NEUROMUSCULAR ACTIVITY DURING BENCH PRESS EXERCISE PERFORMED WITH AND WITHOUT THE PREEXHAUSTION METHOD

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LUIZ MOCHIZUKI,[1] **ROBERTO SIMÃO,**[3] **ALBERTO CARLOS AMADIO,**[1] **AND JÚLIO C. SERRÃO**[1]
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ABSTRACT

Brennecke, A, Guimarães, TM, Leone, R, Cadarci, M, Mochizuki, L, Simão, R, Amadio, AC, and Serrão, J. Neuromuscular activity during bench press exercise performed with and without the preexhaustion method. *J Strength Cond Res* 23(7): 1933–1940, 2009—The purpose of the present study was to investigate the effects of exercise order on the tonic and phasic characteristics of upper-body muscle activity during bench press exercise in trained subjects. The preexhaustion method involves working a muscle or a muscle group combining a single-joint exercise immediately followed by a multi-joint exercise (e.g., flying exercise followed by bench press exercise). Twelve subjects performed 1 set of bench press exercises with and without the preexhaustion method following 2 protocols (P1—flying before bench press; P2—bench press). Both exercises were performed at a load of 10 repetition maximum (10RM). Electromyography (EMG) sampled at 1 kHz was recorded from the pectoralis major (PM), anterior deltoid (DA), and triceps brachii (TB). Kinematic data (60 Hz) were synchronized to define upward and downward phases of exercise. No significant ($p > 0.05$) changes were seen in tonic control of PM and DA muscles between P1 and P2. However, TB tonic aspect of neurophysiologic behavior of motor units was significantly higher ($p < 0.05$) during P1. Moreover, phasic control of PM, DA, and TB muscles were not affected ($p > 0.05$). The kinematic pattern of movement changed as a result of muscular weakness in P1. Angular velocity of the right shoulder performed during the upward phase of the bench press exercise was significantly slower ($p < 0.05$) during P1. Our results suggest that the strategies set by the central nervous system to provide the performance required by the exercise are held constant throughout the exercise, but the tonic aspects of the central drive are increased so as to adapt to the progressive occurrence of the neuromuscular fatigue. Changes in tonic control as a result of the muscular weakness and fatigue can cause changes in movement techniques. These changes may be related to limited ability to control mechanical loads and mechanical energy transmission to joints and passive structures.

KEY WORDS biomechanics, strength training, exercise order, root mean square

INTRODUCTION

An important strategy for strength training is the exercise order. Inadequate sequence of exercises may impair the athlete's capacity to control intensity and volume in each exercise during a training session (43–45,49). Several training methods that change exercise order are applied in strength training. Training sessions usually start with multi-joint exercises involving large-muscle groups (1,46). However, other methods show different exercise sequences, such as the preexhaustion method. The preexhaustion method involves exercising the same muscle or muscle group to the point of muscular failure using a single-joint exercise immediately before a multi-joint exercise (12,13,17,18,20,31,41,49). This method for upper-body strength training using the flying exercise just before the bench press exercise is widely recommended in popular strength training literature (12,13,17,18,31). The high intensities and temporal patterns of activation for pectoralis major and anterior deltoid muscles during flying exercise (19,39,40) and bench press exercise (6,10,16,23,27,32–34) support the application of such a combination of exercises.

In nonscientific weight training literature, the rationale for the preexhaustion method utilization probably lies in increase of motor unit (MU) recruitment during fatigue, resulting in greater muscle activation for subsequent multi-joint exercise (12,13,18,31). But the evidence is contradictory regarding the practical application of this method, both related to training and rehabilitation (4,5,21,43,49). Augustsson et al. (5) observed a decrease in electromyography (EMG) amplitude of the quadriceps muscle during leg press exercise with

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preexhaustion compared to without preexhaustion leg press exercise. Gentil et al. (21) investigated the effects of preexhaustion on upper-body muscle activation during bench press exercise and reported that peck deck exercise performed immediately before bench press exercise lead to similar EMG amplitude of anterior deltoid and pectoralis major muscles. However, they observed the increase in the triceps brachii activation and the worst performance during the bench press exercise with preexhaustion. Despite the decrease in performance, this increase in EMG intensity during preexhaustion may also be altered because fatigue of some muscles can be compensated by increasing motor unit recruitment of other muscles to try to maintain required performance (2,21,36).

However, the neuromuscular recruitment has been assessed only by the EMG amplitude to observe the influence of exercise order as an external stimulus to provide a greater training stimulus on muscles. That is, it has been considered only the tonic aspect of neurophysiologic behavior of motor units during muscular contraction related to intensity of muscular activation (24,25). However, the stimuli regulated by the central nervous system also have phasic aspects of neuromuscular activity related to strategies set by the central nervous system to try to provide the performance required by the motor task (3,8,24,25). The neuromuscular control signal information is encoded in geometric, time, and frequency domains (7,25). According to Basmajian and De Luca (7), the root mean square (RMS) value provides information about geometric (amplitude) and temporal characteristics of MU behavior during muscular contraction. It is important to understand the tonic and phasic characteristics of neuromuscular stimuli to control the performance under the effect of exercise order. Thus, the purpose of the present study is to investigate the effects of exercise order on intensity and duration of upper-body muscle activity during bench press exercise in trained subjects.

