Electromyography Evaluation of Rotator Cuff Manual Muscle Tests

by

Rebecca Louise Brookham

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2008

Authors Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Electromyography Evaluation of Rotator Cuff Manual Muscle Tests

Manual muscle tests (MMTs) are frequently used in clinical settings to evaluate a specific muscle's function and strength in a position at which this muscle is believed to be most isolated from other synergists and antagonists. It is necessary for a muscle to be tested in a state of isolation (as much as is physiologically possible), as interpretation of strength and function can be compromised by the contributions of other active muscles. In the present study, electromyographic activation of 14 shoulder muscles was assessed in 12 males during 29 shoulder exertions. Maximal isolation ratios defined which of these exertions most isolated the rotator cuff muscles. Results confirmed the appropriateness of nine clinical MMTs in isolating the rotator cuff muscles, but suggested that several other exertions were equally appropriate in isolating these muscles. Forces produced during isolation exertions can be compared to patient exertions to promote more objective MMT grading.

Acknowledgments

I would like to thank my advisor Dr. Clark Dickerson for his continual patience, guidance and insight in this research.

Thank you to my committee members Drs. Jennifer Durkin and Richard Wells for their helpful recommendations.

Thank you to Dr. Linda McLean for insertion of the intramuscular electrodes, and to my lab mates for their assistance during data collection.

I especially thank my husband, Aaron, and my parents, Don and Sharon, for their constant love and support in everything that I do.

Dedication

To my loving husband Aaron,

For sometimes pushing, pulling and carrying me… and always walking beside me.

Table of Contents

Page

1.0 Introduction

4.0 Literature Review

4.1 Literature review of manual muscle tests (MMTs)

4.2 Literature review of electromyography

5.0 Proposed Methodology

6.0 Results

7.0 Discussion

List of Tables

List of Illustrations

List of Equations

1.0 Introduction:

Balanced strength within the rotator cuff is critical to the stability of the glenohumeral joint. Manual muscle tests are used to assess the strength of the rotator cuff muscles, although few evaluations of the ability of these tests to isolate the rotator cuff muscles have been made.

1.1 Shoulder stability and the role of the rotator cuff:

Stability of the glenohumeral joint is a concern due to the complex nature of the joint, as it possesses more postural flexibility than any other joint of the body. The shoulder has four articulations: the glenohumeral, acromioclavicular, sternoclavicular and scapulothoracic joints. The stability of the glenohumeral joint is influenced by the marked size difference (4:1) between the convex humeral head and the concave glenoid fossa (Sarrafian et al, 1983). The four rotator cuff muscles (supraspinatus, infraspinatus, teres minor and subscapularis) are critical to the stability of the glenohumeral joint (Figure 1). The rotator cuff is described as a dynamic stabilizer of the shoulder,

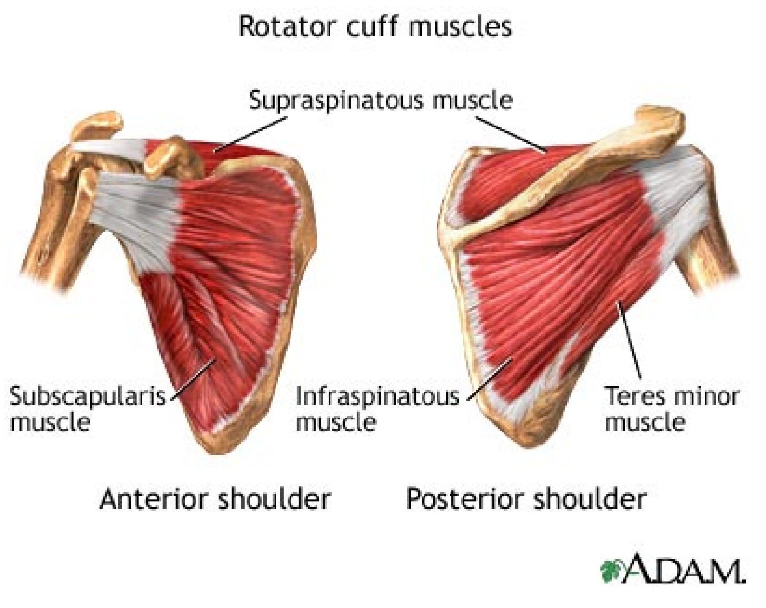


Figure 1: Muscle attachment sites of the four rotator cuff muscles on the scapulae
(http://www.nlm.nih.gov/medlineplus/ency/images/ency/fullsize/19622.jpg)

