Varying the Order of Combinations of Single- and Multi-Joint Exercises Differentially Affects Resistance Training Adaptations

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Abstract

Brandão, L, de Salles Painelli, V, Lasevicius, T, Silva-Batista, C, Brendon, H, Schoenfeld, BJ, Aihara, AY, Cardoso, FN, de Almeida Peres, B, and Teixeira, EL. Varying the order of combinations of single- and multi-joint exercises differentially affects resistance training adaptations. *J Strength Cond Res* 34(5): 1254–1263, 2020—Our study aimed to compare the effects of multi-joint (MJ) and single-joint (SJ) exercises, either isolated or in combination, and in different orders, on cross-sectional area (CSA) of the pectoralis major (PM) and different heads of the triceps brachii (TB), as well as on the one-repetition maximum (1-RM) in the bench press and lying barbell triceps press. Forty-three young men were randomly assigned to one of 4 possible RT protocols: barbell bench press plus lying barbell triceps press (MJ + SJ, $n = 12$); lying barbell triceps press plus barbell bench press (SJ + MJ, $n = 10$); barbell bench press (MJ, $n = 10$); or lying barbell triceps press (SJ, $n = 11$). Results showed significant within-group increases in 1-RM bench press for MJ, MJ + SJ, and SJ + MJ but not for SJ. Conversely, significantly greater within-group increases in elbow extension 1-RM were noted for SJ, MJ + SJ, and SJ + MJ but not for MJ. Significantly greater increases in PM CSA were observed for MJ, MJ + SJ, and SJ + MJ compared with SJ. Significant increases in TB CSA were noted for SJ, MJ + SJ, and SJ + MJ, but not for MJ, without observed between-group differences. Individual analysis of TB heads showed significantly greater CSA increases in the lateral head for MJ, MJ + SJ, and SJ + MJ compared with SJ. Alternatively, significantly greater increases in the long head were observed for SJ, MJ + SJ, and SJ + MJ compared with MJ. CSA increases for the medial head were statistically similar between conditions. Our findings indicate that muscular adaptations are differentially affected by performance of MJ and SJ exercises.

Key Words: isolation exercise, exercise selection, exercise order, strength, muscle hypertrophy

Introduction

Resistance training (RT) has been advocated as a primary strategy to stimulate gains in muscle strength and mass (1,33). These muscular adaptations seem to be affected by the proper manipulation of many variables, including but not limited to exercise selection and order (1,32). General recommendations postulate that RT sessions should involve both multi-joint (MJ) and single-joint (SJ) exercises, where the MJ exercise involve more than one joint acting dynamically and target several muscle groups at a time, whereas the SJ exercise involve one joint acting dynamically and target a primary muscle group (1). Although some studies support this recommendation and have demonstrated greater increases in arm circumference with combined MJ plus SJ exercises (5,7), others have challenged this suggestion showing that MJ and SJ exercises promote similar gains in muscle strength and hypertrophy in untrained individuals (15) and that the addition of SJ exercises to MJ exercises does not elicit additional muscular adaptations in untrained (16) or trained individuals (6,11) or even bodybuilders (4).

A number of points, however, need to be considered in the interpretation of the aforementioned results. Some studies assessed muscle thickness of the elbow flexors with B-mode ultrasound (15,16), whereas others used arm circumference measurements (4–7,11). Because all studies were conducted involving exercises for both flexor and extensor muscles of the elbow joint and circumference measures are not able to separately discriminate the increase in the size of these muscles, it remains inconclusive as to the isolated and combined effects of MJ and SJ exercises on muscle hypertrophy when assessed by magnetic resonance imaging (MRI), which has high reliability values (i.e., coefficient of variation [CV] $<1\%$) and is considered the gold-standard assessment of whole muscle cross-sectional area (CSA) (29). Moreover, the aforementioned findings may have been influenced by other factors, such as exercise order and nonuniform muscle hypertrophy.

Regarding exercise order, current guidelines recommend performing MJ before SJ exercises in an RT program (1). The rationale for this recommendation is based on the assumption that performance of MJ exercise is impaired when the involved muscles are

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prefatigued by SJ exercise (1,30). A limited number of longitudinal studies have attempted to investigate the influence of exercise order on upper limb strength and hypertrophy, and results are somewhat conflicting. Attenuation in muscle strength has been shown for exercises placed at the end of the RT session, regardless of whether they are MJ or SJ (2,12,37,38). Alternatively, muscle hypertrophy has shown contradictory results, with some studies showing no effect of exercise order (3,38) and others reporting that hypertrophy only occurred when a muscle group functioned as an agonist at the onset of the RT session (37). In addition, studies have reported that muscle hypertrophy may occur nonuniformly along the length of a muscle (20,22), and there is evidence that different MJ and SJ exercises may promote differential increases in different regions of a muscle group (18,25). A recent study by Mannarino et al. (21) compared hypertrophic adaptations between MJ and SJ exercises at 3 different sites of the elbow flexors via B-mode ultrasound. After 8 weeks, muscle thickness was more than twofold greater in the arm that performed SJ compared with MJ exercise (11.1 vs. 5.2%, respectively). In addition, Wakahara et al. (40) demonstrated increases in the CSA of the distal triceps brachii (TB) were lower than in the medial and proximal regions after a 12-week program involving performance of the lying barbell triceps press. In a subsequent study, the same group observed a smaller increase in the CSA of the TB at the proximal region compared with the medial and distal regions after a MJ exercise (dumbbell bench press) (39). Although the researchers concluded that hypertrophy along the TB muscle might be different across the long, medial, and lateral heads, no direct measurement of the hypertrophy in the different muscle bellies was made. Therefore, it is conceivable that the discrepancies related to MJ and SJ exercises may be related to nonuniform muscle hypertrophy.

The aim of this study was to compare the effects of a 10-week RT program using MJ and SJ exercises, either isolated or in combination, and in different orders, on CSA of the pectoralis major (PM) and different heads of the TB, as well as on the one-repetition maximum (1-RM) in the bench press and lying barbell triceps press in young, untrained subjects. Considering all exercises involved the same relative loads, we hypothesized that (a) strength gains would follow the specificity principle, without any influence of the exercise selection or order; (b) hypertrophy of the PM would be lower with isolated SJ exercise or when SJ exercise was performed before the MJ exercise (due to fatigue of the TB in the SJ exercise, thereby limiting subsequent MJ exercise performance), whereas hypertrophy of TB would not be influenced by the exercise order (because both the MJ and SJ exercises involve the TB as a synergist and agonist, respectively) and; (c) regardless of the exercise order, MJ plus SJ exercises would result in greater hypertrophy of the lateral, long, and medial heads of TB compared with isolated MJ or SJ exercises.