METHODS

Experimental Approach to the Problem

Electromyography data were recorded from the clavicular head of pectoralis major (PM), anterior deltoids (DA), and long head of triceps brachii (TB) muscles in 2 different conditions: P1 (preexhaustion protocol: flying before bench press) and P2 (no preexhaustion protocol: only bench press). The subjects performed those conditions on 2 different days.

Subjects

The subjects were 12 male (age 27.7 ± 6.2 years, body mass 80.0 ± 11.0 kg, height 1.73 ± 0.05 m, biacromial width [BAW] 41.22 ± 1.77 cm). The BAW constituted an essential condition to normalize the grip width of subjects during bench press and allows comparisons between protocols. All subjects were recreational trainers (8.81 ± 4.26 years of resistance training experience and 6.19 ± 4.33 training hours/week). The inclusion criteria were male subjects from 20 to 35 years old, having at least 4 years of experience with strength training and without orthopedic injury history. All subjects signed a consent form. The experimental procedure was approved by the local ethics committee.

Procedures

Determination of 10 Maximum Repetitions Loads. One week before testing, the subjects performed three 10 repetition maximum (10RM) tests of each exercise on 3 nonconsecutive days. The following strategies were adopted to minimize errors in the 10RM tests: (a) The subjects received standard instructions about data assessment and exercise performance techniques before testing, (b) the exercise technique execution was monitored and corrected when necessary, and (c) the subjects received verbal encouragement during testing.

During the 10RM tests, each subject had a maximum of 3 attempts on each exercise with 5-minute intervals between attempts. If the subject did not accomplish 10RM in the first attempt, the weight was adjusted by 1 to 2 kg before the next attempt. After the 10RM load in a specific exercise was determined, an interval no shorter than 20 minutes was allowed before the 10RM determination of the next exercise. Standard exercise techniques were followed for each exercise. No pause was allowed between downward and upward phases. For a successful repetition, the range of motion was predefined for each exercise. Bench press and flying 10RM load were 87.95 ± 17.25 kg and 26.38 ± 5.88 kg, respectively. The intraclass correlation coefficient (ICC) was $r = 0.96$ and $r = 0.98$ for flying and bench press, respectively.

These are the brief descriptions of the range of motion used to define a successful repetition: (a) Bench press–moving the bar vertically from a chest touch to a fully extended elbow position; and (b) flying–moving simultaneously 2 dumbbells vertically from shoulders horizontally abduced by 90 degrees to nearly 0 degrees.

Measuring Devices. Electromyographic Data Acquisition. Raw EMG signal was recorded (EMG 1000 system, Lynx Tecnologia Eletrônica LTDA) with differential amplification (Common Mode Rejection >100 dB; condition: 10 Vpp, 60 Hz sinusoidal signal). A first-order high-pass Butterworth filter (attenuation below 20 dB/decade cut-off frequency) with 1-Hz cut-off frequency and a second-order low-pass Butterworth filter (attenuation above 40 dB/decade cut-off frequency) with 1 kHz cut-off frequency were applied. The EMG signals were sampled at 1 kHz, amplified 1,000 times with 16-bit resolution, and band-pass filtered between 20 and 500 Hz. All signal processing was run with AqDados 7.02 software (Lynx Tecnologia Eletrônica LTDA).

EMG Electrode Preparation. The site for electrode placement was shaved, abraded, and cleaned with alcohol to facilitate electrode adherence and EMG signals conduction. Bipolar active surface electrodes (silver; recording diameter = 1 mm; distance between electrode center = 1 cm) were used. These electrodes were placed 1 cm away from the motor point of each muscle, parallel to the fibers, and fixed by adhesive tape to avoid motion over the skin. A ground electrode was attached over bone at the clavicle. The motor point as a reference for electrode placement allowed better EMG signal reproducibility across days (41). Motor point localization was performed by the use of an electric pulse generator (OMNI PULSI-901, QUARK, Brazil) with 2 stimulating electrodes: A passive electrode placed on lumbar area and an active one placed over the muscle belly. The generator emits 1-ms pulse trains as tetanizing frequency (20 to 80 Hz), whose intensity was increased until the achievement of visible muscle contraction threshold. Afterward, the electrode was moved over the skin to check the contraction level. The most excitable point was considered to be the motor point. The impedance between electrode pairs, using a 25-Hz signal through the electrodes, was less than 5.0 kΩ. All these procedures were performed by the same investigator.

Kinematics Analysis System. Electromyographic data were synchronized with the kinematic system to define the downward and upward phases of each exercise repetition and right shoulder joint angular velocity. Kinematic data were recorded by a digital camera (Panasonic, model PV-GS50S, 60Hz) and digitalized, stored, and analyzed by the Peak Motus 8.0 system (Peak Performance Technologies, Inc.). Reflexive landmarks were placed at the acromial processes, elbow joints, and wrists and also at the bar. Standard kinematic calibration was performed before trials.