performing two main functions: first, the rotator cuff helps depress the humeral head and prevent superior translation of the humerus; and secondly, the rotator cuff helps keep the humeral head centered within the glenoid fossa during movement (Buschbacher, 1993). Weakness or imbalance of rotator cuff strength can compromise shoulder stability, and allow superior translation of the humeral head, which may result in compression and injury of subacromial tissues (such as the supraspinatus tendon) between the greater tuberosity of the humerus and the acromion (Burke et al, 2002). Maintenance of balanced rotator cuff strength is essential for the stability of the shoulder, and the prevention of injury.

1.2 Economic importance of evaluating rotator cuff strength assessment techniques:

Shoulder injuries are common and costly to Canadian society. Musculoskeletal disorder (MSD) related compensation claims resulted in more than $3.3 billion benefit costs to Ontario between 1996 and 2004 (WSIB, 2005). From 1997 to 2006 there were 57,115 lost time claims due to shoulder injuries in Ontario alone, which included 2,898 rotator cuff tears or syndromes (WSIB, 2006). Injuries resulting from imbalanced or weak rotator cuff muscles (such as subacromial tissue injuries resulting from superior translation of the humeral head) may be prevented, and as a result health care costs lessened, if a proper diagnosis of rotator cuff weakness is made.

1.3 Uses of manual muscle tests:

Manual muscle tests (MMTs) are frequently used in clinical settings to assess patient-specific function and muscle strength in a simple, time and cost-efficient manner. A manual muscle test (MMT) is executed by having a patient exert maximal effort in a defined posture, against static manual resistance provided by a clinician. The clinician considers the applied resistance and interprets the strength and function of the muscle. MMTs are believed to evaluate a specific muscle's function and strength in a position at which this muscle is most isolated from other muscle synergists and antagonists. A muscle should be tested in a state of isolation (as much as is physiologically possible), as interpretation of strength and function can be compromised by the contributions of other active muscles. An example of a MMT is the empty can test (Figure 2). The empty can test is commonly used to assess the strength of the supraspinatus muscle, which assists the deltoid in shoulder abduction (Moore & Dalley, 1999). The empty can test is performed when the patient abducts the shoulder against resistance held by the clinician, while the humerus is internally rotated -45º (thumb down) and flexed forward 30º. This position is believed to maximally activate the supraspinatus, while minimizing the contributions of the middle deltoid in abduction.

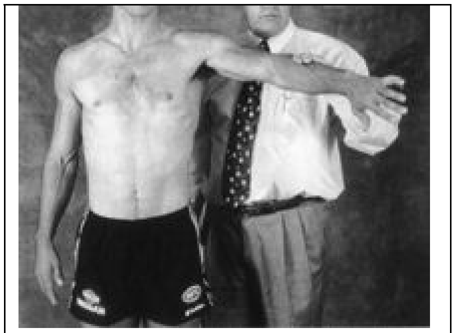


Figure 2: Assessment of the supraspinatus using the empty can test
(http://www.clinicalsportsmedicine.com/chapters/14d.html)

MMTs are also commonly used in electromyographic (EMG) studies to produce muscle-specific activations which confirm proper surface and intramuscular electrode placement (Kelly et al, 1996a; 1996b; Myers et al, 2003). It can be difficult to accurately place electrodes over or inside a muscle of interest due to the complexity of shoulder anatomy (there are many muscles in close proximity), and visual imprecision in detecting muscles due to physical differences between participants (varying muscle length and girth). Once electrode placement has been confirmed, MMTs can be used to help define reference exertions for EMG normalization, to allow pooled comparisons between muscles and participants (Gowan et al, 1987).