Methods

Experimental Approach to the Problem

Before (PRE) the RT program, all subjects were familiarized with performance of the 1-RM test in the barbell bench press and lying barbell triceps press exercises. Seventy-two hours after the first session, subjects repeated the 1-RM test for both exercises and were considered familiarized with the testing procedures when the interday strength variation was $\leq$5%, having the highest value as 1-RM. The 1-RM values for all the subjects were obtained within 4 $\pm$ 1 visits for barbell bench press and 3 $\pm$ 1 visits for lying barbell triceps press. After the fifth week of training, 1-RM was reassessed to adjust the training load. Ninety-six hours after completion of the 10-week training period (POST), subjects were reassessed in the 1-RM test. Subjects were requested to abstain from alcohol in the 48 hours before testing sessions, as well as caffeine in the 24 hours preceding the tests. They arrived at the laboratory at least 2 hours after their last meal and immediately began their warm-up. *Ad libitum* water consumption was allowed during all testing sessions.

The CSA of the PM and TB (whole muscle, as well as the lateral, long, and medial heads) muscles was obtained via MRI 72 hours after the initial 1-RM test. After the baseline MRI assessments, subjects were ranked into quartiles according to 1-RM in the lying triceps extension and whole muscle CSA values of the TB. Subjects from each quartile were then randomized (using https://www.randomizer.org/) to one of 4 possible RT protocols: barbell bench press plus lying barbell triceps press (MJ + SJ, N = 13); lying barbell triceps press plus barbell bench press (SJ + MJ, N = 12); barbell bench press (MJ, N = 12); or lying barbell triceps press (SJ, N = 13). Both PM and TB (including the medial, lateral and long heads) muscle CSA were reassessed at POST, 72 hours after the last RT session. Total training volume (TTV) was calculated for each group during the experimental protocol.

Subjects

Fifty healthy, young, and recreationally active (physical activity performed less than twice a week) men (aged 18–35 years) volunteered to participate in the study. Three subjects dropped out before completion due to low adherence (<85% of all sessions attended), and 4 subjects dropped out due to personal reasons; therefore, data from 43 subjects (MJ = 10; SJ = 11; MJ + SJ = 12; and SJ + MJ = 10) were considered in the analysis. Subjects had not participated in any kind of regular RT within the previous 6 months before the experimental period. To meet inclusion criteria, subjects could not use any dietary supplements during the study and for at least 2 months before the study, as well as any previous administration of anabolic steroids. Subjects were instructed to maintain their habitual diets and were regularly questioned about any change in diet that could potentially influence study results, such as the use of dietary supplements or variances in protein or carbohydrate intake. All subjects were availed to the benefits, discomforts, and risks of the study and then freely signed an informed consent form before participation. The study was conducted according to the Declaration of Helsinki, and the University of São Paulo's research ethics committee approved the experimental protocol.

Procedures

Maximum Dynamic Strength Test (One-Repetition Maximum). Maximum dynamic strength via the 1-RM test in the barbell bench press and lying barbell triceps press exercises, in this order, was interspaced by 30 minutes of recovery and followed the procedures described by Brown and Weir (8). The subjects performed a general 5-minute warm-up running on a treadmill at 9 km·h^{-1}, followed by 3 minutes of recovery. Subsequently, they performed a specific warm-up comprising one set of 8 repetitions at approximately 50% 1-RM and, after a 2-minute rest, an additional warm-up set of 3 repetitions at approximately 70% 1-RM. Both loads were estimated based on the subject's familiarization sessions. Subsequent lifts were single repetitions of progressively heavier loads, until failure. Three minutes after the specific warm-up, the 1-RM test started, and this protocol was used for both exercises. Performance of the barbell bench press was standardized across subjects by using a pronated grip width set at 200% of the biacromial distance; subjects were instructed to fully extend the elbow concentrically and to lightly touch the bar on the pectorals eccentrically. For the lying barbell triceps press, the shoulder angle was set at 90° of flexion; subjects were instructed to fully extend the elbow concentrically and to flex it eccentrically at a 90° degree angle, which was ensured by a metallic bar that limited the barbell displacement during each repetition. A 3-minute rest period was afforded between the attempts, with final values achieved in a maximum of 5 attempts. The greatest load lifted during the attempts was considered as the 1-RM. The CV between 2 1-RM values for the bench press and lying triceps extension exercises, performed on separate days, was 3.0 and 2.8%, respectively.

Pectoralis Major and Triceps Brachii Cross-Sectional Area. The CSA measurement of the PM and TB of the right upper arm was performed by MRI (1.5T Signa LX 9.1; Healthcare, Milwaukee, WI). For both PM and TB measures (including all heads), a T1-weighted, spin-echo, axial plane sequence was obtained using the following parameters: pulse sequence with a field of view = between 400 and 420 mm, repetition time = 350 ms, echo time = from 9 to 11 ms, slice thickness = 0.8-cm, 2 signal acquisitions, and matrix of reconstruction = 256 × 256 mm. Subjects initially rested quietly in the supine position with elbows extended for 15 minutes to allow fluid distribution before the assessments (9). Velcro straps were used to restrain arm movements during image acquisition, and the exact positioning of the individual's arm on the stretcher was demarcated with tape for subsequent similar reproduction of this measurement. Images were obtained on the right side of the body. If a subject's breathing caused an increase in signal noise in the obtained images, the subject was instructed to refrain from breathing at the moment that each scan was undertaken. Initially, the CSA reference point for measurement of the PM was established at the level between the T3/T4 thoracic spine as this point corresponded to the most pronounced CSA of the PM muscle for most subjects. Subsequently, for the whole TB CSA measurement, an initial image was obtained to determine the perpendicular distance from the lateral epicondyle of the humerus to the acromial process of the scapula, which was defined as the length of the segment. The definition of the slice for analysis was individually determined for each subject according to the image in which the whole TB and the boundaries between each head (lateral, long, and medial) were clearly delineated in a single slice. The CSA for the whole muscle and the 3 heads was acquired between 50 and 60% of the segment length. The segment slice was divided into skeletal muscle, subcutaneous fat, bone, and residual tissue. Cross-sectional area measures were then determined by subtracting the bone and subcutaneous fat area. All images were transferred to a computer (Mac OS X, version 10.5.4; Apple, Cupertino, CA), manually outlined, and analyzed using open-source software (OsiriX, version 3.2.1; OsiriX Imaging Software, Geneva, Switzerland). Care was taken to exclude intramuscular fat and blood vessels from MRI analyses. The CSA images were traced in triplicates by a specialized researcher, and their mean values were used for all further analysis. An example of the images obtained from PM and TB (including all heads) muscle CSA using the technique of MRI is presented in Figure 1. All CSA analyses were conducted by the same trained blinded researcher. The CV values between 2 measures performed 72 hours apart for the PM, whole TB, lateral head, long head, and medial head were 0.82, 0.79, 1.12, 1.23, and 0.98%, respectively.

