Rotator-Cuff Muscle-Recruitment Strategies During Shoulder Rehabilitation Exercises

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Context: There are contradictory data on optimal muscle-activation strategies for restoring shoulder stability. Further investigation of neuromuscular-control strategies for glenohumeral-joint stability will guide clinicians in decisions regarding appropriate rehabilitation exercises. Objectives: To determine whether subscapularis, infraspinatus, and teres minor (anteroposterior force couple) muscle activation differ between 4 shoulder exercises and describe coactivation ratios and individual muscle-recruitment characteristics of rotator-cuff muscles throughout each shoulder exercise. Design: Crossover. Setting: Laboratory. Participants: healthy, physically active men, age 20.55 ± 2.0 y. Interventions: 4 rehabilitation exercises: pitchback, PNF D2 pattern with tubing, push-up plus, and slide board. Main Outcomes Measures: Mean coactivation level, coactivation-ratio patterns, and level (area) of muscle-activation patterns of the subscapularis, infraspinatus, and teres minor throughout each exercise. Results: Coactivation levels varied throughout each exercise. Subscapularis activity was consistently higher than that of the infraspinatus and teres minor combined at the start of each exercise and in end ranges of motion. Individual muscle-recruitment levels in the subscapularis were also different between exercises. Conclusion: Results provide descriptive data for determining normative coactivation-ratio values for muscle recruitment for the functional exercises studied. Differences in subscapularis activation suggest a reliance to resist anteriorly directed forces.

Keywords: force couple, EMG, therapeutic exercise, joint stability

Coactivation is the simultaneous contraction of muscles (ie, onset, duration, and amount of activation) around a joint that establishes force couples to increase compressive forces and optimize congruency between articulating surfaces, which is important for stability.1–4 The concept of force couples was introduced by Sherrington5 and studied at the shoulder by Inman et al2 as it relates, directly

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and indirectly, to joint stability. One method to quantify the relationship between force-couple muscles is to calculate coactivation ratios. An important force couple for anteroposterior shoulder stability is the subscapularis opposed by the infraspinatus and teres minor. Cadaveric models suggest that muscle-coactivation ratios of this force couple should vary with joint movement depending on the mechanical advantage of each muscle. However, in vivo data quantifying changes throughout a range of motion have not been reported for rehabilitation exercises. Consideration of these variables may influence clinical decisions regarding the selection of specific rehabilitation exercises and safe ranges of motion for individual patient needs.

Cadaveric research and in vivo studies suggest a theoretical paradigm whereby simultaneous contraction of the force couple created between the subscapularis, infraspinatus, and teres minor is imperative for glenohumeral-joint stability. Although several studies have investigated activation levels (ie, peak, mean) of these muscles independently in the shoulder during rehabilitative and throwing exercises, there are no data on the level of coactivation, as quantified by the ratio between muscles in a force couple, particularly how these values change to accommodate the range of motion and loads incurred while executing specific tasks. Because the muscles that compose this force couple have differing architecture and continuously changing moment arms and length–tension relationships, it may be a misleading oversimplification to suggest that certain exercises promote stability through coactivation for every patient, without fully understanding the changes that may occur as the extremity moves through the exercise’s range of motion. Furthermore, it could be argued that balanced coactivation ratios would impair coordinated shoulder motion during rehabilitation exercises and that selective recruitment of specific muscles, causing an imbalanced ratio, may be more efficient for offsetting potentially deleterious joint loads. Most studies agree that some coactivation is necessary to minimize shearing stresses and excessive motion that could otherwise contribute to the early onset of osteoarthritis, overuse injuries, labral tears, or instability. Others have implied that increased coactivation ratios (ie, duration and quantity) may in fact be a precursor to knee osteoarthritis. However, unbalanced coactivation ratios may also heighten joint stiffness and limit motion at the shoulder, thus enhancing joint stability. Equal coactivation ratios may only be necessary in positions of vulnerability or during the early motor-learning stages of new-skill acquisition, which raises the question of what level of muscle coactivation occurs during the performance of rehabilitation exercises with varying degrees of difficulty.

