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Effects of Concentric Versus Eccentric Strength Training on the Elderly's Knee Extensor Structure and Function

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ABSTRACT

Baptista R, Onzi E, Goulart N, Dos Santos LD, Makarewicz G, Vaz M. Effects of Concentric Versus Eccentric Strength Training on the Elderly's Knee Extensor Structure and Function. **JEPonline** 2016;19(3):120-132. The purpose of this study was to compare the effects of eccentric vs. concentric 12-wk strength training program on the quadriceps properties of elderly men. Twenty-three subjects performed unilateral concentric knee extension on one side and eccentric knee flexion on the contralateral side at 80% of 5 RM. Both protocols increased knee extensor strength. Vastus lateralis fascicle length decreased and pennation angle increased without changes in muscle thickness in both protocols. Patellar tendon length increased after both protocols, but tendon cross-sectional area increased only post-eccentric training. Isometric and dynamic torque increased in both groups. Concentric and eccentric training can be used with similar results in older adults.

Key Words: Strength Training, Aging, Type of Contraction

INTRODUCTION

Strength training is commonly prescribed as an effective way to reverse the loss in muscle mass and strength due to aging, as well as to generate positive morphological and functional adaptations in skeletal muscles (25). It has been suggested that strength training is capable of increasing muscle fiber length and pennation angle in the elderly, which indicates that these training type effects can be verified both in the serial and parallel increase of sarcomeres in this population (30,31).

Skeletal muscle adaptations to strength training are strongly influenced by its architecture. Muscles with larger volume and physiological cross-sectional area generate more force due to the larger myofilaments contents in its myofibrils. Assuming that muscle architecture is highly plastic, understanding how the different mechanical stimuli influence these morphological muscle adaptations is of fundamental importance for health professionals and researchers interested in optimizing muscle function and performance (3) and, in particular, in the elderly.

Tendon adaptation with strength training is another factor that appears to influence the muscle mechanical properties in the elderly. Fyfe and Stanish (12) have demonstrated that strength training increases tendon stiffness due to adaptations to material properties, such as growth in the tendon fibrous structure at the extracellular matrix. These adaptations significantly increase muscle force transmission to the bones through the tendons, increasing the rate of torque development in the muscle.

Neuromuscular plasticity studies (6,24) have suggested an increase in muscle fiber length of muscles subjected chronically to eccentric work, while a reduction (6) or maintenance (24) of fascicle length has been observed in muscles working concentrically. These results are an indication that the contraction type is the main stimulus for these fascicle length changes.

Therefore, one could ask: Which is the best training type to counterbalance the aging effects at the muscular system? The purpose of this study was to compare the effects of an eccentric training program to a concentric training program on the morphological and mechanical properties of the knee extensor muscle-tendon unit in the elderly in an attempt to improve our understanding of the muscular adaptations to resistive exercises in this population.

METHODS

Ethical Aspects

The study was approved by the Research Ethics Committee of both universities where the study was conducted by the protocol number 2008064 and 09/04857. The experiments were undertaken with the understanding and written consent of each subject, and the study was done in accordance with The Declaration of Helsinki.

Subjects

Twenty-three elderly male subjects (62.74 ± 2.20 yrs of age, 80.21 ± 14.82 kg of body mass, and 172.02 ± 6.11 cm of height) agreed to participate in the study. The sample size was calculated based on the equation proposed by Eng (8), which indicates the sample size according to the level of significance, statistical power and expected difference between groups, and standard deviation from previous studies using similar methodology. Muscle thickness and pennation angle were used for sample size calculation based on data from Suetta et al. (36). These variables were chosen for the influence they exert in force production and, consequently, in elderly functionality. With the standard deviation obtained for muscle thickness (1.3 mm) and pennation angle (0.5°), as well as the expected increase of these variables post-strength training (2.2 mm and 1.4°), the sample obtained was 11 and 4 subjects, respectively. Results obtained by Suetta et al. (36) for the maximal power test from the sitting to the standing position were also used for sample size calculation because this is an extremely important functional variable in the elderly. With the standard deviation for this variable (0.4 $W{\cdot}kg^{-1}$), and the expected difference from pre-training to post-training (0.9 $W{\cdot}kg^{-1}$), the sample size was determined as 6 subjects. Therefore, the sample size indicated in the three calculations were added resulting in a sample size of 21 subjects. Due to the possibility of a 20% sample loss, the sample size was increased to 25 subjects. Throughout the study, 2 subjects abandoned the training program. Therefore, 23 subjects finished the study.

