Strength Training's Chronic Effects on Muscle Architecture Parameters of Different Arm Sites

Thiago Matta, Roberto Simão, Belmiro Freitas de Salles, Juliano Spineti, and Liliam Fernandes Oliveira

Rio de Janeiro Federal University, Physical Education Post-Graduation Program, Rio de Janeiro, Brazil

Abstract

Matta, T, Simão, R, de Salles, BF, Spineti, J, and Oliveira, LF. Strength training's chronic effects on muscle architecture parameters of different arm sites. *J Strength Cond Res* 25(6): 1711–1717, 2011—Strength training generates alterations in muscle geometry, which can be monitored by imaging techniques as, for example, the ultrasound (US) technique. There is no consensus about the homogeneity of hypertrophy in different muscle sites. Therefore, the purpose of this study was to compare the muscle thickness (MT) and pennation angle (PA) in 3 different sites (50, 60, and 70% of arm length) of the *biceps brachii* and *triceps brachii* after 12 weeks of strength training. Forty-nine healthy untrained men were divided into 2 groups: Training Group ([TG, $n = 40$] 29.90 ± 1.72 years; 79.53 ± 11.84 kg; 173 ± 0.6 cm) and Control Group ($n = 9$ 25.89 ± 3.59 years; 73.96 ± 9.86 kg; 171 ± 6 cm). The TG underwent a strength training program during 12 weeks, which included exercises such as a free-weight bench press, machine lat pull-down, triceps extension in lat pull-down, and standing free-weight biceps curl with a straight bar. A US apparatus was used to measure the PA and MT at the 3 sites. The maximal voluntary isometric contraction (MVC) test was conducted for each muscle group. After 12 weeks of training, a significant difference was observed between MT in *biceps brachii*, with an improvement of 12% in the proximal site, whereas the distal site increased by only 4.7% ($p < 0.05$). For the long head of the *triceps brachii*, the MT and PA at the 3 sites presented significant increases, but no significant variation was observed among them, probably because of the pennated-fiber arrangement. The MVC increased significantly for both muscle groups. The results indicated that the strength training program was efficient in promoting hypertrophy in both muscles, but with dissimilar responses of the pennated and fusiform muscle architecture at different arm sites.

Key Words resistance-training, muscle geometry, biceps brachii, triceps brachii.

Address correspondence to Liliam Fernandes Oliveira, liliam@eefd.ufrj.br.

25(6)/1711–1717

Journal of Strength and Conditioning Research

Introduction

The plasticity of skeletal muscles, induced by the application of different mechanical stimuli, has been addressed in vivo with image scanning techniques (2,15,16,25). Because the capacity to produce strength in skeletal muscles is affected by its architecture, in particular with respect to the number of muscle fibers in parallel (9,12,18,22), the use of ultrasonography and magnetic resonance imaging proved to be useful in monitoring muscle adaptations to strength training programs (1,11,17,23). Research studies that aim at validating measures with ultrasonography are accomplished in several populations (19,21), in anatomical pieces (14) and through magnetic resonance imaging (24) with significant correlations (e.g., $r = 0.86$ for the volume of elbow flexors). Pennation angle (PA), defined as the angle between muscle fibers and the line of pull of tendons, and muscle thickness (MT) likely reflect muscle hypertrophy in response to strength training protocols (1,6,9,17). However, the hypertrophy results from changes in MT and PA uniformly or heterogeneously distributed along muscle tissue are still unclear, especially concerning muscles with different geometries (20).

Recently, the uniformity of muscle hypertrophy resulting from strength training has been addressed for quadriceps muscles. Seynnes et al. (28) demonstrated that the cross sectional area of the quadriceps muscles increased equally at the distal and at the proximal portions after applying a flywheel training protocol for 5 weeks. In addition, Blazevich et al. (4,6) also reported homogeneous changes in PA along the quadriceps muscles after 5 weeks of isokinetic strength training. However, contrary to these results, when comparing the effects induced by 3 different protocols for strength training applied during 5 weeks to athletes of rugby, soccer, and netball, Blazevich et al. (5) observed differences in PA and MT of the *rectus femoris* and *vastus lateralis* muscles