Electromyographic data were triggered with kinematic data by a synchronization system (Lynx Tecnologia Eletrônica LTDA). Pushing the manual trigger started the EMG data collection and simultaneously sent a square wave sound signal (512 Hz) to the Peak Motus system. This signal was used to define the first movie frame.

Experimental Protocol. Subjects were instructed not to perform any resistance exercises involving the investigated muscles 48 hours before the tests. Each subject was instructed in the proper technique and velocity for each exercise before testing.

All exercises were performed at the load obtained during 10RM tests. Therefore, the load for bench press and flying was the same during P1 and P2. During P1, the subjects performed 1 set (10RM) of the flying exercise, immediately followed by 1 set to failure of bench press exercise. After the flying exercise, 2 assistants took the dumbbells from the subjects' hands and quickly prepared the bar for the bench press. The mean time for exercise exchange in P1 was 11.29 ± 0.67 seconds. P2 involved the performance of 1 set (10RM) of the bench press exercise. P1 and P2 were separated by 48 hours in a balanced crossover design (6 subjects performed P1 first and the other 6 performed P2 first).

In both protocols, the subjects were allowed to perform a warming-up set of 10 to15 repetitions of bench press exercise with 50% of the 10RM load (47).

The Maximal Voluntary Isometric Activation Procedure. The criterion adopted to normalize EMG data was maximal voluntary isometric activation (MVIA). Three MVIAs were performed against a fixed resistance in the following positions: The clavicular head of pectoralis major muscle–in supine position with the right shoulder horizontally abducted at 90 degrees; the anterior deltoid muscle–standing with the right shoulder at 90 degrees of flexion; and the long head of triceps brachii–in supine position with the right shoulder and elbow at 90 degrees of flexion. Each activation was held for 10 seconds with a 20-second rest period between repetitions. Each EMG sample included a MVIA interval of 4 seconds established between the second and the sixth seconds of collection time. The largest RMS value of the 3 MVIAs was designated the reference EMG and used for normalization.

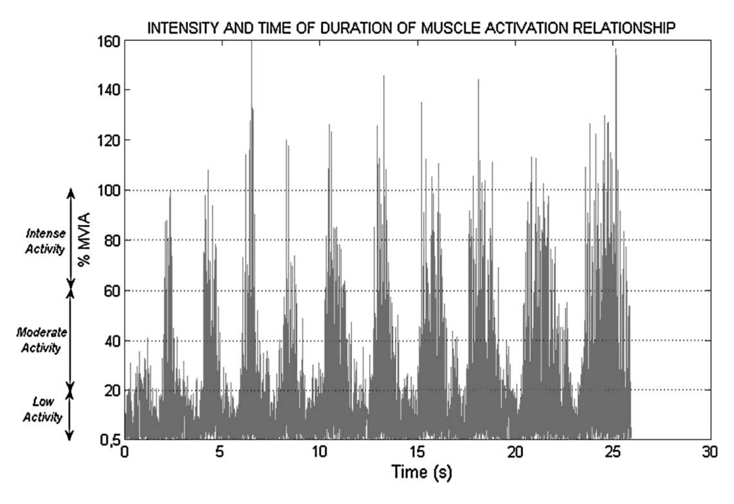

Figure 1. Representation of RMS curve used to determine the relationship between tonic and phasic aspects of neuromuscular activity. EMG signal in RMS curve was divided in established levels of intensity ranges: low activity (0.5 to 20% MVIA), moderate activity (20 to 40% and 40 to 60% MVIA) and intense activity (60 to 80% and 80 to 100% MVIA).

Analysis and Treatment of Electromyographic and Kinematics Data. Digitalization procedures and the calculation of bar vertical linear displacement and right shoulder angular velocity were performed through the software Peak Motus 8.0. Through programs written in Matlab 6.5 (Mathworks Inc.), the electromyographic and