Strength Training

The training sessions occurred twice a week, where subjects had the knee extensors of one limb subjected to an eccentric training program (referred to as the Eccentric Group, EG) and the contralateral side to a concentric training program (i.e., the Concentric Group, CG). The side allocation to each training program was randomly assigned during the first visit to the laboratory. All subjects trained at the same time of the day under the supervision of two researchers who controlled the execution of the exercise duration and 1-min series intervals.

Training was executed with the aid of a conventional knee extensor strength training machine (Taurus®, Porto Alegre, Brazil). This equipment uses symmetrical pulleys with the largest resistance torque applied when the knee is completed extended, with load being reduced during knee flexion.

Training methodology was similar to that of Reeves et al. (28) who compared quadriceps morphological and mechanical adaptation between eccentric training and conventional (concentric-eccentric) programs in the elderly during knee extensor and leg press exercises. According to these authors' eccentric training program, subjects should execute knee extension without any load with the aid of the researcher, who manually raised the load. Next, subjects rested for 0.5 sec so that the load could be transferred to the subjects limb and they should resist the load eccentrically during knee flexion up to 90° (knee fully extended = 0°) during 3 sec (Figure 1).

Concentric training consisted of concentric knee extension with an overload for a period of 3 sec followed by a 0.5 sec pause for the researcher to fully support the load and, then, knee flexion by the subject without any load up to 90° of knee flexion. The load was adjusted throughout the training program when the subjects were able to execute more than 10 RM.

Maximal Strength

Five repetitions maximum (5 RM) were defined as the largest load that subjects could support in a controlled manner during 3 sec of eccentric or concentric knee flexion for only 5 repetitions. The 5 RM test was evaluated before the start of the training program and after 12 wks of strength training.

Vastus Lateralis Muscle Architecture

A linear array ultrasound B-mode system (60 mm, 7.5 MHz - SSD 4000, 51 Hz, ALOKA Inc., Tokyo, Japan) was used to evaluate muscle architecture at rest. Outcome measures included fascicle length, pennation angle and muscle thickness. Subjects were evaluated seated, with the hip flexed at 90° and the knee extended to 10° of knee flexion. The 10° of knee flexion position was chosen for being the usual position generally used for muscle architecture evaluation (30,31) without an excessive stretching of the hamstring muscles at the sitting position. In addition, at this joint angle muscle fascicles were at a configuration that allowed for the full visualization of the muscle fascicles in most evaluations at the ultrasound images. Ultrasound measurements were obtained at 50% of the length of the vastus lateralis muscle over a line between the anterior superior iliac spine and the lateral femur epicondyle (22).

The probe was embedded on a water-soluble acoustic transmission gel that promoted acoustic contact between the probe and the skin without skin depression. The probe was positioned parallel to the direction of the muscle fibers. Anthropometric measures were made from two anatomical points: the distance between the patella proximal margin at the sagital plane and the distance of the mean thigh point at the transversal plane. This created a Cartesian coordinate system (x, y) for the determination for the probe positioning. This coordinate system also allowed for the repositioning of the probe at the post-training evaluations. Post-training evaluations were obtained 48 hrs after the last training session in order to avoid possible post-training edema influence at the muscle architecture images. These images were constantly recorded in DVD by an external DVD recorder (R130/XAZ, Samsung Inc., Seoul, South Korea).