Resistance Training Program. The RT program was performed twice a week (with a minimum 48-hour recovery interval between sessions) for 10 weeks, comprising a total of 20 sessions. At the beginning of each training session, subjects performed a general

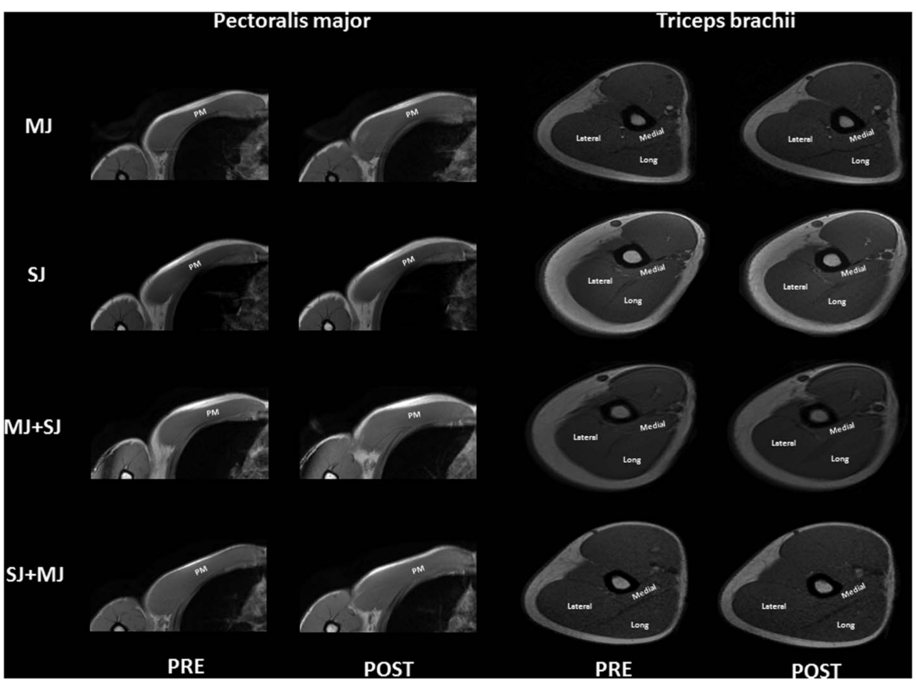

Figure 1. Representative cross-sectional area (CSA) of PM and all heads TB (lateral, long, and medial) from one subject in each group before (PRE) and after (POST) a 10-week resistance training program with multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. The relative CSA changes shown in the figure for PM, lateral, long, and medial head of TB correspond to 10.3, 4.8, 1.3, and 9.8%, respectively for MJ; 0.2, 0.9, 5.2, and 12.5%, respectively for SJ; 12.1, 6.8, 16, and 12%, respectively for MJ + SJ; and 6.0, 5.2, 14, and 11%, respectively, for SJ + MJ.

warm-up at 9 km·h^{-1} on a treadmill for 5 minutes followed by a specific warm-up of 8 repetitions at 50% of 1-RM. After the warm-up, subjects performed the protocol specific to their respective group. Barbell bench press was standardized across subjects by using a pronated grip width set at 200% of the biacromial distance; subjects were instructed to fully extend the elbow concentrically and to lightly touch the bar on the pectorals eccentrically. For the lying barbell triceps press, the shoulder angle was set at 90° of flexion; subjects were instructed to fully extend the elbow concentrically and to flex it eccentrically at a 90° degree angle, which was ensured by a metallic bar that limited the barbell displacement during each repetition. Three sets were performed from the first to the fourth week, 4 sets from the fourth to the eighth week, and 5 sets from the 8th to the 10th week. All protocols were performed at an intensity of 80% 1-RM until muscle failure, with a 3-minute rest period afforded between sets for all groups and between exercises for MJ + SJ and SJ + MJ.

Statistical Analyses

Data are presented as mean ± *SD*, relative changes, and effect sizes (ES). The Kolmogorov-Smirnov test was used to evaluate data normality. Mixed models were performed for PM and whole TB CSA analysis, for CSA analysis in each head of TB (lateral, long, and medial), as well as for 1-RM analysis in the barbell bench press and lying barbell triceps press with "Group" (MJ + SJ, SJ + MJ, SJ, and MJ) and "Time" (PRE and POST) as fixed factors and "Subjects" as a random factor. Whenever a significant *F* value was obtained, a Tukey post hoc test was performed. The analysis of variance, with "Group" as the fixed factor, was used to determine between-group differences for anthropometric variables at baseline, TTV, as well as for relative changes in 1-RM, PM and TB whole CSA, and TB regionalized CSA. Effect sizes were calculated using Cohen's *d* (10) and were classified as follows: <0.2, negligible effect; 0.2–0.39, small effect; 0.40–0.75, moderate effect; and >0.75, large effect. The significance level was set at 5% ($P \leq 0.05$). The statistical software package SAS v.9.5 (Institute, Inc., Cary, NC) was used for the statistical analysis.

Results

Table 1 presents the anthropometric variables of subjects at baseline. No significant between-group differences ($p > 0.05$) were observed for any variable analyzed.