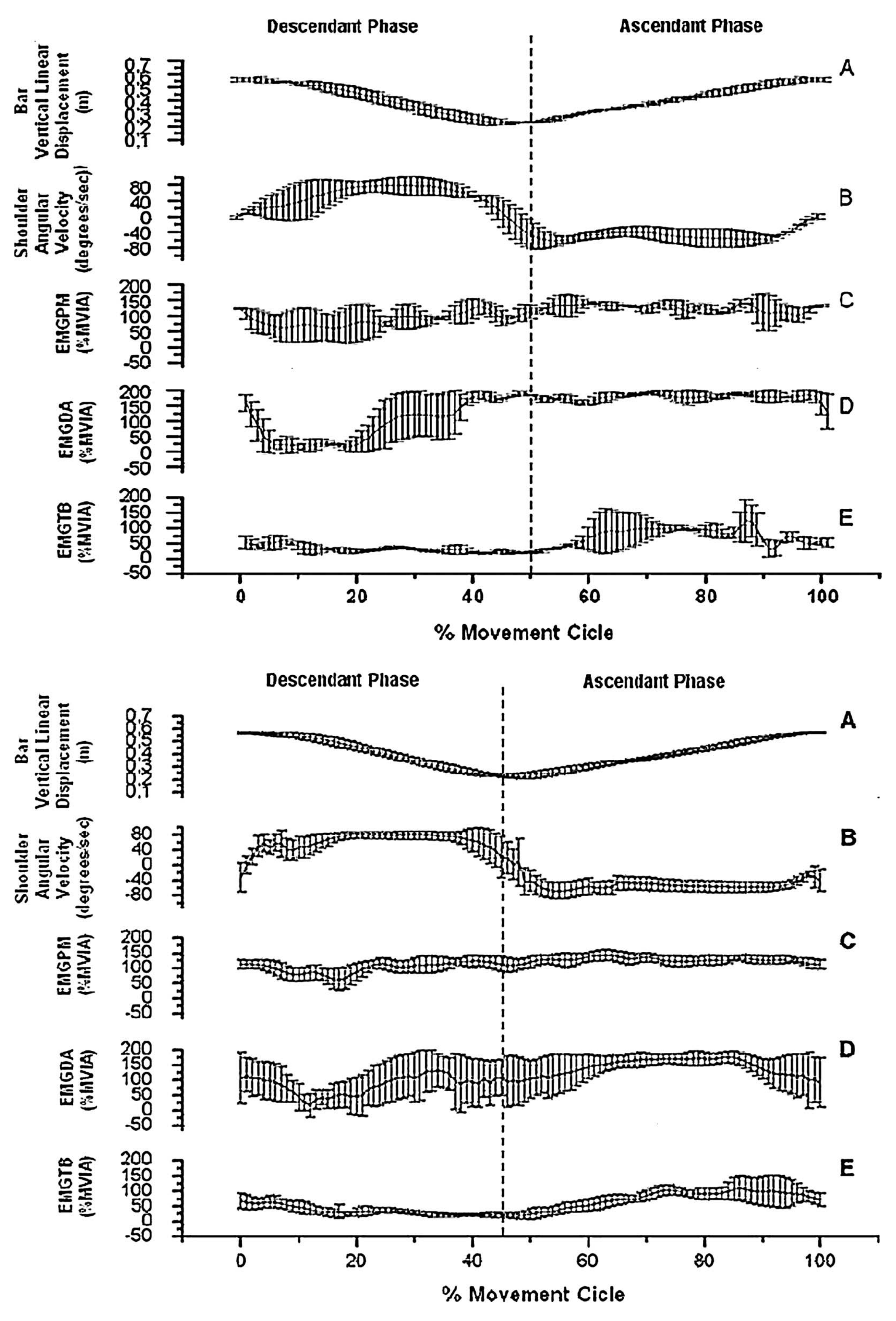

Figure 2. Charts A and B display the bar vertical linear displacement and the right shoulder angular velocity, respectively. Charts C, D and E refer to the linear envelope of muscles PM, DA and TB, respectively. EMG data were normalized by MVIA in the movement cycle for 10 RM of bench press to a representative subject (S8) during protocol with pre-exhaustion (above) and without pre-exhaustion (below).

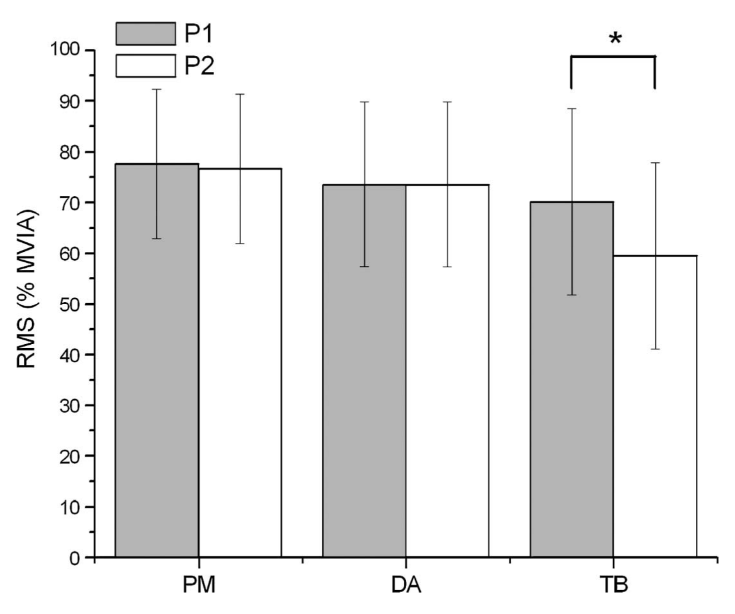

Figure 3. Comparison between protocols P1 (pre-exhaustion) and P2 (with no pre-exhaustion) during bench press exercise. RMS values for PM, DA and TB muscles were normalized by MVIA. (*Significant differences between protocols for $p < 0.05$) n = 82 for P1 and n = 120 for P2.

