling rate of 1000 Hz using a 16-bit A/D converter (Power Lab 16s; ADInstruments, Sydney, Australia), and stored on a personal computer. During the off-line analysis using software (Chart version 7; ADInstruments, Sydney, Australia), the EMG signals were digitally high-pass filtered by using a fourth-order, zero-lag Butterworth filter with a 5-Hz cutoff frequency, followed by a moving root-mean-square filter with a time constant of 50 ms [2]. EMG onset was identified as the time point at which the amplitude of the EMG increased by a magnitude of 2 standard deviations (SDs) of the resting EMG. From the EMG data of the trial in which maximal lifting power was obtained for each subject, rate of EMG rise (RER), determined as the slope (ΔEMG/Δtime) of the filtered EMG signal, was calculated and peak value observed during the trial was adopted as maximal RER.

Leg extension power

Maximal leg extension power was measured using an isokinetic leg extension dynamometer (Kick-Force; Takei, Tokyo, Japan, Fig. 1e). The subjects sat on the seat with support for the back, and the torso was held tightly in the seat. From the hip- and knee-flexed position both at 90°, maximal leg extension power at a velocity of 0.8 m/s was measured. The trials were repeated 5 times with an interval of at least 10 s, and the highest value was adopted as the maximal leg extension power.

Squat and counter-movement jump height

Squat and counter-movement jump height was measured by the use of a mat switch platform (Multi Jump Tester; DKH, Tokyo, Japan, Fig. 1f) [25]. In this system, the jump height was calculated based on the subject’s flight time. The participants were in a standing position, and performed squat and counter-movement jumps as high as possible. The position of the jumper on the mat was the same for takeoff and in landing. When jumping, the participants kept their hands on their hips and jumped vertically with (counter-movement jump) or without (squat jump) counter-movement on the mat switch platform. The participants completed 3 trials for each task with a rest interval of at...
At least 10 s between the trials. The highest value for the 3 trials for each task was used for analysis.

Reproducibility of the measurements
Day-to-day (separated by 3–5 days) reproducibility of the measurements was examined on 6 healthy men (age: 22.3 ± 2.7 years, height: 169.4 ± 4.8 cm, body weight: 70.3 ± 5.7 kg) for the muscle thickness and function (strength and power) variables. Paired t-tests revealed no significant differences between days in all the variables. The coefficient of variation (CV) and the intraclass correlation coefficient (ICC) for each measurement variable were less than 4.3 % and more than 0.80, respectively (see Table 1). The magnitude of ICC was higher than 0.75, which is considered the threshold for reliability [28].

Statistical analysis
Normality of the data was checked and subsequently confirmed using the Kolmogorov-Smirnov test. Descriptive data are presented as mean ± SD. An unpaired Student’s t-test was used to test the baseline difference between groups. A paired Student’s t-test was used to test the difference between pre- and post-test for each group. In addition, relative changes (%) in the strength/power variables for each subject were calculated and compared between the variables by a one-way repeated measures analysis of variance followed by post hoc comparisons (Tukey’s test) to test the difference in the training-induced changes in the variables. A significance level was set at P<0.05. All data were analyzed using SPSS software (version 20.0; IBM Corp., Armonk, N.Y., USA).

Results
No significant baseline differences were found in all the variables (P>0.05) except for lifting power and counter-movement jump height, which were higher in the LST than the LN group. The following shows the changes in each variable after the intervention.

Muscle thickness
Fig. 2 shows the changes in the muscle thickness for both groups. The LST group showed significant gains in the muscle thickness at 70% of the RF (+10%, P=0.026) and at 50% (+6%, P=0.01) and at 70% (+9%, P=0.002) of the VI after the training (Fig. 2, left). No changes were observed in the LN group at all sites (Fig. 2, right).

Isometric torque
Fig. 3 (LST) and Fig. 4 (LN) shows the changes in the strength/power variables. The LST group significantly increased the isometric hip extension torque (+18%, P=0.006, Fig. 3a), but no change was observed in the knee extension torque (Fig. 3b). The LN group did not show any significant changes in the hip extension torque and knee extension torque (Fig. 4).

1-RM squat
The LST group significantly increased the 1-RM squat (+10%, P<0.01, Fig. 3b). No change was observed in the LN group (Fig. 4).

Lifting power and RER
Lifting power did not significantly change in the LST (Fig. 3c) and LN group (Fig. 4c). Maximal RER also did not show any significant changes in all the muscles in both groups (LST: RF; 3320±1631 μV/s vs. 3491±1923 μV/s, VM; 6078±2072 vs. 5590±2844 μV/s, VM; 6801±3312 vs. 5995±3609 μV/s, LN: RF; 4209±1802 vs. 3701±2218 μV/s, VM; 7118±3207 vs. 7845±3617 μV/s, VM; 9126±3098 vs. 8482±3142 μV/s, P>0.05).

Table 1 The coefficient of variations (CVs) and intraclass correlation coefficients (ICCs) of the variables in between-day measurements (n=6).