Table 1

Anthropometrics characteristics of the subjects at baseline.*†

	MJ	SJ	MJ + SJ	SJ + MJ	*p*
Age (y)	23.2 ± 4.9	24.4 ± 5.6	24.8 ± 7.4	22.6 ± 5.0	>0.05
Body mass (kg)	79.8 ± 13.1	81.2 ± 15.3	82.7 ± 15.9	80.7 ± 13.4	>0.05
Height (cm)	174.9 ± 5.9	178.7 ± 9.8	177.8 ± 9.7	176.5 ± 6.1	>0.05

*MJ = multi-joint; SJ = single-joint; MJ + SJ = multi-joint plus single-joint; SJ + MJ = single-joint plus multi-joint exercises.
†Data are presented as mean and *SD*.

Muscle Strength

No significant baseline differences were observed between groups in 1-RM for bench press (MJ: 72.3 ± 19.3 kg vs. SJ: 77.6 ± 21.1 kg vs. MJ + SJ: 75.2 ± 23.5 kg vs. SJ + MJ: 76.6 ± 11.5 kg; all comparisons, $p > 0.05$) or elbow extension (MJ: 36.6 ± 9.5 kg vs. SJ: 42.9 ± 12.6 kg vs. MJ + SJ: 37.2 ± 14.0 kg vs. SJ + MJ: 39.8 ± 6.6 kg; all comparisons, $p > 0.05$).

At POST, 1-RM in the bench press significantly increased (Figure 2A) for MJ ($p < 0.0001$; 27.1 ± 17.7%; ES = 0.91), MJ + SJ ($p < 0.0001$; 23.6 ± 14.4%; ES = 0.70), and SJ + MJ ($p < 0.0001$; 22.3 ± 15.4%; ES = 1.63), but not for SJ ($p = 0.21$; 9.9 ± 10.9%; ES = 0.32).

Conversely, 1-RM in the lying barbell triceps press significantly increased at POST (Figure 2B) for SJ ($p = 0.0001$; 23.2 ± 14.0%; ES = 0.71), MJ + SJ ($p < 0.0001$; 35.3 ± 26.3%; ES = 0.82), and SJ + MJ ($p < 0.0001$; 26.3 ± 17.2%; ES = 1.54), but not for MJ ($p = 0.19$; 18.6 ± 18.5%; ES = 0.75).

The relative change analysis revealed no significant between-group differences for the 1-RM increases in both the bench press (all comparisons, $p > 0.05$) (Figure 3A) and lying barbell triceps press exercises (all comparisons, $p > 0.05$) (Figure 3B).

Whole Muscle Hypertrophy

No significant baseline differences were observed between groups in CSA for PM (MJ: 41.3 ± 3.7 cm^2 vs. SJ: 40.5 ± 8.9 cm^2 vs. MJ + SJ: 39.1 ± 9.4 cm^2 vs. SJ + MJ: 41.0 ± 4.2 cm^2; all comparisons, $p > 0.05$) or TB (MJ: 36.6 ± 9.5 cm^2 vs. SJ: 42.9 ± 12.6 cm^2 vs. MJ + SJ: 37.2 ± 14.0 cm^2 vs. SJ + MJ: 39.8 ± 6.6 cm^2; all comparisons, $p > 0.05$).

At POST, PM CSA significantly increased (Figure 4A) for MJ ($p < 0.0001$; 9.1 ± 5.6%; ES = 0.95), MJ + SJ ($p < 0.0001$; 10.6 ± 6.1%; ES = 0.41), and SJ + MJ ($p = 0.006$; 5.6 ± 5.1%; ES = 0.51), but not for SJ ($p = 0.99$; −0.8 ± 1.9%; ES = 0.05).

Triceps brachii CSA significantly increased at POST (Figure 4B) for SJ ($p < 0.0001$; 9.5 ± 4.8%; ES = 0.56), MJ + SJ ($p < 0.0001$; 11.5 ± 5.1%; ES = 0.47), and SJ + MJ ($p < 0.0001$;

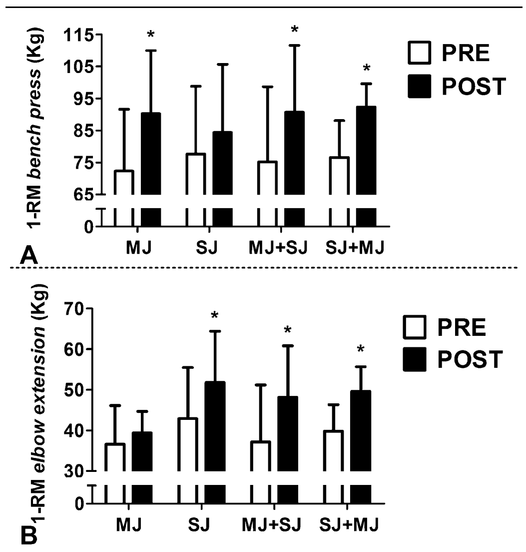

Figure 2. A) Maximum dynamic strength (one-repetition maximum [1-RM], in kg) in the bench press exercise before (PRE) and after (POST) a 10-week resistance training program with multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) 1-RM (in kg) in the elbow extension exercise PRE and POST a 10-week resistance training program with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol * refers to a significant within-group effect ($p < 0.05$).

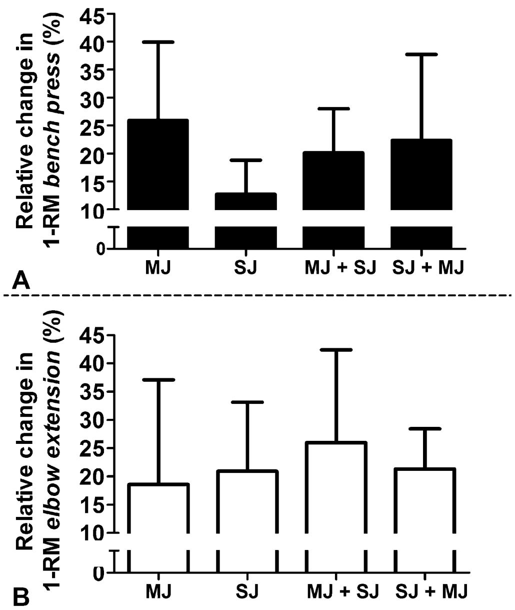

Figure 3. A) Relative change in the bench press maximum dynamic strength (one-repetition maximum [1-RM], in kg) with the multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) Relative change in the elbow extension 1-RM with MJ, SJ, MJ + SJ, and SJ + MJ exercises.