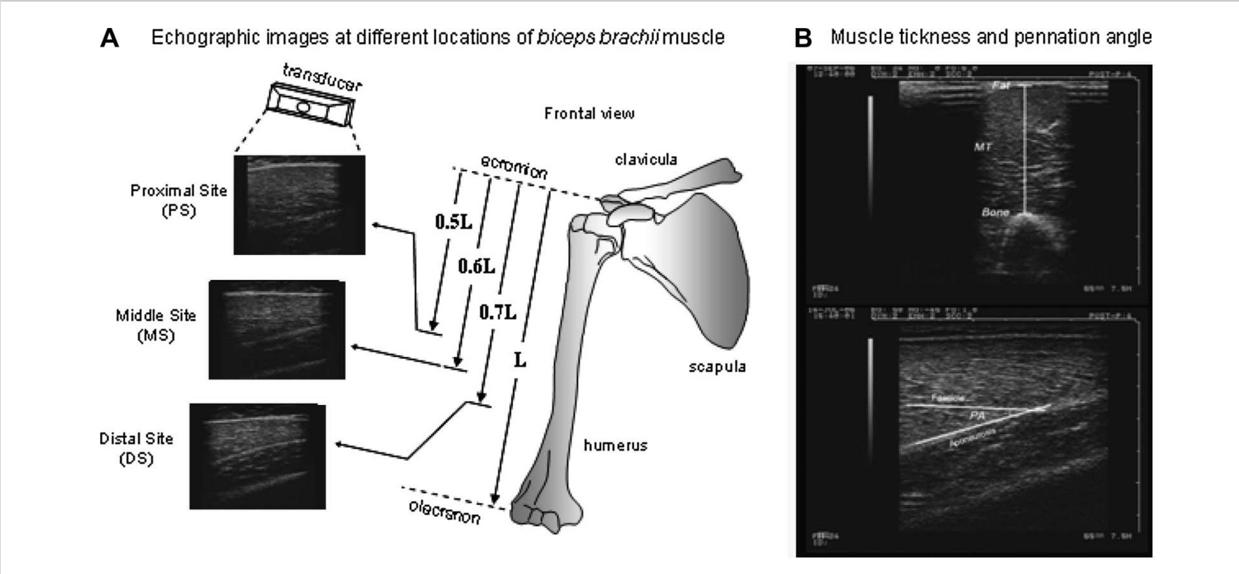

Figure 1. (A) Echographic images at different locations of the *biceps brachii* muscle; (B) muscle thickness of the *biceps brachii* and pennation angle of the long head of the *triceps brachii*.

between the distal and proximal sites (DS and PS). Besides dealing exclusively with leg muscles, these studies focused only on short-term effects of strength training.

Muscle adaptations after short-term training programs comprising elbow flexors and extensors are reported only for 1 muscle site. Although significant increases in MT and PA have been reported for subjects undergoing prolonged intense strength training (7,20,23), it is not clear if these adaptations are homogeneously distributed along the muscle geometry.

Therefore, the aim of this study was to investigate the effects of a 12-weeks' strength training protocol on the architecture of the *biceps brachii* and *triceps brachii* muscles with ultrasound (US) scanning. Possible heterogeneities in the distribution of such architectural changes are evaluated by considering individual sites of each muscle, namely, proximal, central, and distal.

Methods

Experimental Approach to the Problem

The participants from the Sergeants School from Brazil Navy were randomly assigned to a control group (CG) and a training group (TG). The strength training program was conducted in a nonlinear periodized fashion by TG during 12 weeks (24 sessions), 2 sessions per week with, at least, a 72-hours interval between sessions. The CG continued performing the regular military physical activity component during the 12-week period but not the strength training program. The exercises of the training program were as follows: free-weight bench press, machine lat pull-down, triceps extension in lat pull-down, and barbell biceps curl. To describe the changes of the *biceps brachii* and *triceps brachii* muscles after the strength training program, the PA, MT, and 8-second maximal voluntary isometric contraction test (MVC) of these muscles were measured before and after 12 weeks (pre and posttraining periods).

Subjects

Forty-nine healthy male subjects were divided into 2 groups: the TG group ($n = 40$; 29.90 ± 1.72 years; 79.53 ± 11.84 kg; 173 ± 6 cm) and the CG group ($n = 9$; 25.89 ± 3.59 years; 73.96 ± 9.86 kg; 171 ± 6 cm). To be included in the study, all participants (29) (a) had to be physically active but had not performed resistance training for at least 6 months before the start of the study; (b) should not have performed any type of regular physical activity for the duration of the study other than the prescribed resistance training and regular military physical activity program; (c) should not have had any functional limitation for the resistance training or the performance of the tests; (d) should not have presented any medical condition that could influence the training program; and (e) should not have used any nutritional supplementation (the military diet was the same for all the participants). This study was approved by the ethical committee of the Clementino Fraga Hospital at Rio de Janeiro Federal University and was consistent with their requirement for human experimentation. Each subject was informed of the purpose and procedures of this study and possible risks of the measurements beforehand. Written informed consent was obtained from each subject.