Ultrasound images were synchronized with the torque and EMG signals through a sync pulse at the data acquisition system and a stopwatch (HORITA Video Stop Watch VS – 50; HORITA Co., Inc., California, USA) at the DVD recorder. This allowed for the selection of the images corresponding to the resting period at both systems. Muscle architecture data were recorded in DVDs, and the vídeo obtained was transformed into MPEG format by the BitRipper program (Binotex, USA). Ultrasound images were selected from specific times of the MPEG vídeo file using the Virtual Dub program (Avery Lee, USA). Ultrasound images were analyzed through script files created in MATLAB (MATLAB version 7.3.0.267, MathWorks, Inc., Natick, MA).

One single image from each muscle was used for data analysis, and three fascicles from each image were analyzed. The mean value was calculated from these three muscle fascicles for fascicle length and pennation angle. For muscle thickness, three measurements were obtained from each image: (i) a proximal; (ii) one from the middle of the image; and (iii) a distal. Muscle thickness was determined as the mean value among these three measurements.

Muscle thickness was obtained from the distance between the deep and the superficial aponeuroses (22). Pennation angle was determined as the angle between the fascicle line of action and the deep aponeurosis. Fascicle length was defined as the length of the fascicle along its trajectory between the deep and superficial aponeuroses. Fascicle length was normalized to thigh length (relative length). Thigh length was determined as the distance between the great trochanter and the lateral epicondyle of the femur (23).

Patellar Tendon Morphological Properties

Patellar tendon morphological properties were obtained with subjects seated with the knees and hips flexed at 90° and the linear probe positioned at two distinct positions at the patellar tendon: (a) at the sagital plane to determine tendon length; and (b) at the transversal plane to obtain tendon cross-sectional area (13). Tendon length was determined as the distance between the insertion point at the tibia and at the patella. Cross-sectional area was obtained with the probe transversally positioned at 50% of the tendon length (13). Anatomical marks were made at the skin and measurements of the distance of the probe to the lateral malleolus were used to control for a similar probe position between the pre-training and post-training evaluations.

Patellar tendon morphological properties were subjected to the same procedures described above for VL architecture in terms of data collection in order to obtain the ultrasound images and during data analysis. Patellar tendon length was determined as the distance between its origin at the patellar apex and its insertion at the tibia (13) through the ImageJ software (National Institute of Health - NIH, USA). The patellar tendon cross-sectional area was determined by calculating the tendon area from the transversal image of the tendon through ImageJ (National Institute of Health - NIH, USA) program (37).

Knee Extensor Mechanical Properties

Subjects were seated on the isokinetic dynamometer (Biodex Medical System, Shirley – NY, USA), and knee extensor torques were obtained from both limbs. The flexed hip joint was maintained at approximately 85° (20) with the subject fixed to the chair with Velcro straps at the chest, abdomen, and thigh. The subject’s leg was fixed to the dynamometer arm by a Velcro strap 3 cm above the medial malleolus. The apparent axis of the knee joint was aligned with the dynamometer axis of rotation. Upper limbs were maintained crossed in front of the chest with the subject’s hand firmly grasping the strap.

Each subject executed a familiarization session that consisted of maximal isometric voluntary contractions at different knee joint angles and concentric and eccentric contractions at different angular velocities. After familiarization, the subjects executed one maximal voluntary isometric knee extensor contraction at four different joint configurations: 30°, 50°, 60°, and 70° of knee flexion (full knee extension = 0°), in this order, for a period of 5 sec each. These joint angles were chosen for being the normal range of motion used in strength training programs for the elderly (11).

All subjects were instructed: (a) to produce maximal force as fast as possible until they reached their maximal force generating capacity; and (b) to maintain this maximal effort for at least 1 sec before relaxing. Herzog and ter Keurs (17) proposed that this procedure helped to guarantee all muscle fibers remained at a constant fiber length during force production.