Traditionally, closed-chain activities (exercises with a fixed base) have been identified as providing dynamic stability through muscle coactivation. However, these exercises do not replicate most activities required of the upper extremity. Activities of daily living, as well as most sport-specific requirements associated with the shoulder, are open chain (distal segment not fixed). Finally, neuromuscular characteristics vary among different populations and therefore should also be taken into consideration when integrating these tasks into individual rehabilitation programs for a safe and successful recovery. For this reason, clinicians have relied on theoretical models for shoulder rehabilitation progression with regard to coactivation relationships. Exercises to promote dynamic stability via force-couple coactivation that are frequently used in clinical rehabilitation include pitchback with a Plyoball, abduction/adduction motions on a slide board with the subject in
a push-up position, push-up plus, and the proprioceptive neuromuscular facilitation diagonal 2 (PNF D2) pattern.

This study aims to provide information about the role of shoulder-muscle coactivation so clinicians have evidence of muscle recruitment in healthy individuals while they perform rehabilitation exercises, therefore promoting their use in individualized programs. Specifically, our aims were to address the following questions: Are mean rotator-cuff muscle-coactivation ratios different between the 4 shoulder exercises examined in this study? What is the role of coactivation levels, as quantified by ratios, throughout the entire motion (ie, pattern) of a rehabilitation exercise? If rotator-cuff muscle coactivation is not predominant, what muscles are selectively recruited during each exercise?

Methods

A crossover design was used in this study. Electromyographic (EMG) signals were recorded from the infraspinatus, teres minor, and subscapularis during the execution of 4 shoulder rehabilitation exercises.

Thirty-three healthy, physically active men (age 20.55 ± 2.0 y, height 176.34 ± 4.6 cm, weight 77.31 ± 12.5 kg) participated in this study. We tested the dominant arm (right, n = 26; left, n = 7), defined as the arm used to throw a ball. Subjects with a history of surgery, episodes of shoulder instability in the past year, or injury within the past 6 months that caused suspension of physical activity were excluded. In addition, all subjects underwent an upper extremity screen by an orthopedic surgeon to rule out pathology and instability of the shoulder by assessing range of motion, strength, glenohumeral laxity, rotator-cuff impingement, and neurologic status. All subjects signed an informed consent approved by the university’s institutional review board before testing.

We simultaneously recorded EMG activity from the infraspinatus, teres minor, and subscapularis muscles during the following shoulder rehabilitation exercises: pitchback with Plyoball, PNF D2 pattern, push-up plus, and slide board (Figure 1A–D). The ground electrode, a self-adhesive Ag/AgCl bipolar surface electrode (272, Noraxon USA Inc, Scottsdale, AZ), was applied to the skin over the ipsilateral clavicle according to standard skin-preparation and placement procedures.37 We placed intramuscular fine-wire bipolar electrodes into the muscles under sterile conditions using the single-needle technique described by Basmajian and DeLuca.37 Dual 50.8-μm diameter Stablohm 800A stainless-steel wires insulated with heavy polynylon (California Fine Wire Co, Grover, CA) were inserted following standard procedures,38–40 and placement was confirmed by monitoring EMG activity during manual muscle testing using an oscilloscope (MyoResearch software; Noraxon USA Inc).41 Bipolar electrodes were connected to spring cables on a Noraxon Telemyo (Noraxon USA Inc) frequency-modulated electromyograph transmitter.42

The sampling rate was 2500 Hz, based on recommendations of the International Society of Electrophysiology and Kinesiology and previously established guidelines.43 All raw data were preamplified (total gain 2000, common-mode rejection ratio of 130 dB and filtered to produce a bandwidth of 10–2000 Hz). Raw signals were converted from analog to digital using a 12-bit analog-to-digital card (Keithley Metrabyte DAS-1000, Keithley Instruments, Inc, Tauton, MA). Data
Figure 1 — Each of the 4 rehabilitation exercises studied is represented. The start, middle, and end positions of the exercise are pictured and correspond with the depicted coactivation patterns. A: During the pitchback exercise, the subject threw a weighted ball into an inclined trampoline and the ball rebounded back to the subject. Beyond 20% of the movement, coactivation values decreased. B: The PNF D2 movement was performed in the extension/flexion direction using elastic tubing as resistance. Coactivation values increased at the end range of motion. C: From a kneeling position, the subject performed a push-up-plus exercise. Coactivation values increased during the “plus” portion of the exercise, when the body was pushed up farther (using scapular protraction). D: From a kneeling position, the subject performed the slide-board exercise—horizontal abduction/adduction on a plastic sliding surface. Coactivation increased at the end range of horizontal abduction, when the exercise was more difficult.
were then full-wave rectified with a sixth-order Butterworth filter and smoothed over a 15-millisecond moving window using MyoResearch software (version 2.11, Noraxon USA Inc). The amplitude of muscle activity was normalized using the maximal voluntary contraction for each muscle elicited during standardized manual muscle tests. Normalized muscle-activity area was calculated as the sum of the amplitudes of integrated EMG activity over the total time of the trial. The time-normalized EMG area of each muscle was used to calculate coactivation ratios and to analyze individual muscle activity. Mean coactivation ratio was calculated using the EMG-area values of muscles in the anteroposterior force couple, such that the subscapularis was divided by the sum of the infraspinatus plus teres minor. EMG area was time-normalized into 100 data points to analyze mean coactivation-ratio recruitment patterns that represented the entire range of motion for the exercise. Every 10 data points were averaged to represent 10% of the total exercises (100/10 = 10). Each 10% increment of the motion was compared between exercises.