1.4 Deficient evaluation of the ability of MMTs to isolate rotator cuff muscles:

Despite the fact that rotator cuff MMTs are used to confirm electrode placement and assess specific muscle strength and function, few electromyographic evaluations of these tests exist to confirm their ability to isolate the muscle of interest. Using MMTs to identify the specific strength contribution of a muscle, when it is unknown if that muscle is being tested in a position of maximal isolation, raises several risks for clinicians and researchers. Using test postures that fail to isolate the muscle of interest may result in inaccurate diagnostic assessments, as other muscles may contribute to the exertion. These inaccuracies would compromise interpretation of strength and function of the muscle of interest. For similar reasons, researchers may obtain invalid and inconsistent EMG data when MMTs are used as reference exertions for EMG normalization or to confirm electrode placement.

Many authors have attempted to selectively activate specific muscles; however, their choice of methodological approaches causes some concern. Generally, their isolation techniques entailed choosing a posture that produced a maximal percentage of a maximal voluntary contraction (MVC) for the muscle of interest, but did not consider contributions of the other muscles (Townsend et al, 1991; Greis et al, 1996; Dekker et al, 2003; Suenaga et al, 2003; Tokish et al, 2003). Thus, it follows that while these studies identified exertions that produce maximal activation of the rotator cuff muscles, they did not necessarily confirm exertions that isolate these muscles.

The term ‘muscle isolation’ is not standardized in this field of literature, further confusing the issue. Webster’s dictionary (1993) defines the term ‘isolate’ as “to separate from another substance so as to obtain pure or in a free state”. Isolation of a muscle in this sense would be defined by having the muscle of interest active in a posture during which all other muscles are inactive. This is a very unlikely state for the closely related muscles of the rotator cuff, as these muscles work in concert to maintain the stability of the humeral head in the glenoid fossa. Therefore, in this paper, *functional isolation* of the rotator cuff is defined as an exertion during which the muscle of interest is most activated, when all other surrounding muscles (synergists and antagonists) are least activated.

Evidence in the literature is limited regarding the evaluation or standardization of rotator cuff MMTs, and resultantly, exertions proven to functionally isolate these muscles have not yet been identified. Functional isolation is important as it enables a better functional assessment of the muscle of interest, and helps clinicians and researchers to make precise diagnoses and design treatment protocols for specific injuries. Diagnostic and treatment improvements may help reduce the incidence and rehabilitation process of shoulder injuries, and the associated health care costs. The lack of literature in this area and limitations found in existing studies demonstrate the need for a thorough EMG study of rotator cuff MMTs.

2.0 Purposes:

The purposes of this research were to:

- Evaluate 29 rotator cuff MMTs with EMG to identify which exertions most functionally isolate the four rotator cuff muscles. For each of the four rotator cuff muscles, isolation was determined by the maximal ratio of:

$$\frac{\dfrac{\%\text{MVC activity of rotator cuff muscle of interest}}{100}}{\dfrac{\sum \%\text{MVC of all other 13 recorded muscles}}{1300}}$$

- Determine the force outputs produced at the hand or wrist (in Newtons) during which each of the rotator cuff muscles were isolated

By improving evaluation techniques of the rotator cuff, and identifying associating normative force outputs, these findings will allow clinicians and researchers to confidently and accurately attain muscle-specific strength-based information. These isolation exertions can then be used to diagnose muscle weaknesses or injuries, so that therapeutic approaches and preventative measures can be planned appropriately. These interventions may prevent some shoulder injuries, and in turn decrease associated health care costs to our society. The investigation will also provide insight into the fundamental mechanics of the rotator cuff elements.