Estimation of Muscle Architecture

A US device (EUB-405, Hitachi, Tokyo, Japan with a linear probe of 7.5 MHz) was used to scan the *biceps brachii* and

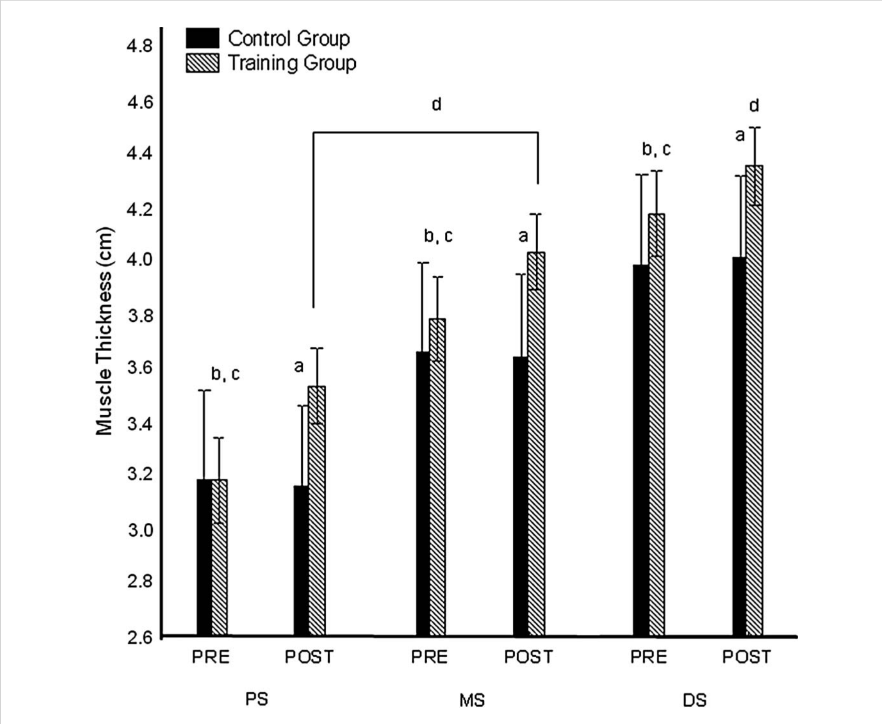

Figure 2. Muscle thickness (mean and *SD*) of the *Biceps Brachii* in proximal, middle, and distal arm sites in pre and post-12 weeks of resistance training. (A) Difference between groups posttraining (training group [TG] and control group [CG]); (B) difference between pre and posttraining (only for TG); (C) difference between proximal site (PS)-pre, midsite (MS)-pre, and distal site (DS)-pretraining (only for TG); (D) difference between PS-post and MS-post for DS-post training (only for TG) ($p < 0.05$).

triceps brachii muscles at 3 different sites, termed as proximal (PS), midsite (MS), and distal (DS). These sites were defined, respectively, as 50, 60, and 70% of the distance between the posterior crista of the acromion and the olecranon of the elbow joint, starting from the latter (Figure 1A), as proposed by Miyatani et al. (24). The US probe was centered with respect to each location (Figure 1A), and the echographic images were recorded with subjects standing in the upright position and their arms alongside the body, after coating the transducer with a water-soluble transmission gel.

Muscle thickness of the *biceps brachii* and of the *triceps brachii* long head was estimated from digitized images of each site of these muscles, with the probe transversally positioned with respect to the segment. The MT was defined as the distance from the interface between the muscle and bone tissues to the interface between the muscle and fat tissues (Figure 1B). The PA was estimated as the acute angle between 2 lines fitted to the fascicles and to the deep aponeurosis of *triceps brachii* muscle (Figure 1B). Both MT and PA were computed with a custom graphical interface developed in Matlab 7.0.1 (The Mathworks, Natick, MA, USA). These variables were estimated twice for each subject, muscle, and muscle portion, and the averaged value was considered for further analysis. To certify that US measures pre and posttraining were accomplished in the same site, an individual adhesive transparent plastic tape, with the respective marks for PS, MS, and DS, was used along the 12 weeks (4).