kinematic data were interpolated, EMG signal was normalized by MVIA, the upward and downward phases of the exercises were automatically identified, RMS value for upward phase of each repetition was calculated, and a RMS curve for each repetition was generated. This RMS curve was used to determine the relationship between tonic and phasic aspects of neuromuscular activity (i.e., the relationship between intensity of muscle activation and time of duration of muscle activation). To do so, the EMG signal in RMS curve was divided in established levels of intensity ranges: Low activity (0.5 to 20% MVIA), moderate activity (20 to 40% and 40 to 60% MVIA), and intense activity (60 to 80% and 80 to 100% MVIA) (Figure 1). This way, the program calculated how long the intensity of the EMG signal remained in each level of intensity range. Muscular activity was considered valid only above 0.5% of MVIA. Below this value, the muscle was considered inactive.

Statistical Analyses

Results are presented in values of mean ± SD. The conditions of normality and homogeneity of variances of data set were tested using the Shapiro-Wilkes test. RMS intensity between exercise order (P1 and P2) was compared using the Wilcoxon nonparametric test. RMS intensities among muscles (PM, DA, and TB) were compared using the Friedman nonparametric test. Established levels of intensity ranges, peak of muscle activity in linear envelope, right shoulder angular velocity, number of repetitions, and grip width during bench press exercise were compared between P1 and P2 using the paired T-student parametric test. An alpha level of 0.05 was used for all comparisons.

RESULTS

The linear envelope analysis did not show significant differences in peak of muscle activity between P1 and P2. For preexhaustion bench press (P1), the activity peaks of muscles PM, DA, and TB occurred, respectively, at 93.55 ± 37.53%, 90.24 ± 38.64%, and 92.22 ± 36.79% of the movement cycle. For bench press with no preexhaustion, the activity peaks of muscles PM, DA, and TB occurred, respectively, at 93.75 ± 24.20%, 94.76 ± 25.61%, and 98.22 ± 5.30% of the movement cycle (Figure 2).

Significantly higher RMS amplitude during the bench press exercise set was observed for TB ($p = 0.012$) with preexhaustion exercise compared to without preexhaustion exercise. The difference between conditions ranged from 59.49 ± 10.65% MVIA in P2 to 70.12 ± 18.37% MVIA in P1. However, no significant differences for DA and PM EMG intensity were reported between exercise orders during bench press exercise. The difference between protocols ranged from 76.67 ± 18.26% MVIA in P2 to 77.64 ± 14.67% MVIA in P1 for PM ($p = 0.48$) and from 72.29 ± 17.10% MVIA in P2 to 73.55 ± 16.21% MVIA in P1 for DA ($p = 0.60$) (Figure 3). No significant differences were seen between PM and DA for P1 and P2. Moreover, for P2, PM and DA muscle activation were significantly higher than TB activation ($p = 0.04$).

There were no significant changes in established levels of intensity ranges between P1 and P2. However, during 2 conditions, significantly ($p = 0.01$) longer TB activation was reported within the low activity range (0.5 to 20% MVIA) compared to PM and DA. PM and DA muscles kept active longer within the moderate activity range (20 to 40% MVIA and 40% to 60% MVIA) (Figure 4).

Angular velocity of the right shoulder performed during the upward phase of bench press exercise was significantly slower ($p = 0.03$) during P1. For preexhaustion bench press the velocity was −72.71 ± 16.83 degrees/s^{-1} and for bench press without preexhaustion the velocity was −82.31 ± 18.13 degrees/s^{-1}.

Subjects performed significantly fewer exercise repetitions ($p = 0.023$) during P1 (6,75 ± 2,14 repetitions) compared to P2 (10 repetitions). There was no difference in grip width