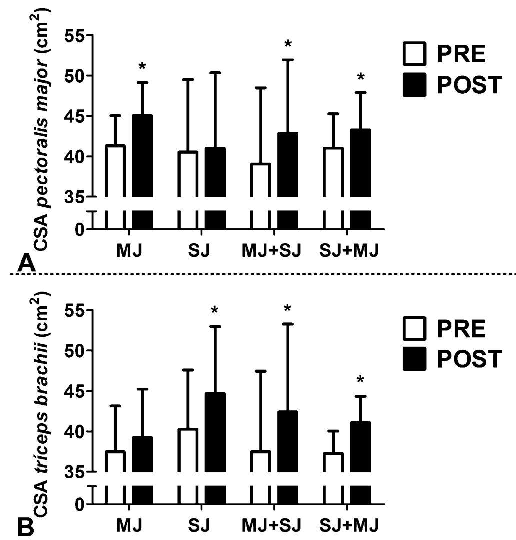

Figure 4. A) Cross-sectional area (CSA, in cm^2) of the pectoralis major muscle before (PRE) and after (POST) a 10-week resistance training program with multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) CSA (in cm^2) of the triceps brachii muscle PRE and POST a 10-week resistance training program with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol * refers to a significant within-group effect ($p < 0.05$).

10.4 ± 6.1%; ES = 1.26), but not for MJ ($p = 0.20$; 4.8 ± 4.2%; ES = 0.30).

The relative change analysis (Figure 5A) revealed a significant difference for the CSA increases in PM for MJ, MJ + SJ, and SJ + MJ compared with SJ (all comparisons, $p < 0.05$). On the other hand, the relative change analysis did not reveal any significant between-group difference for the CSA increases in TB (Figure 5B; all comparison, $p > 0.05$).

Triceps Brachii Regional Hypertrophy

No significant baseline CSA differences were observed between groups for the TB lateral head (MJ: 18.2 ± 3.1 cm^2 vs. SJ: 19.9 ± 4.4 cm^2 vs. MJ + SJ: 19.1 ± 5.9 cm^2 vs. SJ + MJ: 18.9 ± 2.4 cm^2; all comparisons, $p > 0.05$), long head (MJ: 14.3 ± 2.3 cm^2 vs. SJ: 15.5 ± 3.9 cm^2 vs. MJ + SJ: 14.0 ± 4.2 cm^2 vs. SJ + MJ: 13.9 ± 1.4 cm^2; all comparisons, $p > 0.05$), or medial head (MJ: 4.9 ± 1.0 cm^2 vs. SJ: 4.9 ± 1.7 cm^2 vs. MJ + SJ: 4.3 ± 0.7 cm^2 vs. SJ + MJ: 4.5 ± 0.5 cm^2; all comparisons, $p > 0.05$).

Significant increases in TB lateral head CSA occurred (Figure 6A) for MJ ($p = 0.02$; 7.2 ± 5.4%; ES = 0.35), MJ + SJ ($p = 0.0002$; 7.1 ± 2.8%; ES = 0.27), and SJ + MJ ($p = 0.0005$; 7.0 ± 5.1%; ES = 0.70), but not for SJ ($p = 0.97$; 0.6 ± 3.8%; ES = 0.17).

Significant increases in TB long head CSA occurred (Figure 6B) for SJ ($p < 0.0001$; 17.5 ± 7.3%; ES = 0.72), MJ + SJ ($p < 0.0001$; 18.2 ± 11.5%; ES = 0.55), and SJ + MJ ($p = 0.01$; 14.0 ± 9.2%; ES = 0.91), but not for MJ ($p = 0.99$; 2.1 ± 2.9%; ES = 0.12).

Significant increases in TB medial head CSA occurred (Figure 6C) for SJ ($p = 0.001$; 14.0 ± 7.1%; ES = 0.24), MJ + SJ ($p < 0.0001$; 16.2 ± 11.2%; ES = 0.88), and SJ + MJ ($p = 0.0009$; 14.7 ± 8.0%; ES = 0.93), but not for MJ ($p = 0.19$; 7.3 ± 5.0%; ES = 0.33).

The relative change analysis revealed a significant difference for the CSA increases in TB lateral head for MJ, MJ + SJ, and SJ + MJ compared with SJ (all comparisons, $p < 0.05$) (Figure 7A). Contrarily, the relative change analysis revealed a significant difference for the CSA increases in TB long head for SJ, MJ + SJ, and SJ + MJ compared with MJ (all comparisons, $p < 0.05$)

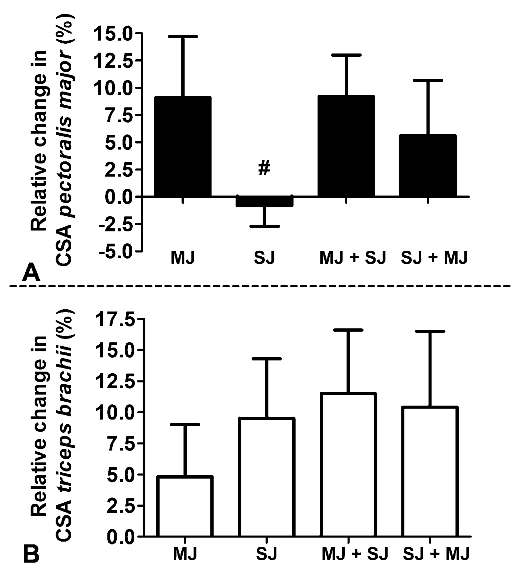

Figure 5. A) Relative change in the pectoralis major cross-sectional area (CSA, in cm^2) with the multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) Relative change in the triceps brachii CSA (CSA, in cm^2) with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol # refers to a significant difference from SJ ($p < 0.05$). The symbol $ refers to a significant difference from MJ ($p < 0.05$).