Muscle Strength

Maximal voluntary isometric contractions (MVCs) were applied to investigate the effectiveness of the training protocol on the improvement of muscle strength for the *biceps* and *triceps brachii*. Subjects performed 2 MVC trials of 8 seconds after verbal command, with 2 minutes' rest between trials. The highest force value was considered for analysis. For the elbow flexors, the subjects, in a sitting position, had the right elbow flexed at 90° and the forearm in the supine position. For elbow extensors, the subjects were in a supine position with the right shoulder and elbow flexed at 90° and the forearm in neutral position. The wrist was wrapped by a strap fixed to a rigid cable connected to the force transducer fixed on the floor. A similar protocol was used (26) for acquisition of the MVC test signs a system, a cell of load of 200 kg and the sign of force was recorded through the software MIOGRAPH 13 (MIOTEC–Biomedical Equipments, Porto Alegre, Brazil).

Training Procedures

The free-weight bench press, machine lat pull-down, barbell biceps curl, and triceps extension in lat pull-down exercises were selected because of the involvement of the muscles analyzed. A nonlinear periodized resistance training program was used. In 1 session were accomplished 4 sets with light intensity (12–15 repetitions) in each exercise with 1-minute rest between the sets, in the next session were accomplished 3 sets with moderate intensity (8–10 repetitions) in each exercise with 2 minutes' rest between the sets, and in the third and final session of the cycle were accomplished 2 sets with high intensity (3–5 repetitions) in each exercise with 3 minutes' rest between the sets. During the exercise sessions, participants were verbally encouraged to perform all sets to concentric failure, and the same definitions of a complete range of motion were used to define completion of a successful repetition. There was no attempt to control the velocity of the repetitions performed. Whenever an individual could perform

Table 1. Statistical interaction among muscle sites and pre and post-12 weeks of strength training in MT and PA (only *triceps brachii*) for the TG.*

p Value	MT biceps brachii	MT triceps brachii	PA triceps brachii
	0.025	0.229	0.848

*MT = muscle thickness; PA = pennation angle; TG = training group.

more than the prescribed number of repetitions for all sets of a given exercise, the resistance for that particular exercise was increased. An experienced strength and conditioning professional supervised all training sessions. The frequency of the training program was 2 sessions per week with at least 72 hours of rest between sessions. A total of 24 sessions (8 cycles of 3 sessions) was performed in the 12 weeks' training period with all sessions occurring between 7 and 8 AM. Before each training session, the participants performed a specific warm-up, consisting of 20 repetitions with approximately 50% of the resistance used in the first exercise of the training session. Adherence to the program was 100% for TG.

Statistical Analyses

Adaptations of muscle geometry, because of the application of the 12 weeks' strength training protocol, were evaluated by comparing changes in MT and PA between groups and muscle portions, before and after the training period. Intraclass correlation coefficients (ICCs) were used to determine MT measurement test–retest reliability. Retest correlation was measured by Pearson correlation coefficient (r). Because the distribution of MT and PA values was Gaussian, as confirmed by applying Kolmogorov–Smirnov tests, a multifactorial design (multivariate analysis of variance, 3 muscle sites $\times$ 2 groups $\times$ 2 pre–post measurements) was applied for comparisons, with before–after factor as repeated measures. The Tukey post hoc test was used for pairwise comparisons of mean values. A 2-way ANOVA (2×2) was applied to compare the results between MVC tests pre and posttraining program and between groups. Statistical analyses were carried out with the Statistica 7.0 software (Statsoft, Inc., Tulsa, OK, USA), and the significance level was set to 5% ($p \leq 0.05$).

Results

The MT test–retest reliability showed a high ICC at baseline for biceps brachii (PS, $r = 0.98$, $SEM = 0.64$; MS, $r = 0.97$, $SEM = 0.61$; DS, $r = 0.93$, $SEM = 0.51$), and after 12 weeks of training (PS, $r = 0.96$, $SEM = 0.54$; MS, $r = 0.93$, $SEM = 0.51$; DS, $r = 0.98$, $SEM = 0.46$). For triceps brachii, MT also showed a high ICC at baseline (PS, $r = 0.96$, $SEM = 0.51$; MS, $r = 0.98$, $SEM = 0.56$; DS, $r = 0.94$, $SEM = 0.46$) and posttraining (PS, $r = 0.98$, $SEM = 0.54$; MS, $r = 0.97$, $SEM = 0.51$; DS, $r = 0.98$, $SEM = 0.45$) for TG.