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>CV (%)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle thickness</td>
<td>1.0–2.9</td>
<td>0.80–0.96</td>
</tr>
<tr>
<td>Isometric hip extension torque</td>
<td>2.3</td>
<td>0.98</td>
</tr>
<tr>
<td>Isometric knee extension torque</td>
<td>3.0</td>
<td>0.98</td>
</tr>
<tr>
<td>1RM of squat</td>
<td>1.9</td>
<td>0.96</td>
</tr>
<tr>
<td>Lifting power</td>
<td>4.3</td>
<td>0.83</td>
</tr>
<tr>
<td>Leg extension power</td>
<td>0.8</td>
<td>0.99</td>
</tr>
<tr>
<td>Squat jump height</td>
<td>1.8</td>
<td>0.96</td>
</tr>
<tr>
<td>Counter-movement jump height</td>
<td>2.1</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The range in the muscle thickness means the range of 7 measurement sites.

Fig. 2 Changes in the muscle thickness of the quadriceps femoris; the rectus femoris (top row) and the vastus intermedius (middle row) measured at 30% (proximal), 50% (middle) and 70% (distal) of the femur, and the vastus lateralis and the vastus medialis (bottom row) before (open bar) and after (closed bar) the LST (left) and the LN (right) training. Values are mean ± SD. An asterisk (*) indicates a significant (P<0.05) difference from the pre-test.

Leg extension power
Leg extension power did not significantly change in the LST (Fig. 3c) and LN group (Fig. 4c).

Squat and counter-movement jump height
There were no significant changes in both squat and counter-movement jump height in both groups (Fig. 3d, 4d).

Differences in the training-induced changes in the variables
Fig. 5 shows the relative changes in each variable from pre-values for the LST group; those for the LN group are not shown because no significant changes were observed in all the variables in the LN group (Fig. 4). The change of the isometric knee extension torque was significantly lower than that of the isometric hip extension torque. Notably, the changes of the power-
related variables (i.e., lifting power, leg extension power, and jump heights) were all lower than those of the strength variables measured under the zero (isometric) or slow speed conditions (i.e., isometric hip extension and 1-RM squat).

Discussion

The main finding obtained here was that LST significantly increased muscle size and strength, although the gains in muscle thickness and strength depended on the measurement sites and variables, respectively, but it did not produce significant changes in all of the power-related variables. This supports our hypothesis, and suggests that LST can increase muscle size and task-related strength but has little effect on power production during dynamic explosive movements.

In the LN group, there were no significant changes in all the variables. Tanimoto and Ishii [27] reported a similar result that 12-week knee extension training using LN did not increase isometric knee extension strength. It has been reported that training load at +65% 1-RM is less effective than high-load (65–85% 1-RM) resistance training for increasing strength and size of the muscles [9]. These findings together with the current result indicate that LN resistance training does not provide a sufficient training stimulus for increasing muscle size and strength for healthy young males. On the other hand, the LST group significantly increased muscle thickness, isometric hip extension torque and 1-RM squat. The gain in 1-RM squat (+10%) in this study was the same as that (+10%) observed in the seventh week of the 13-week LST squat training conducted by Tanimoto et al. [26]. As possible explanations for increasing muscle size and strength by LST, Tanimoto and Ishii [27] suggested that the tonic force generation pattern in LST causes increase in intramuscular pressure, restricting blood flow to the active muscles, and it results in muscle deoxygenation and enhanced secretion of growth hormone by intramuscular accumulation of metabolic subproducts (e.g., lactate). Furthermore, Burd et al. [8] reported that greater time under tension with the same load and repetitions (i.e., similar conditions used in this study; LST vs. LN) increased the acute amplitude of mitochondrial and sarcoplasmic protein synthesis and also resulted in a robust stimulation of myofibrillar protein synthesis after resistance exercise. Thus, it is reasonable to assume that such factors as enhanced metabolic stress and subsequent increases in myofibrillar protein synthesis contributed to the gains in the muscle size and strength observed in this study.