Muscle-activity data were collected during 4 shoulder rehabilitation exercises. Each exercise was first described and demonstrated to the subject, followed by the subject’s performance of at least 3 practice trials. Verbal feedback was provided to ensure proper form during the maneuvers. Data were collected during 10 exercise repetitions with a 15-second rest between repetitions and a 3-minute rest between exercises. Exercise order for each subject was determined using a Latin-square table.

The pitchback was executed from a kneeling position with the test arm in 90° shoulder abduction and 90° elbow flexion (Figure 1A). The subject was instructed to throw a 1-kg weighted Plyoball toward a 45° to 60° inclined trampoline, positioned 2 m away, and catch the ball as it rebounded. Subjects were encouraged to throw the ball as hard as possible, catch it, and return to the start position before the next repetition. Each repetition was performed in approximately 1.5 seconds.

The diagonal movement pattern of shoulder abduction/flexion was followed for the PNF D2 pattern (Figure 1B). Subjects assumed a kneeling position and started with the dominant-arm hand in front of the opposite hip. They were instructed to flex and horizontally abduct the shoulder 180° and 140°, respectively, until the arm was overhead. Elastic tubing (moderate tension) was secured by the subject’s contralateral knee and used as resistance during the movement pattern. The amount of resistance was set according to manufacturer guidelines so the subject could perform no more than 15 repetitions. Each repetition was performed in approximately 4 seconds.

The push-up plus started with the subject in a prone position with hands shoulder width apart and chest on the floor (Figure 1C). Subjects were instructed to perform a traditional push-up supporting body weight on their hands and feet (toes). The “plus” component of the exercise required actively and maximally protracting the scapulae at the top of the push-up before moving back down to the floor. Each repetition was performed in approximately 3 seconds.

Horizontal shoulder abduction/adduction was performed on a slide board (Exertools, Novato, CA; Figure 1D). Subjects started in a push-up position with their elbows extended and body weight distributed on their hands and knees. They initiated horizontal shoulder abduction while maintaining elbow, trunk, and hip extension. Subjects were encouraged to horizontally abduct as far as possible while maintaining elbow extension. When the end range of horizontal abduction was reached (self-determined based on elbow-extension criteria), the subject returned
to the start position of horizontal adduction. Subjects wore cotton coverings on their hands to decrease friction. Each repetition was performed in approximately 3 seconds.

Descriptive and inferential statistics were calculated using EMG data. Differences in mean coactivation ratio between the 4 shoulder rehabilitation exercises were determined by a 1-way analysis of variance. Analyses of muscle-coactivation levels during a movement pattern were based on previously published procedures in which the entire exercise was divided into 10% increments. This allowed differences in mean coactivation ratio of each period between the 4 shoulder rehabilitation exercises to be determined using nonparametric Wilcoxon rank-sum tests. Differences in EMG area under the curve for the subscapularis between the 4 shoulder rehabilitation exercises were determined using a 1-way analysis of variance. The same analysis was performed for the EMG area under the curve for the infraspinatus and teres minor. Tukey’s honestly significant difference with Bonferroni correction ($P = .0125$) was used for post hoc analyses when significant differences were found.

All data were analyzed using the Statistical Package for Social Sciences (version 12.0, SPSS Inc, Chicago, IL) for Microsoft Windows. The $\alpha$ level was set at $P \leq .05$ a priori for statistical significance.

**Results**

Mean coactivation ratios ranged from 47% to 60% (Figure 2) for the 4 rehabilitation exercises examined. There were no differences ($P > .05$) in the mean coactivation ratios among the 4 exercises completed in this study.