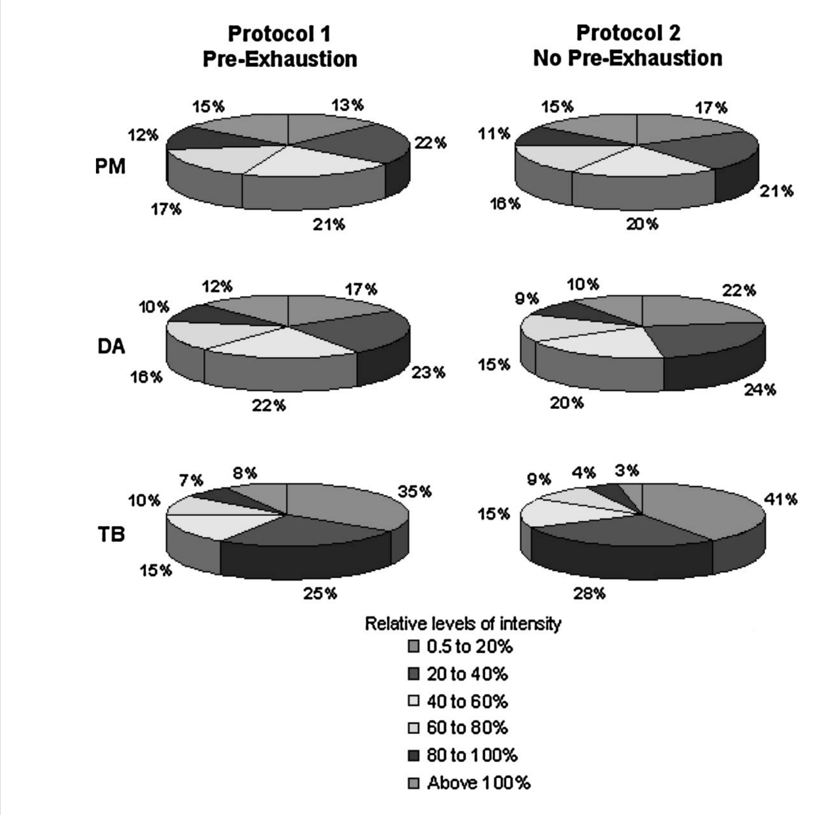

Figure 4. The relationship between tonic (intensity) and phasic (time of duration) control of muscle activation during movement cycle during pre-exhaustion (P1) and no pre-exhaustion (P2) conditions. N = 82 for P1 and n = 120 for P2.

between P1 and P2 (194.95 ± 8.85% BAW and 194.78 ± 9.01% BAW, respectively).

DISCUSSION

The most important result in this study was that preexhaustion did not affect the temporal pattern of muscular activity and MU recruitment of PM and DA muscles, but it did lead to a 17.87% increase in EMG intensity of TB muscle during bench press. Similarly, Gentil et al. (21) reported a significant increase of 33.67% in TB muscle activation during bench press exercise with preexhaustion exercise and nonsignificant differences for PM and DA. They performed a similar study with bench press exercise after the peck deck exercise. They suggest that MU activation does not increase as a result of the preexhaustion method. Augustsson et al. (5) analyzed the effect of preexhaustion before leg press exercise. They found no changes in gluteus maximus activation and significant decreases in rectus femoris and vastus lateralis intensities of activation. They suggest that the preexhaustion method must be reconsidered for its effectiveness in enhancing strength and muscle size gains.

The increase in EMG intensity of TB muscle during P1 may be associated with alterations in tonic muscle control (3,8,24,25). According to Humphrey and Freund (24) once a strategy set by the central nervous system to perform a motor task is chosen, it is implemented by activation of a group of muscles in the appropriate sequence. However, the particular muscle grouping is not fixed, being formed and reformed afresh each time. The selection of the correct muscles to be activated is simplified by certain rules. One rule of muscle combination may be to minimize expenditure of energy. Another related rule may be to make use of predictable forces such as gravity or inertial interactions among the body segments (24). The MU recruitments and firing rate to execute intended movements are regulated by the descending command from the central nervous system and can be modulated by afferent feedback during muscular weakness or fatigue (2,14,25,35,48). Despite the decrease in performance, this ability of the central nervous system to make use of afferent feedback to modulate intended movements during muscular weakness may explain the increase in TB MU recruitment. Other studies (2,21,26,36) also support this explanation. In these studies, weakness of some muscle or muscle group affected the tonic neuromuscular recruitment patterns of synergists to try to maintain required performance. This modulation by afferent feedback involves the remarkable adaptability of the chemical synaptic to short-term physiological changes (25). That is, the adaptability of an intended movement involves changes in efficiency of the existing chemical synaptic connections.

Other evidence that supports the use of modulation by afferent feedback during fatigue in the present study is related to the phasic characteristics of neuromuscular recruitment (i.e., the relationship between intensity and time of duration of muscle activation). Such a relationship has been investigated recently by literature related to strength training as an exercise-associated stimulus, which is important for neuromuscular adaptation and strength gains (11,22). Thus, by analyzing the levels of intensity ranges, longer TB muscle activity was observed in low activity range (0.5 to 20% MVIA) during the movement cycle of bench press exercise in both protocols (35% in P1 and 41% in P2). However, longer

PM and DA muscles activities were observed within the moderate activity range (20 to 60% MVIA) during P1 and P2 (43% in P1 and 41% in P2 for PM; and 45% in P1 and 44% in P2 for DA), but no significant differences between conditions (P1 and P2) were observed. Additionally, no significant differences between P1 and P2 were found in temporal pattern of activation as shown by linear envelope analysis. These findings suggest that despite increasing tonic characteristics of neuromuscular activity, phasic characteristics remained unchanged. This is in accordance with Sarre and Lepers (42), who observed the same relationship to assess the strategies set by the central nervous system to provide the power output required throughout a prolonged pedaling exercise performed at different cadences. Our results differ from those of Clark et al. (9). Those authors observed that fatigue affected the recruitment pattern, with the longer hip extensors activation during the extension phase. Therefore, our results suggest that the strategies set by the central nervous system to provide the performance required by the exercise are held constant throughout the exercise, but the tonic aspects of the central drive are increased to adapt to the progressive occurrence of the neuromuscular fatigue.