In the LST group, however, no changes were found in isometric knee extension torque and the power-related variables, in spite of the significant increases in muscle thickness, isometric hip extension torque, and 1-RM squat. Also, muscle thickness increased only in the RF (distal site) and VI (distal and middle sites), and no changes were found in the VL and VM (discussed later). These results indicate that the observed gains in muscle strength and thickness in the LST group cannot be solely attributed to the enhanced metabolic stress and/or myofibrillar protein synthesis. As a well-documented fact, a training-induced strength gain is most clearly observed in the task performed in the training regimen, and this is called “task-specificity” [23]. For example, Sale et al. [24] reported that 19-week leg press training significantly increased 1-RM leg press as well as muscle size of the quadriceps femoris, but no change was found in maximal isometric knee extension strength, highlighting the importance of neural factors (e.g., coordination among synergist muscles) that contribute to the torque output (strength). In this study, the subjects performed squat training only. Thus, it is possible that the training-induced strength gains were only observed in 1-RM squat, which is the same exercise task performed in the training regimen, and hip extension, which is the major action when (or a similar movement to) performing squats. On the other hand, Tanimoto and Ishii [27] reported a significant increase in isometric knee extension strength after the LST training, but this is probably attributed to the fact that the training was performed by knee extension in their study. In addition, while the LST group increased muscle size and strength, the power-related variables such as maximal lifting power and leg extension power did not change (Fig. 3.5). Considering the significant increase in isometric hip extension strength, it is reasonable to assume that the power-related variables in the leg extensors (lifting and leg extension power and jump performance) would increase as well. However, the current result contradicts this, indicating that LST can increase muscle size and strength but has little effect on power production during dynamic explosive movements. As stated earlier, Kanehisa and Miyashita [18] reported that resistance training using slow speed had little effect on power production at a high speed. Furthermore, Tanimoto et al. [26] reported that LST changed muscular activity and force generation patterns during dynamic movements to be more tonic, which may have unfavorable effects on dynamic power production. It has been suggested that instantaneous increase in muscle activation (i.e., less tonic activation) is crucial for achieving high explosive power [1]. To support this notion, some studies [2,12] have reported that a training-induced increase in the rate of force development, which is an index of the explosive power, was accompanied by an increase in RER. In this study, we found no significant changes in maximal lifting power from the squatting position and RER in the quadriceps femoris muscle during the task. This suggests that LST induces neither unfavorable nor favorable adaptations (i.e., decreased and increased RER, respectively), and thus has little effect on dynamic power production. Behm and Sale [7] described that the principle stimuli for the high-velocity-specific training response are the repeated attempts to perform ballistic contractions and the high rate of force development of the ensuing contraction, regardless of muscle action (isometric or concentric). Considering this, it is assumed that the lack of improvement in the dynamic power-related variables in the LST group would be attributed to the training modality adopted (i.e., slow movement and tonic force generation).

The training intervention period set in this study was 8 weeks. This is shorter compared to the previous studies that conducted LST training for 12–13 weeks [26,27]. As a result, we cannot rule out the possibility that LST would increase explosive power to some extent when the training period is extended longer than 8 weeks (e.g., 12–13 weeks). However, as mentioned, Tanimoto et al. [26] reported that 13-week LST training changed muscular activity and force generation patterns during dynamic movements to be tonic. Also, Tanimoto and Ishii [27] observed no increases in single-joint isokinetic knee extension strength at middle-high speed (90, 200, 300 deg/s) after 12-week LST training. On the other hand, several studies have found significant increases in explosive power or strength at high speed after short-term (<8 weeks) resistance training using ballistic movement and/or intention to move fast [11], indicating that changes (improvements) in power-producing capacity often occur within...
a relatively short-term. Considering these findings together, it is reasonable to assume that LST training has little, if any, effect on explosive power even when the training period is extended for a long-term, for example 12 weeks or longer.

In the LST group, muscle thickness increased in the RF at 70% and in the VI at 50% and 70% of the femur, but not in the other sites. It has been reported that muscle hypertrophy occurs inhomogeneously among and along quadriceps femoris muscle after resistance training [13,21]. As a reason for such inhomogeneous changes after resistance training, the inter- and intra-muscle differences in activation level during exercise have been proposed [21,29]. Regarding the inter-muscle differences, Narici et al. [21] reported that muscle activation level during lowering phase of dynamic knee extension is higher in the RF than in the other 3 muscles composing the quadriceps femoris muscle. Thus, it is possible that the RF was activated higher than the other 3 muscles in the descending phase of the squat as well, providing higher training stimulus to the RF. Additionally, it has been reported that muscle activation level of the VI is higher than the other 3 muscles during submaximal isometric knee extension [30]. Furthermore, the muscle activation level of the VI has been shown to be higher than the other 3 muscles during knee extension in the knee-flexed position [5,22]. Considering these findings together with the fact that we used 50% (submaximal) 1-RM load and parallel squat (knee-flexed position), muscle activation level (training stimulus) might have been higher in the VI than in the other 3 muscles at some phases during LST. As for the intra-muscle differences, Akima et al. [6] reported that muscle activation in the distal region of the RF during isokinetic knee extension was higher than that in the proximal region, which could at least in part explain the observed changes in muscle thickness in this study. Ema et al. [13] and Narici et al. [21] reported similar results to ours that a relative increase in the VI than in the other 3 muscles composing the quadriceps femoris muscle. It is possible that the RF was activated higher than the other 3 muscles composing the quadriceps femoris muscle after high-load or power training and consequently increased muscle power. Furthermore, the muscle activation level of the VI has been shown to be higher than the other 3 muscles during knee extension [30]. Additionally, it has been reported that muscle activation level of the VI is higher than the other 3 muscles during submaximal isometric knee extension [30]. Furthermore, the muscle activation level of the VI has been shown to be higher than the other 3 muscles during knee extension in the knee-flexed position [5,22]. 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