Our main result demonstrated the nonproportional hypertrophy of the *biceps brachii* after the training program. Figure 2 illustrates the results for MT. The MT significantly increased for the 3 sites after the training program ($p < 0.05$, $p < 0.05$, and $p = 0.003$ for PS, MS, and DS, respectively), and the MT of the PS remained significantly lower than the distal one, since pre test configuration ($p < 0.05$ for pre and posttraining). This increase was not proportional along the muscle, in which the MT at PS increased approximately

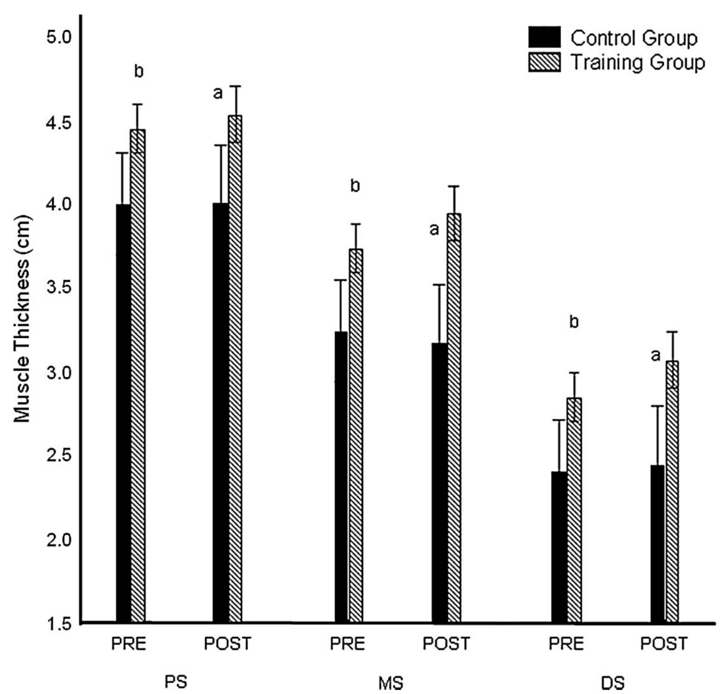

Figure 3. Muscle thickness (mean and *SD*) of the *Triceps Brachii* in proximal, middle, and distal arm sites in pre and post-12 weeks of resistance training. (A) Difference between groups posttraining (training group [TG] and control group [CG]); (B) difference between pre and posttraining (only for TG) ($p < 0.05$).

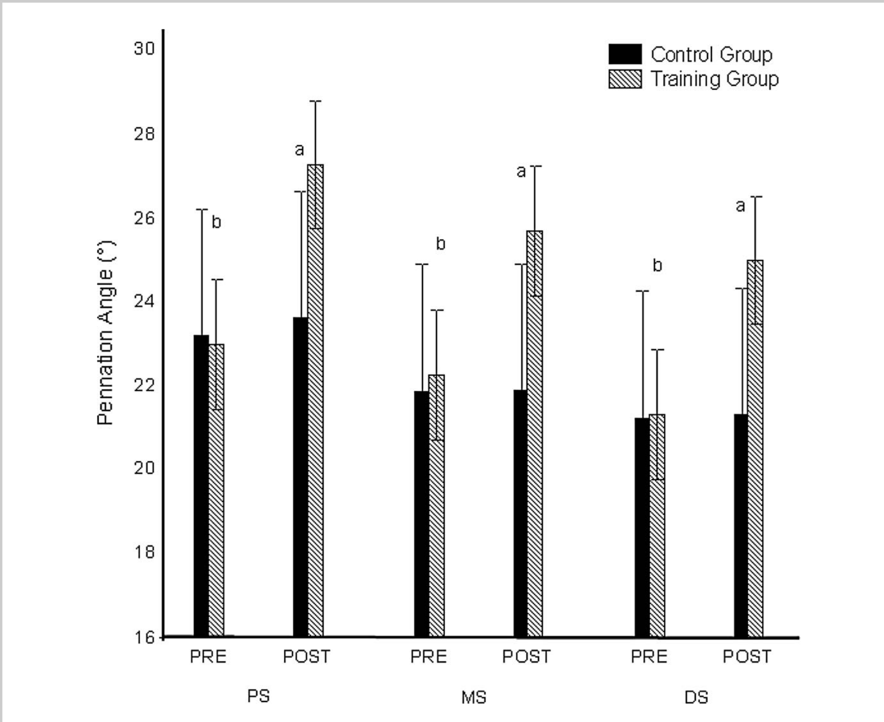

Figure 4. Pennation angle (mean and *SD*) of the *Triceps Brachii* in (mean and *SD*) of the *Biceps Brachii* in proximal, middle, and distal arm sites in pre and post-12 weeks of resistance training. (A) Difference between groups posttraining (training group [TG] and control group [CG]); (B) difference between pre and posttraining (only for TG) ($p < 0.05$).