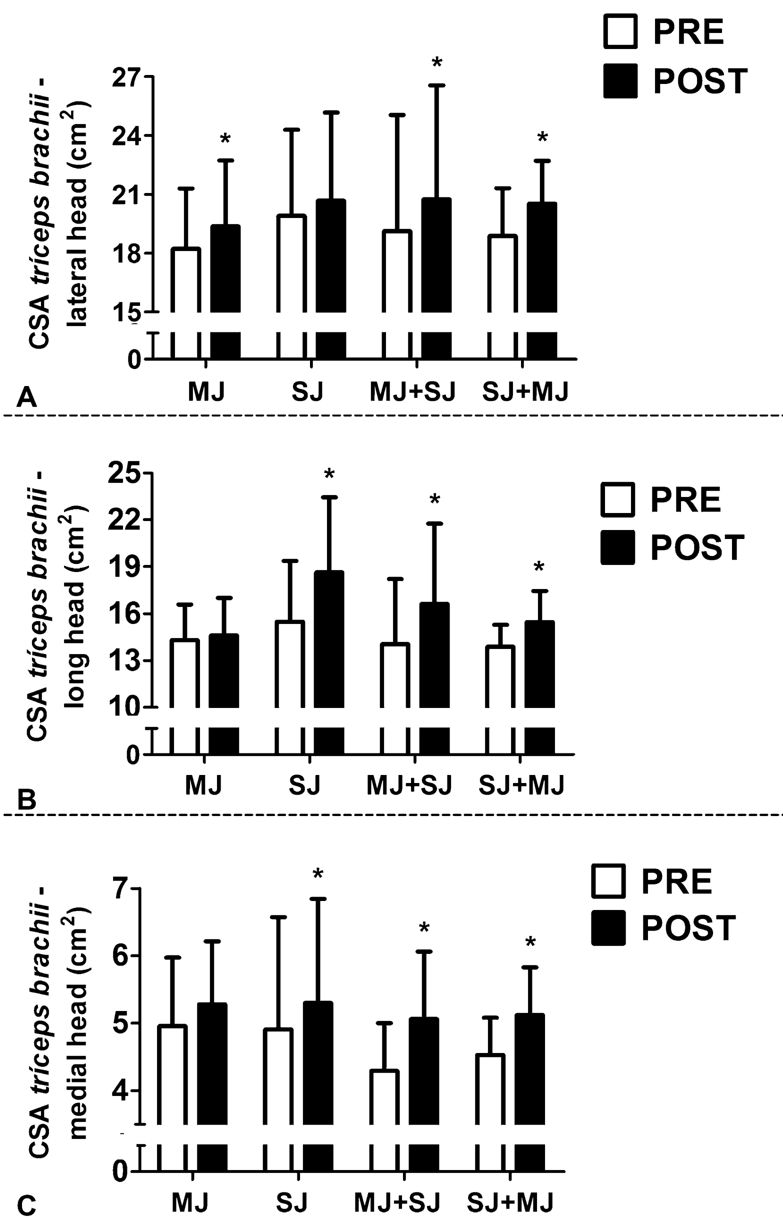

Figure 6. A) Cross-sectional area (CSA, in cm^2) of the triceps brachii lateral head before (PRE) and after (POST) a 10-week resistance training program with MJ, single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) CSA (in cm^2) of the triceps brachii long head PRE and POST a 10-week resistance training program with MJ, SJ, MJ + SJ, and SJ + MJ exercises. C) CSA (in cm^2) of the triceps brachii medial head PRE and POST a 10-week resistance training program with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol * refers to a significant within-group effect ($p < 0.05$).

(Figure 7B). No between-group significant differences for the CSA increases in TB medial head were detected (all comparisons, $p > 0.05$) (Figure 7C).

Total Training Volume

A significantly greater TTV for the bench press was found for the MJ group compared with SJ and SJ + MJ (for both comparisons, $p < 0.05$) (Figure 8A). Conversely, a significantly greater TTV for the lying barbell triceps press was found for the SJ and SJ + MJ groups compared with MJ and MJ + SJ (all comparisons, $p < 0.05$) (Figure 8B).

Discussion

The main findings of the present study were as follows: (a) All groups increased 1-RM strength consistent with the exercise specificity, without influence of exercise selection or order. (b) Despite of the lack of significant between-group differences in PM muscle hypertrophy across the groups that trained the barbell bench press exercise, the relative hypertrophic change was lower when the lying barbell triceps press was performed first in the sequence (SJ + MJ = +5.6%; MJ + SJ = +10.6%; MJ = +9.1%). (c) Whole TB muscle hypertrophy was not affected by the exercise order, although exercise selection may have had some

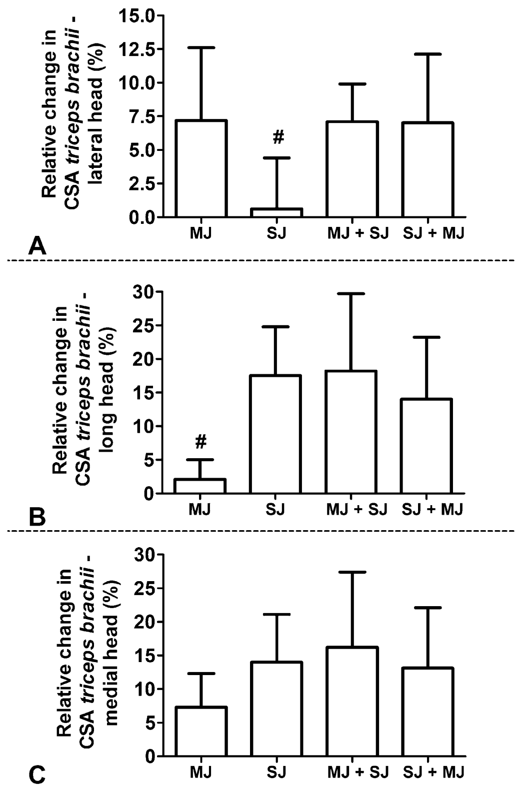

Figure 7. A) Relative change in the triceps brachii lateral head cross-sectional area (CSA, in cm^2) with the multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) Relative change in the TB long head CSA (CSA, in cm^2) with MJ, SJ, MJ + SJ, and SJ + MJ exercises. C) Relative change in the TB medial head CSA (CSA, in cm^2) with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol # refers to a significant difference from all other protocols (all comparisons $p < 0.05$).