A 2-min interval was observed between contractions to minimize possible fatigue and/or force-time history effects. The test was repeated if the following situations were observed: (a) when the subject or the researcher felt that the effort was not maximal or (b) when the contraction was not maintained for at least 1 sec (17).

In addition, three maximal knee extensor concentric and eccentric torques were obtained at four different angular velocities: 60°·s^{-1}, 120°·s^{-1},, 180°·s^{-1},, and 240°·s^{-1}, (11). A 2-min interval was observed between each angular velocity in order to minimize possible fatigue effects. Eccentric contractions were represented as negative torque with a minus sign. The torque-angle relation (T-A) was obtained from the maximal voluntary isometric torque at each joint angle. Absolute torque values were normalized by the peak torque.

Among the three torque-velocity curves obtained at the concentric and eccentric contractions, only the curve with the peak torque was used for analysis at each angular velocity. Torques obtained at the angular velocity of 60°·s^{-1}, were used to normalize the torques obtained at the other angular velocities. The reason for using this dynamic torque for normalization as opposed to using the maximal isometric torque was to use a more functional situation for normalization of the dynamic torques. Mean and standard deviation values were calculated for all torque values at all isometric and dynamic contractions. During torque and muscle architecture evaluations, the researchers were blinded to the leg training program.

Statistical Analysis

A two-way (eccentric versus concentric training) repeated measures (pre-training versus post-training) ANOVA, with a 5% significance level, was used to compare: (a) the vastus lateralis muscle architecture (fascicle length, pennation angle, and muscle thickness); (b) the patelar tendon morphological properties (tendon length and anatomical cross-sectional area); (c) the torque angle relation; and (d) the torque-velocity relation between the concentric and eccentric groups.

Significant differences were determined by the Bonferroni *post-hoc* test. An independent Student *t*-test was used to compare the relative changes from pre to post-training between groups, with a 5% significance level. Statistical analysis was performed with the GraphPad Instat 3.06 software (GraphPad Software, San Diego, California, USA).

RESULTS

Maximal Strength, Muscle Architecture, and Patellar Tendon Morphological Properties

The main results from this study reveal that both the 12-wk concentric training program and the 12-wk eccentric training program improved strength, muscle architecture, and tendon structure.

Maximal strength (measured by the 5 RM test) increased linearly throughout the eccentric training program, from 35.43 ± 6.01 kg at the pre-training to 41.30 ± 5.88 kg ($P<0.05$) after 6 wks and then 45.65 ± 6.96 kg at the end of the training ($P<0.05$). On the other hand, the strength increase occurred only at the first, 6 wks of concentric training, from 22.61 ± 3.95 kg to 25.87 ± 3.58 kg ($P<0.05$) and, then, it stabilized (26.74 ± 4.67 kg) at the end of the training. Despite the changes in the strength production, muscle architecture modifications were similar between groups. There was a significant ($P<0.05$) increase in patellar tendon cross-sectional area post-eccentric, but not during the post-concentric training (Table 1).

Table 1. Changes in Vastus Lateralis (VL) Muscle Architecture and Patellar Tendon (PT) Morphology in Concentric (Con) and Eccentric (Ecc) Groups.

	Conc Pre	Conc Post	Δ Conc (%)	Ecc Pre	Ecc Post	Δ Ecc (%)
VL Fascicle Length (mm)	172.75 ± 78.07	129.59 ± 47.93	(-)24.98	168.89 ± 73.39	122.97 ± 39.12	(-)27.19
VL Pennation Angle (°)	6.79 ± 3.31	9.68 ± 3.79	42.56	7.44 ± 4.28	9.62 ± 3.84	29.3
VL Muscle Thickness (mm)	16.75 ± 5.28	18.17 ± 5.17	8.48	16.36 ± 6.10	17.59 ± 5.19	7.52
Patelar Tendon Length (mm)	37.88 ± 3.98	45.00 ± 5.85	18,00	38.29 ± 4.88	43.81 ± 5.23	14.42
Patelar Tendon Cross Section Area (mm^2)	9.35 ± 2.91	9.87 ± 1.78	5.56	9.15 ± 1.45	10.30 ± 1.30	12.57

Caption: VL Fascicular Length (FL); Relative Fascicular Length (RFL); VL Pennation Angle (PA); VL Muscle Thickness (MT); Patellar Tendon Length (PTL); Patellar Tendon Cross Section Area (PTCSA); Δ % change between pre-training and post-training; * P<0.05.