3.0 Hypotheses:

The following three hypotheses were made:

- The clinical MMT exertions will be most effective in isolating the rotator cuff muscles.
- The rotator cuff muscles will be most isolated in exertions that are based on the primary action of the rotator cuff muscle of interest.
- Some muscles are similarly isolated (obtain highest isolation ratios) when performing multiple exertions.

Kelly et al (1996a) examined 29 different exertions, and determined the supraspinatus, infraspinatus and subscapularis to be isolated within clinical MMTs (full can test, external rotation, and the lift-off test, respectively). Past works have demonstrated the rotator cuff muscles are best assessed during exertions of their respective main actions (external rotation (infraspinatus and teres minor), internal rotation (subscapularis), and abduction (supraspinatus)) (Moynes 1982; Townsend et al, 1991; Kelly et al 1996a; Suenaga et al, 2003). Due to the postural similarity of many exertions, it was anticipated that isolation ratios would be numerically similar, and therefore, isolation of some muscles would be achieved in multiple exertions.

4.0 Literature review

Manual muscle tests are used to assess the strength of rotator cuff muscles during exertions in which they are believed to be most isolated from other surrounding muscles. However, few studies have evaluated the ability of manual muscle tests to isolate the rotator cuff muscles. Due to the size and depth of these muscles, intramuscular electrodes are crucial in the recording of signals from the rotator cuff.

4.1 Literature review of manual muscle tests (MMTs)

Manual muscle tests are commonly used by clinicians to assess muscle strength, although present methods of grading are subjective. Few rotator cuff isolation exertions have been identified, as past MMT evaluations generally have not considered surrounding muscle contributions.

4.1.1 General review of manual muscle tests (MMTs):

Clinicians use various MMTs to identify specific muscle weakness resulting from disease, injury or disuse (Ruwe et al, 1994, Herbison et al, 1996, Bohannon et al, 2005); but there is little consensus or standardization regarding which exertions most effectively assess muscle strength. Sapega (1990) encouraged the use of dynamometry during assessment to confirm strength, as MMTs are least subjective only in the poorest grades, for which weakness has reached a debilitating degree. Sapega (1990) cautioned that there be careful positioning during assessment, as small changes in position can affect strength. Kuhlman et al (1992) also recommended standardized strength testing positions. They tested the external rotation and abduction strength of 39 participants at several angles in the scapular plane. The suprascapular nerve of four participants was later blocked, and strength differences before and after the nerve block were compared and assumed to be due to the contributions of supraspinatus and infraspinatus. The supraspinatus and infraspinatus contributed a variable amount to strength in abduction and external rotation throughout the various ranges of motion. Kuhlman et al (1992) concluded that standardized positions are needed for strength assessment.

Standardization of MMTs has been attempted through isolation of the muscle of interest. Unfortunately, the term ‘muscle isolation’ is not standardized in this field of literature. A dictionary defines the term ‘isolate’ as “to separate from another substance so as to obtain pure or in a free state” (Merrian-Websters, 1993). In the true sense of the word, isolation of a muscle would be thought of as having the muscle of interest active in a posture during which all other surrounding muscles are inactive. This is a very unlikely state for the closely related muscles of the shoulder. True isolation has been shown to be a very unlikely state in other body regions as well. Mirzabeigi et al (1999) attempted to selectively challenge the vastus medialis oblique (VMO) from the vastus lateralis, vastus intermedius and vastus medius longus muscles. Intramuscular electrodes were used and eight participants were tested during nine isometric exercises. The VMO was not significantly activated more than the other recorded muscles, and Mirzabeigi et al (1999) concluded that the VMO could not be isolated during these isometric exercises. Therefore, perhaps *functional isolation* is a better term used to describe selectively assessing the strength of a muscle. In this paper, functional isolation of the rotator cuff is achieved during an exertion in which the muscle of interest is most activated while all other surrounding muscles (synergists and antagonists) are least activated.