Changes in tonic control as a result of the muscular weakness and fatigue can cause changes in movement techniques (38). Right shoulder angular velocity was significantly slower during P1 in comparison to P2. This variation changes the movement pattern from muscular weakness (15,30,37). A more comprehensive kinematic analysis is required. These muscular weaknesses induced by exercise order can lead to changes in movement control, which are related to limited ability to control mechanical loads and mechanical energy transmission to joints and passive structures (28,29).

PRACTICAL APPLICATIONS

The present findings demonstrated that, independent of the preexhaustion method, bench press exercise is capable of generating an effective neuromuscular stimulus for PM and DA. According to our findings, it is possible that this method was only efficient to generate an increased neural stimulus on TB muscle during bench press performed immediately after flying exercise. However, that is not the preexhaustion purpose as initially conceived in the strength training context because an increasing effect in the PM muscle was expected. Therefore, our data suggest that using the preexhaustion method to generate higher neural stimulus on PM should reconsider its effectiveness. Additionally, muscular weakness induced by preexhaustion changed the kinematic pattern of movement. This change requires caution because limited ability to control movement is related to abnormal mechanical loads at joints and passive structures. These abnormal loads may be a factor involved in injury development during exercise.

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We state that the results of the present study do not constitute endorsement of the product by the authors or the NSCA.

REFERENCES

1. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc* 34: 364–380, 2002.
2. Akima, H, Foley, JM, Prior, BM, Dudley, GA, and Meyer, RA. Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. *J Appl Physiol* 92: 679–684, 2002.
3. Ashe J. Force and the motor cortex. *Behav Brain Res* 87: 255–296, 1997.
4. Augustsson, J, Thomeé, R, and Karlsson, J. Ability of a new functional deficits after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 12: 350–356, 2004.
5. Augustsson, J, Thomeé, R, Hörnstedt, P, Lindblom, J, Karlsson, J, and Grimby, G. Effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise. *J Strength Cond Res* 17: 411–416, 2003.
6. Barnett, C, Kippers, V, and Turner, P. Effects of variation of the bench press exercise on the EMG activity of five shoulder muscles. *J Strength Cond Res* 9: 222–227, 1995.
7. Basmajian, J and De Luca, CJ. *Muscles alive: Their functions revealed by electromyography.* 5th ed. Baltimore: Williams & Wilkins, 1985.
8. Burke, RE and Edgerton, VR. Motor unit properties and selective involvement in movement. *Exerc Sport Sci Rev* 3: 31–81, 1975.
9. Clark, BC, Manini, TM, and Ploutz-Snyder, LL. Fatigue-induced changes in phasic muscle activation patterns during dynamic trunk extension exercise. *Am J Phys Med Rehabil* 86: 373–379, 2007.
10. Clemons, JM and Aaron, C. Effect of grip width on the myoelectric activity of the prime movers int the bench press. *J Strength Cond Res* 11: 82–87, 1997.
11. Crewther, B, Cronin, J, and Keogh, J. Possible stimuli for strength and power adaptation–Acute mechanical responses. *Sports Med* 35: 967–989, 2005.
12. Darden, E. The pre-exhaustion principle in strength training. *Athletic J* 63: 46–67, 1983.
13. Dobbins, B. Design principles. *Muscle Fitness* 61: 148–151, 2000.
14. Donoghue, JP and Sanes, JN. Motor areas of the cerebral cortex. *J Clin Neurophysiol* 11: 382–396, 1994.
15. Duffey, MJ and Challis, JH. Fatigue effects on bar kinematics during the bench press. *J Strength Cond Res* 21: 556–60, 2007.
16. Elliot, BC, Wilson, GJ, and Kerr, GK. A biomechanical analysis of the sticking region in the bench press. *Med Sci Sports Exerc* 21: 450–462, 1989.
17. Everson, J. Weider training principles. *Muscle Fitness* 55: 96–99. 1994.
18. Fajardo, JT. *Nuevas tendencias en fuerza y musculación* Barcelona: Ergo, 1999.
19. Ferreira, MI, Büll, ML, and Vitti, M. Electromyographic validation of basic exercises. IV Analysis of the deltoid muscle (anterior portion) and pectoralis major muscle (clavicular portion) in frontal-lateral cross dumbbells exercises. *Electromyogr Clin Neurophysiol* 43: 67–74, 2003.
20. Fleck, SJ and Kraemer, WJ. *Designing Resistance Training Programs.* 3rd ed. Champaign, IL: Human Kinetics, 2004.