There were statistically significant differences ($P < .05$) in each 10% increment of mean coactivation-recruitment patterns between the 4 shoulder rehabilitation exercises studied (Figure 1A–D). In general, the most prominent differences of higher coactivation ratios (eg, subscapularis activation more than infraspinatus and teres minor) for an exercise corresponded with exercise initiation (~0–20% of the

![Figure 2](Image) — Mean coactivation between the 4 rehabilitation exercises.
exercise) and when the glenohumeral joint was in a position of vulnerability at end ranges of motion (flexion, abduction, and/or external rotation).

Analysis of each muscle individually revealed statistically significant differences (P < .05) in subscapularis activation but not infraspinatus or teres minor between the 4 shoulder rehabilitation exercises (Figure 3). Subscapularis-muscle activity was significantly greater during the push-up-plus exercise (88.8% ± 77.5%/s) than in the pitchback (48.4% ± 40.5%/s) and PNF D2 (44.4% ± 39.9%/s) exercises (Figure 3).

**Discussion**

This study was conducted to determine whether coactivation levels, as measured by a ratio, between the subscapularis, infraspinatus, and teres minor necessary for anteroposterior stabilization of the glenohumeral joint differ between 4 clinically used shoulder rehabilitation exercises. In addition, we determined whether coactivation levels change throughout an exercise’s range of motion (eg, movement pattern) and whether the activation of individual muscle-recruitment levels differs between the 4 exercises. In addition to variability between exercises, there were large differences in muscle recruitment between subjects, suggesting individualized responses to exercises and the need to base decisions on exercises in a rehabilitation program on individualized patient needs. The results of this study are 3-fold. EMG data revealed that mean coactivation-ratio patterns differ between the rehabilitation exercises studied. Patterns demonstrate how coactivation ratios vary, or fluctuate, within the execution of each exercise (Figure 1). Finally, imbalanced coactivation ratios may reflect a greater reliance on individual muscle recruitment, specifically the subscapularis, or activation of muscles not analyzed.
during these exercises. These may be strategies used at the start of exercise to initiate movement and in end-range positions that are vulnerable to offset shear forces and maintain joint stability.\textsuperscript{17,50}

We examined the role of the glenohumeral force couple created between the subscapularis, infraspinatus, and teres minor.\textsuperscript{9,22} The synergism between these muscles, particularly during humeral flexion and abduction,\textsuperscript{2,22,32,45} maintains joint stability through humeral-head centering and compression while resisting the superior shear force and anteroposterior translations.\textsuperscript{7,13,29,51} Previous studies report that muscle coactivation is greater in weight bearing (ie, coactivation ratio balanced and closer to 1:1), which advocates shoulder rehabilitation exercises such as the push-up plus to enhance joint stability.\textsuperscript{5,16,47,48} Our results show that mean coactivation ratios are comparable between the 4 rehabilitation exercises studied regardless of whether they have a weight-bearing component. There appears to be substantial variation between subjects, so decisions to include a rehabilitation exercise should be based on desired improvements in function for individualized patient needs. For example, our results indicate that initiation of movements and/or positions of vulnerability are factors with greater influence on coactivation-ratio levels. However, to fully appreciate muscle activation in response to functional demands, coactivation ratios should be quantified throughout the rehabilitation exercise instead of relying on a single value that may be misleading or more appropriate for isolated positions.

To our knowledge, this is the first study to examine these muscles simultaneously throughout the range of motion used to perform rehabilitation exercises and report a pattern of coactivation ratios. Our data revealed that the coactivation ratio varied greatly over the duration of each task and that the pattern of coactivation ratios was different between exercises (Figure 1). It was further observed that regardless of level of resistance, or complexity, coactivation ratios are imbalanced and considerably greater, meaning subscapularis activity was more than that of the infraspinatus and teres minor combined, during the initial of movement for each exercise and in the middle of the exercise when the arm is in a vulnerable, or end-range, position. This may suggest that coactivation assists with stability by “setting” or positioning the humeral head before executing the movement.\textsuperscript{8,52} The quantitative and qualitative (Figures 4–7) differences observed in the coactivation-ratio patterns, both within and between tasks, may better reflect the demands placed on this force couple during rehabilitation exercises and can be used for clinical decisions regarding exercise selection and the apparent muscle effort needed during specific ranges of motion as they relate to individual patient deficits. However, to appreciate the variation in coactivation ratios through the exercise’s range of motion (measured in 10% increments) and resistance during the rehabilitation exercises studied, one must also consider the recruitment of individual muscles that compose this force couple.