4.1.2 Subjectivity of the MMT grading system:

Current MMT framework is contingent upon subjective scoring measures of perceived strength. Clinicians are required to apply a sufficient force to resist a movement, and while assessing the resistive strength displayed by the muscle under observation, make a judgment about the strength of that muscle. It is possible that strength of either the clinician or the patient may affect the interpretation of muscle strength; a weaker clinician may be over powered by a stronger patient, which may result in an overestimation of the patient's muscle strength. In clinical quantification of muscle strength, MMTs are often graded on a scale from 0 to 5 (Table 1) (Janda 1983). For further categorization, the scale is expandable through addition of a plus (slightly above this strength grade) or minus (slightly below this strength grade) sign to the grades.

Table 1: Grading of manual muscle tests (Janda 1983)

Grade 5 (Normal)	Normal, very strong muscle with full ROM and able to overcome considerable resistance. This doesn't mean muscle is normal in all circumstances (example: fatigue).
Grade 4 (Good)	Muscle with good strength and a full ROM, able to overcome moderate resistance.
Grade 3 (Fair)	Muscle with complete ROM against gravity only when resistance is not applied.
Grade 2 (Poor)	Very weak muscle with complete ROM only when gravity is eliminated by careful positioning of patient.
Grade 1 (Trace)	Muscle with evidence of slight contractility but no effective movement.
Grade 0	Muscle with no evidence of contractility.

Note: Use + or – if strength of muscle lies between 2 grades.

The MMT grading scale is subjective because it is based on the tester's personal judgment regarding the force that the patients are able to resist against (above the grade of 3). Kneplar & Bohannon (1998) quantified the influence of multiple factors on forces applied during simulated MMTs of elbow flexion and hip abduction. The multiple factors examined were: participant gender, trial timing (week 1 or week 2), side (left, right), muscle action (elbow flexion, hip abduction), MMT grade (3+, 4-, 4) and tester. In this study, ten testers (5 males with a mean age of 25.6 years and mean grip strength of 545 N, and 5 females with a mean age of 26.6 years and mean grip strength of 351 N) were instructed to apply forces against which they would expect a patient to hold at a grade of 3+ (minimum force), 4- (near moderate force) and 4 (moderate force), out of a total of 5. A modified sphygmomanometer placed between the tester's hand and patient's extremity was used to measure the pressure (in millimeters of mercury) applied by the testers. The testers applied forces, at the three specified grades, to the patient's during both specified MMTs in two sessions (each session one week apart). Results from a multi-factorial ANOVA indicated there were no significant differences in the pressures applied to either gender, either side or for either session (week 1 or week 2). However, the results indicated that the muscle action tested influenced the forces, as testers did not show comparable forces for the two different actions tested (elbow flexion and hip abduction). Furthermore, results of the study indicated that although the forces increased with increasing grades (3+ to 4, out of 5); there were significant differences in the forces applied between testers for each grade. This highlights the subjectivity of MMT grading scales, and calls into question the ability of different clinicians to apply comparable forces for MMT grades of 3+, 4- and 4 out of 5 during elbow flexion and hip abduction MMTs.

The ambiguity of the MMT grading scales challenges the utility of these scales for assessing small changes in strength. Changes in elbow flexor strength of 88 post-spinal cord injury patients were evaluated with the use of a MMT, and these results were compared to changes in strength that were measured by a hand held myometer (Herbison et al, 1996). Participants (78 males and 10 females with a mean age of 34 years) had injuries at C4-C8 neurological levels, and initially had a minimum of grade 3.5 for an elbow flexion MMT. Data was collected at 72 hours; 1, 2, 3 weeks; and 1, 2, 3, 6, 12, 18 and 24 months post spinal cord injury. Results indicated that significant changes in muscle strength were measured by the myometer (up to a mean of 232% change increases), in the absence of changes detected by the MMT grading scale. Similarly, the sensitivity of a MMT in determining muscle strength of knee extension using the MMT grading scale compared to a hand-held dynamometer were assessed by Bohannon (2005). One hundred and seven participants (55 men and 52 females, with a mean age 62.1 years) participated in the study. The ability of the MMT to detect between-side differences (15 – 30%) in strength identified by dynamometry, as well as the ability of the MMT to identify non-dominant and dominant knee extension forces less than normal was assessed. Normal predicted knee extension forces were based on the patient's age, gender and weight. MMTs identified 48 participants as having between-side differences in strength, whereas 100 participants were identified by dynamometry as having between-side differences in strength. MMTs identified 59.3% of the participants as having less than normal knee extension forces, whereas 96.7% of participants were identified with dynamometry. The sensitivity of the MMT compared to the dynamometry in identifying strength differences between-sides, and deficits relative to normal strength, never exceeded 72.3%. These studies suggest that large changes in strength may be missed when using the MMT grading scale.