12%, whereas at DS, it increased 5%. The same MT variations observed occurred between TG posttraining and GC. Table 1 demonstrates the interaction between training and muscle sites ($p = 0.025$) that ratify the heterogeneous increase of biceps brachii MT after strength training.

The MT of the *triceps brachii* (Figure 3) significantly increased for the MS and DS after the training period ($p = 0.019$ and $p = 0.009$, respectively). The results for the PA (Figure 4) showed a significant increase for the 3 sites after the training ($p < 0.05$, $p = 0.002$, and $p = 0.008$, respectively). There were no differences in the PA among the sites studied before and after the training. Table 1 presents the p values among muscle sites and training program for the TG interaction and demonstrate the homogeneous hypertrophy of the *triceps brachii* based on both MT and PA parameters ($p = 0.229$ and $p = 0.848$, respectively).

The results for the MVC for elbow extension were 227.91 ± 47.83 and 258.52 ± 47.34 N ($p = 0.017$) and for elbow flexion were 338.62 ± 48.21 and 370.55 ± 53.17 N ($p = 0.025$), pre and post the strength training protocol, respectively.

For the muscle geometry parameters analyzed, there were no differences between CG and TG before the training program. For the CG, all the values pre and post 12 weeks' period were similar ($p > 0.05$).

Discussion

The possible differences between the adaptations of these 2 muscles with a different muscular architecture are a question raised by Kawakami et al. (20), and the results of this study can demonstrate the variation of the muscular parameters in a different way for the *biceps brachii* and the long head of the *triceps brachii*. The heterogeneous hypertrophy of the *biceps brachii* muscle, resulting from 12 weeks of strength training, was the key finding of this study. Curiously, the long head of the *triceps brachii* muscle did not exhibit a similar adaptation to strength training. The application of 12 weeks of strength training resulted in a disproportional increase of MT between different sites of the *biceps brachii*, with the PS showing the highest increase in thickness (12%) when compared with the other sites (7.5 and 5% for central and distal sites, respectively; Figure 2).

Even though the arrangement of the muscle fibers in the *biceps brachii* is typically associated with a fusiform architecture, the geometry than conventional reasoning can provide (8,27). The distal biceps tendon flattens into a strap-like internal aponeurosis, located along the distal centerline of the muscle and spans 34% of the length of the *biceps brachii* long head muscle (Lm) (3). Pappas et al. (27) examined the uniformity of shortening in the human *biceps brachii* muscle–tendon complex using magnetic resonance imaging. Shortening along the anterior boundary of the *biceps brachii* was relatively uniform during the active elbow flexion, with lower and high loads. In contrast, shortening along the centerline was nonuniform, being significantly lower in magnitude at the distal end (~0.15Lm) of the muscle, which contains aponeurosis tissue, compared with increased shortening at the midportion of the muscle (0.4–0.7 Lm). To which extent this increased shortening at biceps midportion could reflect in a more pronounced proximal hypertrophy, as verified in this study, is still to be clarified.

With respect to the specific site changes of the *triceps brachii* MT, Kawakami et al. (20) reported a significant increase in MT for 5 subjects after 16 weeks of strength training for elbow extension, when analyzing the muscle site corresponding to 60% of the arm length. We also found a statistical increase for the MS, which was measured at 60% arm length. Contrarily, Blazevich and Giorgi (7), using the same protocol as ours, did not find any significant increase of the MT at 50% of the arm length of 10 already hypertrophied subjects after 12 weeks of strength training. In our study, there was also no statistical variation between pre and posttraining in proximal MT measured at 50% arm length. By analyzing the DS, we found an increase similar to that of the MS, after the training program. Concerning MT absolute data, the values given in the literature range from 3.00 to 3.80 cm for nontrained subjects who were physically active to a moderate degree, respectively (10,24). Those findings are closely related to our results at baseline (3.54 $\pm$ 0.51 cm). We did not find comparisons among the MT at different muscle sites (Figure 3). This can be attributed to the complex functioning of the long portion of the *triceps brachii*, a multiarticular muscle (5), which at the same time acts as an extensor of the elbow and the shoulder. Another important factor is the anatomical structure differentiated with 3 portions of the same distal insertion and different proximal origins, beyond muscle.

The PA adaptation in response to strength training was first described by Kawakami et al. (20) who compared the triceps long head PA of control subjects and body builders at 60% arm length and found values ranging from 15 to 33°, respectively, which includes data reported on Olympics Athletes from different modalities (14–27°) (12). Specific data for participants of strength training programs describe a *triceps brachii* PA of 21.7° for young strength trainees (13), which is similar to the values of this study (ranging from 22 to 26°).