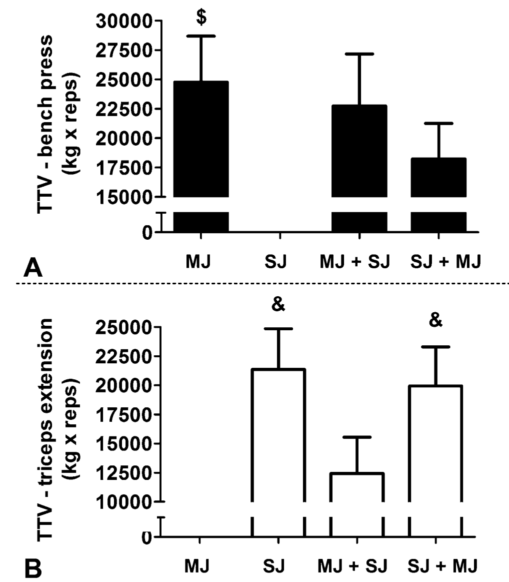

Figure 8. A) Total training volume (TTV, in kg × repetitions) of the bench press exercise during the 10-week resistance training program with multi-joint (MJ), single-joint (SJ), MJ plus SJ (MJ + SJ), and SJ plus MJ (SJ + MJ) exercises. B) TTV (in kg × repetitions) of the elbow extension exercise during the 10-week resistance training program with MJ, SJ, MJ + SJ, and SJ + MJ exercises. The symbol $ refers to a significant difference from SJ and SJ + MJ (all comparisons $p < 0.05$). The symbol & refers to a significant difference from MJ and MJ + SJ (all comparisons $p < 0.05$).

degree of influence because improvements were only detected for the groups that directly involved TB as an agonist (SJ, MJ + SJ, and SJ + MJ) as opposed to as a synergist (MJ). (d) Muscle hypertrophy of all TB heads only occurred when both MJ and SJ were combined within the same session (SJ + MJ and MJ + SJ).

Studies comparing dynamic strength gains in MJ and SJ exercise have shown conflicting results, with some demonstrating similar increases between conditions (15) and others reporting greater increases for MJ exercise (28). Discrepancies in these findings may be attributed to the used testing protocol. Specifically, Gentil et al. (15) showed similar increases in strength between MJ and SJ using a nonspecific test (isokinetic dynamometer), whereas Paoli et al. (28) found a strength advantage for MJ exercise when using a specific test (1-RM test for the same exercise used for the MJ protocol). There is evidence that the results of isokinetic and 1-RM tests are not equivalent (14) and that RT-induced strength gains are predicated on the specificity principle (21,23). Our results support this hypothesis, as no significant improvement in 1-RM was detected in the barbell bench press for the SJ group or in the lying barbell triceps press for the MJ group.

Intriguingly, strength increases were similar between conditions despite a reduction in TTV in the last exercise of the session for the MJ + SJ and SJ + MJ groups. These results are somewhat in conflict with previous studies that reported detrimental effects on muscle strength when MJ or SJ exercises were performed at the end of a session (2,12,37,38). Discrepancies may be related to the different training protocols used because previous studies based training loads on a zone of maximum repetitions, while we equated loads based on a relative intensity of load (i.e., 80% 1-RM). It has been suggested that the greatest gains in muscle strength during RT are achieved by the use of higher loads (19,24,35). These results are theorized to occur through alterations in neuromuscular factors including greater recruitment of motor units, higher firing rate of motor units, and/or greater changes in the agonist-antagonist co-activation rate compared with lower loads (13). Therefore, our findings suggest that the exercise specificity principle may have a greater impact on muscle strength gains compared with exercise selection or order, at least when a high relative load is prescribed. It also is conceivable that the similar strength increases observed in our study may be at least in part related to the fact that all groups trained to muscle failure, raising the possibility that the level of effort exerted during performance plays a dominant role in results. This hypothesis warrants further study.

Some studies indicate gains in muscle hypertrophy are optimized with combined performance of MJ and SJ exercises vs. MJ only (5,7), whereas others show MJ and SJ produce similar muscle hypertrophy in this muscle complex (15). Furthermore, some studies show no additional gains in muscle hypertrophy with MJ + SJ vs. MJ alone in untrained (16), trained (6,11), and bodybuilders (4). Accordingly, a recent review on the topic concluded that SJ exercises are not necessary to maximize muscle adaptations (17), although this review has come under scrutiny based on the limitations in evidence to support this conclusion (31). Thus, a number of limitations in the existing literature must be taken into account when attempting to draw evidence-based conclusions. Among them, a majority of studies have assessed growth via circumference measurements, which provide only crude estimates of changes in muscle mass; studies that have used more accurate assessments of muscle thickness by ultrasound have done so only at a single site of the elbow flexors (15,16). Given evidence that the elbow flexors adapt in a non-homogeneous manner (22), Mannarino et al. (21) recently filled an important gap in the current literature by comparing MJ and SJ exercises involving the elbow flexors and assessing muscle thickness at 3 different sites of this muscle group. Results showed greater muscle hypertrophy of the elbow flexors during SJ exercise (i.e., biceps curl) vs. MJ exercise (i.e., dumbbell row). Consistent with these findings, the PM and whole TB muscle hypertrophy in our study mainly occurred when these muscles were involved as agonists in the barbell bench press and lying barbell triceps press exercises, respectively.