Accurate assessment of muscle strength is important in the clinical setting, as detection of strength improvement or deterioration may help in proper rehabilitation planning and evaluation. The results of these studies demonstrate the superiority of dynamometry to subjective grading when identifying differences or impairments in muscle strength, and suggest the value of using hand dynamometers to measure muscle force during rotator cuff MMTs.

4.1.3 Limited evaluation and identification of MMTs that isolate the rotator cuff:

Although activity of the rotator cuff has been measured in several studies, there have been few studies which have identified positions in which the rotator cuff muscles are most isolated. In terms of intramuscular EMG investigations, this data type has been recorded for the rotator cuff during different tasks such as pitching (Gowan et al., 1987) and the breaststroke in swimming (Ruwe et al., 1994). Results of these studies are vague about the specific function of these muscles since authors only describe when these muscles are most active during a certain phase of the activity under study. Further, these authors did not identify postures that primarily activated the muscle of interest.

Literature is limited concerning the identification of MMTs that isolate the rotator cuff muscles. Only one study, Kelly et al (1996a), has done an EMG examination of the rotator cuff muscles (excluding teres minor) during manual muscle testing positions, with the purpose of defining optimal MMTs that isolate the rotator cuff muscles. In this study, EMG was recorded from 8 muscles of the non-dominant (left) shoulders of 11 male participants (mean age 28.5 years). Bipolar intramuscular electrodes were inserted into the supraspinatus, infraspinatus and subscapularis muscles. Bipolar arrangements of surface electrodes were placed over the pectoralis major, latissimus dorsi, and the anterior, middle and posterior deltoid. Each participant performed 27 core isometric exertions that included elevation, external rotation and internal rotation at three levels of scapular elevation (0º, 45º, 90º) and at three degrees of humeral rotation (0º, 45º (external rotation), -45º (internal rotation)). Two additional tests, the Gerber push-off and the Gerber push with force test, were also performed. A total of 29 isometric contractions were completed. Each participant's wrist was attached to a dynamometer that measured the force generated during each exertion. Five of the 11 participants repeated all 29 exertions after 30 minutes of rest for repeatability measures. Optimal MMTs were determined based on 4 criteria: maximal activation of the cuff muscle, minimal activation from involved synergists, good test-retest reliability, and minimal positional pain provocation. A blocked, mixed-model ANOVA was used for the mean integrated EMG (IEMG) of the core 27 exertions. The three main effects of the ANOVA included the type of exercise, degree of initial scapular elevation, and degree of humeral rotation. The ANOVA was used to determine which exertions produced maximal neural activation (significantly greater IEMG) of the three rotator cuff muscles. The IEMG from these exertions, along with the IEMG from the two Gerber tests, were then rank-ordered and used to determine optimal MMTs by minimizing (subtracting) synergistic contractions (contractions of muscles that complement the action of the supraspinatus, infraspinatus and subscapularis), and considering the same-day reliability of the test. Kelly et al (1996a) concluded that the optimal tests for isolating the supraspinatus, infraspinatus and subscapularis were respectively:

- elevation at 90º scapular elevation and 45º external rotation
- external rotation at 0º scapular elevation and 45º internal rotation
- Gerber push with force test