Theoretically, if excessive shearing forces are imparted on the joint in the course of rehabilitation exercises, selective muscle recruitment (asynchronous firing) may occur to offset these joint loads in an attempt to maintain joint congruency.\textsuperscript{4,8,10} This was observed in association with higher-velocity exercises or during multiplanar tasks. For example, the pitchback (Figure 1A) closely resembles overhead throwing. Coactivation peaked at the beginning of the exercise (0–20% of the exercise’s range of motion), when anteriorly directed shear forces are high,\textsuperscript{4,8} and were reduced during the other 10% increments of throwing. These coactivation-ratio
Figure 4 — Activation of each muscle in the anteroposterior force couple during the pitchback. The start, middle, and end position of the exercise are pictured and correspond with the amplitude of muscle-activation pattern depicted.
Figure 5 — Activation of each muscle in the anteroposterior force couple during the PNF D2. The start, middle, and end position of the exercise are pictured and correspond with the amplitude of muscle-activation pattern depicted.
Figure 6 — Activation of each muscle in the anteroposterior force couple during the push-up plus. The start, middle, and end position of the exercise are pictured and correspond with the amplitude of muscle-activation pattern depicted.
Figure 7 — Activation of each muscle in the anteroposterior force couple during the slide-board exercise. The start, middle, and end position of the exercise are pictured and correspond with the amplitude of muscle-activation pattern depicted.
values suggest greater reliance on selective recruitment from the subscapularis as an anterior check rein during maximal external rotation, which shifts to reliance on the infraspinatus and teres minor during deceleration when these muscles are eccentrically loaded. It is during these phases of pitching that there is the highest likelihood of injury. Clinically, focusing on maximal external rotation to enhance or elicit coactivation and selective activation during the deceleration portion of the exercise may be appropriate and can be achieved using eccentric training of the infraspinatus and teres minor to prevent injury and promote stabilization. 

When we examined individual muscle recruitment, the subscapularis was the only muscle that had significant activation differences between the rehabilitation exercises (Figure 3). Subscapularis-muscle activity was comparable between the push-up-plus and slide-board exercises, although only the push-up plus was statistically significantly different—both considerably greater—than its activation during the pitchback and PNF D2 exercises. Therefore, our results may be used to verify the integration of the push-up-type positions (both push-up plus and slide board) into rehabilitation programs to target the subscapularis. The push-up plus has also been advocated to recruit the scapular stabilizers. 

Our results show that muscle recruitment increases at the start of the exercise’s movement or when the arm is at its end range during the exercise. Therefore, clinicians should carefully consider exercise selection in designing programs. Changes in joint angle and resistance through the exercise’s range of motion affect each muscle’s activation (EMG) response. These data can be used to maximize the most effective strategies to limit humeral-head translation and protect the glenohumeral joint through dynamic stabilization.

There are limitations to our study. First, healthy men 18 to 25 years of age were tested to answer our research questions; results provide normative data for clinicians but do not reveal how muscles activate in patients with shoulder injury. Second, other dynamic stabilizers of the shoulder such as the deltoid, supraspinatus, pectoralis minor and major, biceps brachii, latissimus dorsi, and serratus anterior that were not examined should be considered. Their roles in stability are well established in the literature and may warrant use of these rehabilitation exercises for their synergistic activity and contributions to joint stability. Third, we evaluated the subscapularis-muscle activity from a single site. Some researchers suggest differentiating the upper from lower subscapularis fibers as a result of separate innervations. We agree that this is important; however, we sought to emphasize how these muscles function simultaneously as a group, regardless of innervation, during dynamic movements. Finally, care must be taken when drawing inferences from EMG data regarding joint loads or tension because muscle architecture and length–tension changes may influence these results.

Conclusion

Overall, these data provide normative values on what may be considered “optimal” muscle-recruitment strategies in healthy men specific to these rehabilitation exercises. Mean coactivation levels were high for all the exercises, but further analysis throughout the motion cycle revealed greater variation with the highest levels at the initiation of movement or in positions in which resistance was high. These data also highlight the potential role for selective recruitment when high coactivation ratios
suggest higher reliance on the subscapularis to maintain glenohumeral stability, particularly in positions that stress anterior joint stability. These findings may be used to compare with pathologic populations to gain further insight to appropriate and effective rehabilitation for restoring dynamic stability.

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