Knee Extensor Mechanical Properties

Both the concentric and the eccentric groups showed a similar (P>0.05) increase in maximal isometric torques at the knee joint angles of 50°, 60°, 70°, and 90° (P<0.05), but not at 30° (P>0.05). Concentric training led to a torque increase at the eccentric angular velocities of -240°·sec^{-1}, -180°·sec^{-1}, -120°·sec^{-1}, -60°·sec^{-1}, at the maximal isometric contraction (0°/sec) and at the concentric angular velocities of 180°·$sec^{-1}$and 240°·sec^{-1} (P<0.05). Eccentric training caused a significant torque increase at the maximal isometric contraction (0°·sec^{-1}) and at the concentric and eccentric angular velocities of 60°·sec^{-1}, 120°·sec^{-1}, and 180°/sec (P<0.05). No between-groups differences were observed (P>0.05). The normalized torque-angle and torque-velocity relations were similar (P>0.05) between the two training groups.

DISCUSSION

Maximal Strength and Muscle Architecture

As muscle architecture gains were similar post concentric and eccentric training regimens, the linear strength increase observed at the 5 RM test might be related to the larger mechanical load that eccentric contractions place on skeletal muscle. Indeed, a meta-analysis related to the outcomes post strength training indicated that, despite the test and training velocity, eccentric training executed at high intensities is associated with a larger strength improvement compared to concentric training (32).

When performed isolated, eccentric muscle actions have demonstrated several distinct physiological properties from those observed for concentric actions. For example, different neural activation patterns have been observed with these two types of muscle contractions (9). Compared to concentric actions, eccentric contractions are characterized by a broader and faster cortical activity as movements are executed (10) as well as by different patterns of motor unit activation (26), and by faster neural adaptations secondary to strength training (18).

Our muscle architecture results agree with those by Reeves and colleagues (28) who evaluated 9 subjects that performed a 14-wk conventional strength training program that consisted of concentric and eccentric muscle actions and 10 subjects that performed a 14-wk knee extensor eccentric training program. Reeves et al. (28) observed a fascicle length increase in the vastus lateralis muscle of both groups, although the increase was higher (20%) with the eccentric training program compared to the conventional training program. They also observed an increase of 35% in vastus lateralis pennation angle of the conventional training group, but not in the eccentric (5%) training group. Muscle thickness also increased in a similar way in both training groups.

Blazevich et al. (4) evaluated the effects of 10 wks of eccentric training (n=12) versus 10 wks of concentric training (n=12) in young subjects. They found a 4.7% increase in fascicle length in both groups, and suggested that something else other than contraction type was the main factor for the specific training adaptations. They speculated that the joint range of motion used for the training programs (100º to 5º, 0º = full knee extension), which was similar to the one used in present study (100º to 0º) might have been the primary stimulus for the observed adaptations in fascicle length. This joint range of motion is substantially higher than that observed during walking, which is about 25º (1), running at about 55° (2), jumping at about 80° (5), and stair climbing with a joint range of motion of about 88° (1). This factor could be considered as a larger stimulus than that generated by movements within a normal joint range of motion.

However, Blazevich et al. (3) eccentric and concentric training programs were conducted with an isokinetic dynamometer, using a series of six maximal voluntary contractions with maximal muscle contraction throughout the entire range of motion. This is important as our results indicate that, in addition to the contraction type and the joint range of motion used during training, it is also important to determine the biomechanical characteristics of the equipment used for training in order to better understand the skeletal muscle morphological adaptations that result from strength training.