Our study showed PA increases in all 3 muscle sites, compared to the baseline values. Kawakami et al. (20) found a significant increase of 29% in PA measured at 60% of the arm length, after 16 weeks of isokinetic training, whereas in our study, for this same level, we observed a 16% increase. This difference could be explained by the different methodology of strength training, in which Kawakami et al.'s (20) participants practiced 4 weeks more with the isokinetic machine. We did not find other studies relating PA responses at different sites of the *triceps brachii*. For the quadriceps PA, Blazevich et al. (4,6) demonstrated no differences at 3 sites after 5 weeks of strength training program and suggested that it was because of the short-term strength training applied. In our study, the *triceps brachii* PA increased uniformly ($p = 0.848$) along the 3 levels even after 12 weeks of training. The *triceps brachii* long head, as the quadriceps muscles, are considered a pennated muscle, with its staple fibers terminating at the tendon (or aponeurosis) at a certain angle to the line of pull of the muscle. This arrangement allows more attachment of contractile materials and provides high force production and less range of motion (20,22). Different from the *biceps brachii*, the internal aponeurosis of the *triceps brachii* runs longitudinally along the whole muscle, which can lead to a uniform strain during the contraction resulting in a similar hypertrophy along the sites studied.

In addition to the MT, the muscular strength also increased for the 2 muscles studied, for the *biceps brachii*, the subjects had an increase of 10% in the MVC and 14% for *triceps brachii*, indicating that strength training with 4 exercises during 12 weeks was efficient for the development of muscular strength. Based on these findings, we conclude that the 12 weeks of strength training is efficient to modify the muscle strength and architecture of the 2 muscles studied. The *biceps brachii* response was different for the MT between sites, whereas the *triceps brachii* had uniform increases in the muscle parameters studied.

Practical Applications

The main purpose of this study was to verify regional hypertrophies of muscles with different muscular fiber architecture after the short-term strength training program. The elbow flexor exercises (machine lat pull-down and standing free-weight biceps curl) resulted in pronounced hypertrophy of the PS of the fusiform *biceps brachii* long head compared to the distal one, whereas the triceps exercises (free-weight bench press, machine lat pull-down, and lat pull-down triceps extension) resulted in a uniform hypertrophy of the *triceps brachii* pennated fibers. These results suggest that prescription of the presented 12 weeks' strength training program is effective in generating increases in MT at different muscle sites. Additionally, this study used the ultrasonography imaging technique, which is an inexpensive method and can be easily applied to verify muscle architecture parameters. The results of this study indicated that this method allows one to accurately assess the arm muscle hypertrophy in response to specific strength training programs.

Acknowledgments

Thiago Matta gratefully acknowledges CAPES for financial support of the 'Muscle Biomechanics Cooperation Network.' Dr. Roberto Simão would like to thank the Brazilian National Board for Scientific and Technological Development (CNPq).

References

1. Aagaard, P, Andersen, JL, Dyhre-Poulsen, P, Leffers, AM, Wagner, A, Magnusson, SP, Halkjaer-Kristensen, J, and Simonsen, EB. A mechanism for increased contractile strength of human pennate muscle in response to strength training: Changes in muscle architecture. *J Physiol* 534: 613–623, 2001.
2. Alegre, LM, Jimenez, M, Gonzalo-Orden, JM, Martín-Acero R, and Aguado, X. Effects dynamic resistance training on fascicle length and isometric strength. *J Sports Sci* 24: 501–508, 2006.
3. Asakawa, DS, Pappas, GP, Delp, SL, and Drace, JE. Aponeurosis length and fascicle insertion angles of the biceps brachii. *J Mech Med Biol* 13: 1–7, 2002.
4. Blazevich, A, Gill, N, Deans, N, and Zhou, S. Lack of human muscle architectural adaptation after short-term strength training. *Muscle Nerve* 35: 78–86, 2007.
5. Blazevich, A, Gill, ND, Bronks, R, and Newton, RU. Training-specific muscle architecture adaptation after 5-wk concurrent training in athletes. *Med Sci Sports Exerc* 35: 2013–2022, 2003.