21. Gentil P, Oliveira, E, Rocha Júnior, VA, Carmo, J, and Bottaro, M. Effects of exercise order on upper-body muscle activation and exercise performance. *J Strength Cond Res* 21: 1082–1086, 2007.
22. Gillies, EM, Putman, CT, and Bell, GJ. The effect of varying the time of concentric and eccentric muscle actions during resistance training on skeletal muscle adaptations in women. *Eur J Appl Physiol* 97: 443–453, 2006.
23. Glass, SC and Armstrong, T. Electromyographical activity of the pectoralis muscle during incline and decline bench presses. *J Strength Cond Res* 11: 163–167, 1997.
24. Humphrey, DR and Freund, HJ. *Motor Control: Concepts and Issues.* Hoboken, NJ: John Wiley & Sons, 1991.
25. Kandel, ER, Schwartz, JH, and Jessel, TM. *Principles of Neural Science.* 4th ed. New York: McGraw-Hill Companies, 2000.
26. Kay, D, St. Clair Gibson, A, Mitchell, MJ, Lambert, MI, and Noakes, TD. Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *J Electromyogr Kinesiol* 10: 425–431, 2000.
27. Keogh, JWL, Wilson, GJ, and Weatherby, RP. A cross-sectional comparison of different resistance training techniques in the bench press. *J Strength Cond Res* 13: 247–258, 1999.
28. Lafortune, MA, Lake, MJ, and Hennig, EM. Dominant role of interface over knee angle for cushioning impact loading and regulating initial leg stiffness. *J Biomech* 29: 1523–1529, 1996.
29. Lafortune, MA, Lake, MJ, and Hennig, EM. Differential shock transmission response of the human body to impact severity and lower limb posture. *J Biomech* 29: 1531–1537, 1996.
30. Le Bris, R, Billat, V, Auvinet, B, Chaleil, D, Hamard, L, and Barrey, E. Effect of fatigue on stride pattern continuously measured by an accelerometric gait recorder in middle distance runners. *J Sports Med Phys Fitness.* 46: 227–31, 2006.
31. Little, J. The theory of muscle growth: One man's perspective on the pre-exhaustion concept. *Muscle Fitness* 54: 96–98. 1993.
32. McCaw, ST and Friday, JJ. A comparison of muscle activity between a free weight and machine bench press. *J Strength Cond Res* 8: 259–264, 1994.
33. Mookerjee, S, and Ratamess, N. Comparision of strength differences and joint action durations between full and partial range-of-motion bench press exercise. *J Strength Cond Res* 13: 76–81, 1999.
34. Newton, RU, Kraemer, WJ, Häkkinen, K, Humpries, BJ, and Murphy, AJ. Kinematics, kinetics, and muscle activation during explosive upper body movements. *J Appl Biomech* 12: 31–43, 1996.
35. Nichols, TR, Cope, TC, and Abelew, TA. Rapid Spinal mechanism of motor control. *Exerc Sport Sci Rev* 27: 255–284, 1999.
36. Nyland, JA, Caborn, DN, Shapiro, R, and Johnson, DL. Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surg Sports Traumatol Arthrosc* 5: 162–167, 1997.
37. Orishimo, KF and Kremenic, IJ. Effect of fatigue on single-leg hop landing biomechanics. *J Appl Biomech* 22: 245–54, 2006.
38. Paavolainen, L, Nummela, A, Rusko, H, and Häkkinen, K. Neuromuscular characteristics and fatigue during 10km running. *Int J Sports Med.* 20: 516–521, 1999.
39. Rodrigues, JA, Büll, ML, Dias, GAR, Gonçalves, M, and Guazzelli, JF. Electromyographic analysis of the pectoralis major and deltoideus anterior muscles in horizontal "flyer" exercises with loads. *Electromyogr Clin Neurophysiol* 43: 413–419, 2003.
40. Rodrigues, JA, Büll, ML, Dias, GAR, Gonçalves, M, and Guazzelli, JF. Electromyographic validation of the pectoralis major and deltoideus anterior muscles in inverted "flying" exercises with loads. *Electromyogr Clin Neurophysiol* 45: 425–432, 2005.
41. Roy, SH, De Luca, CJ, and Schneider, J. Effects of electrode localization on myoelectric conduction velocity and median frequency estimates. *J App Physiol* 61: 1510–1517, 1986.
42. Sarre, G and Lepers, R. Neuromuscular function during prolonged pedalling exercise at different cadences. *Acta Physiol Scand* 185: 321–328, 2005.
43. Sforzo, GA and Touey, PR. Manipulating exercise order affects muscular performance during a resistance exercise training session. *J Strength Cond Res* 10: 20–24, 1996.
44. Simão, R, Farinatti, PT, Polito, MD, Maior, AS, and Fleck, SJ. Influence of exercise order on the number of repetitions performed and perceived exertion during resistance exercise. *J Strength Cond Res* 19: 152–6, 2005.
45. Simão, R, Farinatti, PT, 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.
46. Stone, MH and Wilson, D. Resistive training and selected effects. *Med Clin North Am* 69: 109–122, 1985.
47. Tan, B. Manipulating resistance training program variables to optimize maximum strength in men: A review. *J Strength Cond Res* 13: 289–304, 1999.
48. Thickbroom GW, Phillips, BA, Morris, I, Byrnes, ML, and Mastaglis, FL. Isometric force-related activity in sensorimotor cortex measured with functional MRI. *Exp Brain Res* 121: 59–64, 1998.
49. Wathen, D. Exercise order. In Essentials of strength training and conditioning. T. Baechlet, eds. Champaign, IL: Human Kinetics, 1994. pp. 431–434.