Tendon Morphological Properties

Our findings show a significant increase at the patellar tendon anatomical cross-sectional area only when the quadriceps muscles were trained eccentrically, although both patellar tendons showed an increase in length. The larger mechanical load during eccentric training compared to concentric training might have resulted in a larger increase in connective tissue content that strengthens its structure. Stanish et al. (35) and Fyfe and Stanish (12) suggest that during eccentric training the tendon is exposed to larger forces compared to concentric training, thus they are exposed to a larger remodeling stimulus.

Ress and colleagues (27) used a method that combines ultrasound and motion analysis with the simultaneous measurements of force and electromyography to compare the physiological stimulus to the calcaneal tendon during the two types of muscle contraction. They demonstrated that the peak force at the tendon during eccentric exercise is of a similar magnitude to the one measured during concentric exercise. This reinforces the idea from

Stanish et al. (35) that the force magnitude applied to the tendon might not be the only factor responsible for the adaptations observed at post-eccentric training.

Although Rutherford et al. (33) in vitro results suggest that peak force generated eccentrically is higher than peak force generated concentrically, this probably does not apply in the in vivo situation. In fact, the physiological joint range of motion allows for different mechanical loads as those that can be applied during in vitro studies. Also, these authors found a sinusoidal overload pattern during eccentric exercise that was not observed during concentric exercise (27). This force fluctuation probably reflects the difficulty to control the movement during the active muscle lengthening, a similar experience to that of lifting a large weight concentrically, which is easier from the motor control perspective than when lowering the weight eccentrically. This force fluctuation would be the stimulus for tendon remodeling.

The patellar tendon hypertrophy observed in the present study is compatible with the results from Seynnes et al. (34). They reported an average increase of 3.7% at the patellar tendon anatomical cross-sectional area. In this regards, Reeves et al. (29) did not observe an increase in the patellar tendon anatomical cross-section area in the 9 subjects that were subjected to 14 wks of conventional strength training. However, the authors did observe an increase in tendon stiffness, which they attributed to a change in the tendon material properties with training without changes in its size.

This different hypertrophic behavior might be related to the larger tendon overload caused by the eccentric training, given that the conventional strength training load is limited to the maximal load that can be lifted concentrically. Therefore, our results seem to be consistent with the theory that mechanical stress, as determined by strength training, determines an increase in protein synthesis at the extracellular matrix of tendons (21).

Muscle Mechanical Properties

Several studies have demonstrated that skeletal muscle morphological adaptations, such as changes in fiber length, lead to changes in muscle mechanical properties (7,14-16,19). However, it is not likely that this effect when caused by strength training represents a change at the range of action of the fascicles, especially since Reeves and colleagues (30,31) have demonstrated that the force-velocity relation is not influenced by strength training using regular strength training machines. Interestingly, our results disagree with their findings, given that we observed a torque increase in both strength-training modalities both at concentric and eccentric angular velocities thereby affecting the torque-velocity relationship.

Reeves and colleagues (28) observed that when the elderly were subjected to eccentric training they increased their torques at the eccentric angular velocities of the torque-velocity relation, but not at the concentric ones. On the other hand, when the elderly subjected to the conventional strength training, they showed torque increases only at the concentric angular velocities. Reeves et al. (28) attributed these findings to the specificity of the strength training executed, with emphasis at the concentric part at the conventional training and exclusive eccentric training on the eccentric elderly group.

CONCLUSIONS

Concentric and eccentric strength training performed at each lower limb produced similar between-limb structural (muscle architecture) and strength (maximal torque) changes, with similar changes at the torque-angle and torque-velocity relations in healthy elderly subjects. Nevertheless, eccentric training generated a larger increase in strength as measured by the 5 RM test and a larger increase at the patellar tendon anatomical cross-sectional area. The mechanical overload produced by the strength-training machine seems to be more important than the contraction type used for strength training at the knee extensor muscles.

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