Similarly, 2 other studies (26,27) showed muscle hypertrophy double that for the PM compared with the TB (~40 vs. ~20%, respectively) after 24 weeks of MJ exercise (bench press), indicating hypertrophic adaptations are superior when muscles act as agonists as opposed to synergists. In contrast to these findings, we did not observe significant whole muscle TB hypertrophy after isolated MJ, although the increase exceeded the CV for this measurement (~5.0%). This discrepancy potentially could be explained by the differences in the samples and duration of intervention periods between our study and that of Ogasawara et al. (26,27). Therefore, we cannot rule out the possibility that TB muscle hypertrophy would manifest with isolated MJ exercise over a longer time frame. On the other hand, the attenuated hypertrophic response of the TB during MJ exercise may be explained by its role as a synergist, which seemingly impedes full stimulation of the muscle complex (26,27). Collectively, these results suggest that muscle hypertrophy is favored in muscles acting as agonists, regardless of the exercise selection (i.e., MJ or SJ). Exercise order, however, could be an intervening factor in hypertrophic adaptations because the PM showed approximately half (+5.6%) of the relative CSA increase when SJ was performed before MJ (i.e., SJ + MJ) compared with MJ (+9.1%) or MJ + SJ (+10.6%). The same interference of exercise order was not observed for whole muscle TB hypertrophy when MJ was performed before SJ (MJ + SJ = +11.5%; SJ + MJ = +10.4%; SJ = +9.5). The reason for the blunted increase in PM hypertrophy for the SJ + MJ protocol may be due to fatigue of the TB from performance of the lying barbell triceps press, which conceivably limits subsequent bench press performance. Consequently, the ~18% attenuation in bench press TTV in the SJ + MJ sequence, although not statistically significant, may explain the lower PM muscle hypertrophy compared with MJ and MJ + SJ, given evidence of a dose-response relationship between TTV and muscle hypertrophy (34). Conversely, despite a decreased TTV (~33%) for the lying triceps extension in the MJ + SJ sequence, hypertrophy in the TB muscle was not negatively affected. A possible explanation for such a finding may be explained by the fact that both the MJ and SJ used in the current study involve the TB (i.e., as a synergist and agonist, respectively), and the combination of MJ + SJ seemingly provides a sufficient stimulus to the muscle complex. Thus, when the goal is to maximize muscle hypertrophy, it is important to consider the exercise prescription not only in terms of exercise selection and order but also by the involvement of the target muscles as a synergist or agonist.

It is noteworthy that most studies investigating the combined performance of MJ and SJ exercises (4–7,11,16) used arm circumference measures during RT programs comprising exercises also involving the elbow extensors muscles. This is problematic because (a) circumference measures are known for their poor internal validity (36) and (b) the increased arm circumference may have been influenced by increase of the flexors and extensors muscles, not evaluated separately in these studies. Research indicates that the TB may experience different patterns of regional muscle hypertrophy between SJ (40) and MJ exercises (39). Our findings support this notion as hypertrophy of the TB lateral head mainly occurred from MJ exercise performance, whereas hypertrophy of the TB long head mainly occurred from performance of SJ exercise. This could be explained by the differential muscle activation of each head of TB during SJ and MJ exercises. Wakahara et al. (40) demonstrated a lower percentage of muscle activation (evaluated by T2 MRI in the middle region of the TB) for the lateral head compared with long and medial heads after SJ (lying triceps extension). In a follow-up study by the same group (39), a MJ exercise (dumbbell press) elicited a lower percentage of muscle activation for the TB long head compared with lateral and medial heads. These discrepancies may be explained by the fact that the long head is a biarticular muscle that has distinct length-tension implications depending on shoulder positioning, whereas the medial and lateral heads are uniarticular muscles that are pure elbow extensors. Thus, during MJ exercise that involves horizontal abduction of the shoulder (bench press's eccentric movement), the long head of the triceps is shortened and thus becomes actively insufficient in subsequent elbow extension, which in turn allows the remaining heads to accomplish a greater amount of work (32). On the other hand, SJ exercise with the elbow at 90° flexion (lying triceps extension) may have enabled the long head to maintain an optimal length-tension relationship and hence optimize the interaction among the actin and myosin filaments to produce force. Interestingly, the medial head did not display statistically significant muscle hypertrophy after MJ exercise despite achieving a percentage increase similar to that of the lateral head (medial = 7.3% and lateral = 7.2%) and with previous studies showing the muscle activation similar than that of lateral head (39). It can be speculated that our relatively small sample may have compromised statistical power and resulted in a type 2 error for this outcome.

Exercise order had no major influence on regional muscle hypertrophy of the TB. Owing to the hypertrophy of the lateral and long heads mainly occurred from MJ and SJ exercises, respectively, MJ plus SJ exercises, regardless of their order, optimized the muscle adaptations, what might be recommended for best results in whole muscle hypertrophy. Importantly, our findings reinforce the fact that the analysis of a muscle group as a whole vs. as a single muscle may profoundly influence the interpretation regarding exercise selection. Thus, future studies should seek to include both types of measurements to provide robust insights into muscular adaptations.

Our study has several noteworthy limitations. First, our results are specific to young, untrained men; it remains uncertain whether observed changes in regional hypertrophy would be similar for other populations such as women, elderly, or trained individuals. Second, the small sample size compromised statistical power and thus may have limited the ability to detect significant differences in several outcome measures. Despite this limitation, analysis of relative change provides a reasonable basis for drawing inferential conclusions from the results. Third, although we used a gold-standard measure for muscle hypertrophy (i.e., MRI), measurements were taken only at the mid-point of the PM and TB muscles. Thus, we cannot be certain that our findings apply to other regions of these muscles (i.e., proximal and distal) or to other muscle groups. Moreover, nutritional intake was not directly regulated throughout the study. However, the subjects were regularly questioned as to any changes in normal eating habits, and none was reported.

In conclusion, our data suggest that MJ and SJ exercises, either performed in isolation or combined in different orders, do not affect muscle strength gains, provided a high load is maintained between protocols. This finding indicates that the magnitude of load and exercise specificity is the primary determinant in muscle strength gains. In addition, regardless of the exercise selection, we conclude that muscle hypertrophy is optimized in exercises where muscles act as agonists, and hence, exercise order might influence adaptations. Finally, muscle hypertrophy of all triceps heads occurred only when MJ and SJ exercises were performed in combination. The findings suggest that nonuniform muscle hypertrophy is maximized by the combination of MJ and SJ exercises, possibly due to length-tension relationships that influence regional differences in muscle activation between exercises.

Practical Applications

From an applied standpoint, our results indicate that exercise order does not influence 1-RM increases in either the bench press or lying triceps extension. Thus, when the goal is to maximize strength gains, practitioners can choose to perform these exercises in whatever order is most convenient. Alternatively, there seems to be a modest attenuation of increases in CSA of the PM when an SJ exercise targeting the TB is performed before MJ. It therefore seems beneficial to perform exercises where the pectorals are the agonists first in the sequence when the goal is to maximal hypertrophy of this muscle complex. Finally, we show a benefit to performing a combination of exercises that vary in length-tension relationships when the goal is to maximize muscle development of all 3 heads of the TB.

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