6. Blazevich, A, Gill, ND, and Zhou, S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anatomy* 209: 289–310, 2006.
7. Blazevich, AJ and Giorgi, A. Effect of testosterone administration and weight training on muscle architecture. *Med Sci Sports Exerc* 33: 1688–1693, 2001.
8. Blemker, SS, Pinsky, PM, and Delp, SL. A 3D model of muscle reveals the causes of nonuniform strains in the biceps brachii. *J Biomech* 38: 657–665, 2005.
9. Burkholder, TJ, Fingado, B, Baron, S, and Lieber, RL. Relationship between muscle fiber types and sizes and muscle architectural properties in the mouse hindlimb. *J Morphol* 221: 177–190, 1994.
10. Fukunaga, T, Miyatani, M, Tachi, M, Kouzaki, M, Kawakami, Y, and Kanehisa, H. Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand* 172: 249–255, 2001.
11. Huijing, PA and Jaspers, RT. Adaptation of muscle size and myofascial force transmission: A review and some new experimental results. *Scand J Med Sci Sports* 15: 349–380, 2005.
12. Ichinose, Y, Kanehisa, H, Ito, M, Kawakami, Y, and Fukunaga, T. Relationship between muscle fiber pennation and force generation capability in Olympic Athletes. *Int J Sports Med* 19: 541–546, 1998.
13. Ikegawa, S, Funato, K, Tsunoda, N, Kanehisa, H, Fukunaga, T, and Kawakami, Y. Muscle force per cross-sectional area is inversely related with pennation angle in strength trained athletes. *J Strength Cond Res* 22: 128–131, 2008.
14. Infantolino, BW, Gales, DJ, Winter, SL, and Challis, JH. The validity of ultrasound estimation of muscle volumes. *J Appl Biomech* 23: 213–217, 2007.
15. Jones, DA and Rutherford, OM. Human muscle strength training: The effects of three different regimens and the nature of the resultant changes. *J Physiol* 391: 1–11, 1987.
16. Kanehisa, H, Nagareda, H, Kawakami, Y, Akima, H, Masani, K, Kouzaki, M, and Fukunaga, T. Effects of equivolume isometric training programs comprising medium or high resistance on muscle size and strength. *Eur J Appl Physiol* 87: 112–119, 2002.
17. Kawakami, Y. The effects of strength training on muscle architecture in humans. *Int J Sport Health Sci* 3: 208–217, 2005.
18. Kawakami, Y, Abe, T, and Fukunaga, T. Muscle fiber pennation angles are greater in hypertrophied than in normal muscles. *J Appl Physiol* 74: 2740–2744, 1993.
19. Kawakami, Y, Abe, T, Kaneshisa, H, and Fukunaga, T. Human skeletal muscle size and architecture: Variability and interdependence. *Am J Hum Biol* 18: 845–848, 2006.
20. Kawakami, Y, Abe, T, Kuno, S, and Fukunaga, T. Training induced changes in muscle architecture and specific tension. *Eur J Appl Physiol* 72: 37–43, 1995.
21. Kubo, K, Kanehisa, H, Azuma, K, Ishizu, M, Yakuno, S, Okada, M, and Fukunaga, T. Muscle architectural characteristics in women aged 20–79 years. *Med Sci Sports Exerc* 35: 39–44, 2003.
22. Lieber, RL. *Skeletal Muscle Structure, Function, & Plasticity–The Physiological Basis of Rehabilitation* (2nd ed.). Philadelphia, PA: Lippincott Williams & Wilkins, 2002.
23. Mccall, GE, Byrnes, WC, Dickinson, A, Pattany, PM, and Fleck, SJ. Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. *J Appl Physiol* 81: 2004–2012, 1996.
24. Miyatani, M, Kanehisa, M, Ito, M, Kawakami, Y, and Fukunaga, T. The accuracy of volume estimates using ultrasound muscle thickness measurements in different muscle groups. *Eur J Appl Physiol* 91: 264–272, 2004.
25. Narici, MV, Roi, GS, Landoni, L, Minetti, AE, and Cerretelli, P. Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *Eur J Appl Physiol* 59: 310–319, 1989.
26. Oliveira, LF, Matta, TT, Alves, DS, Garcia, MAC, and Vieira, TMM. Effect of the shoulder position on the biceps brachii EMG in different dumbbell curls. *J Sports Sci Med* 8: 24–29, 2009.
27. Pappas, GP, Asakawa, DS, Delp, SL, Zajac, FE, and John, E. Nonuniform shortening in the biceps brachiiduring elbow flexion. *J Appl Physiol* 92: 2381–2389, 2002.
28. Seynnes, OR, De Boer, MD, and Narici, MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol* 102: 368–373, 2007.
29. Simão, R, Farinatti, PTV, Polito, MD, Viveiros, L, and Fleck, SJ. Influence of exercise order on the number of repetitions performed and perceived exertion during resistance exercise in women. *J Strength Cond Res* 21: 23–28, 2007.