The results of this study are an important contribution to the continuing investigations of rotator cuff isolation in MMTs; however there are some limitations to the findings of Kelly et al (1996a). The authors gave no evidence for the assumed synergists of the rotator cuff, ignoring the possibility that shoulder muscle function changes with posture (Liu et al, 1997), and therefore, rotator cuff synergists may change as posture changes. Furthermore, the study was limited to recording eight muscles, so it was possible that key synergists were not measured (for example, the teres minor was not recorded, and it has been found to act in synergy with infraspinatus in external rotation (Townsend et al, 1991; Ballantyne et al, 1993). The lift-off test (in this paper termed the Gerber push with force test) was identified as the optimal MMT for the subscapularis muscle. This conclusion may be flawed because this test was assessed independently from the other 27 core exertions – it was excluded from the ANOVA as it did not fit the format of the other tests. Since this test was excluded from the ANOVA, and the IEMG was assessed only by rank-order, it is not known if the lift-off test produced a significantly higher IEMG in the subscapularis than the other 28 exertions.

Kelly et al (1996b) further endeavored to define isometric MMTs that would elicit maximal activation of the rotator cuff (excluding teres minor) and five other shoulder muscles. Nine male participants were tested with a mean age of 28.2 years. The authors used the same methodology (same electrode arrangement and same 27 core MMTs), and same analysis procedures (IEMG) as used in their 1996a paper (and described above). The results from the blocked mixed-model ANOVA indicated which MMTs produced significantly greater IEMG for the eight shoulder muscles. Some muscles were maximally activated in one posture (subscapularis, pectoralis major and middle deltoid), and other muscles were maximally activated in up to 9 MMTs (anterior deltoid). Some of these MMTs were found to maximally activate more than one muscle, therefore four MMTs that maximally activated all eight muscles were identified as follows:

- Elevation at 90º scapular elevation and 45º internal rotation was found to maximally activate the supraspinatus, anterior and middle deltoid
- External rotation at 90º scapular elevation and 45º internal rotation was found to maximally activate the infraspinatus and posterior deltoid
- Internal rotation at 90º scapular elevation and neutral humeral rotation was found to maximally activate the subscapularis and latissimus dorsi
- Internal rotation at 0º scapular elevation and neutral humeral rotation was found to maximally activate the pectoralis major

Kelly et al (1996b) concluded that these four MMTs, which maximally activated the shoulder muscles, could be used for EMG normalization purposes. It is important to note that the exertions that isolated rotator cuff muscles in Kelly et al (1996a) are not the same exertions as those that maximally activated the rotator cuff muscles in Kelly et al (1996b), indicating that exertions of isolation may be different than exertions of maximal activation. Few formal electromyographic evaluations of rotator cuff MMTs exist in the literature, and limitations associated with reported studies suggest that isolation exertions for these muscles have not yet been identified.

4.1.4 Previous investigations of MMTs used to assess the subscapularis:

A MMT called the ‘lift-off test’ was developed by Gerber & Krushell in 1991 to diagnose tears of the subscapularis tendon. The lift-off test is performed by having the patient place one arm behind their back, with the dorsum of the hand resting in the region of the mid-lumbar spine (shoulder extension and internal rotation). The patient then moves the hand away from the back by further internally rotating the humerus and extending the shoulder. The elbow should be kept at a constant angle of flexion. An inability to perform the lift-off test indicates weakness of internal rotation and increased external rotation with pain at the extreme end range of motion. The lift-off test has been proven to reliably diagnose subscapularis tears (confirmed by imaging) and decreased strength of internal rotation (Gerber & Krushell, 1991):

- a pathological lift-off test was identified in 8 out of 9 full rotator cuff tears involving the subscapularis
- a normal lift-off test was identified in 100 out of 100 normal shoulders
- a normal lift-off test was identified in 27 out of 27 full rotator cuff tears not involving the subscapularis
- a pathological lift-off test was identified in 12 out of 12 isolated subscapularis tears tested (there were a total of 16 isolated subscapularis tears, but 4 subjects were not tested with the lift-off)

Surgery was performed on the 16 male participants with isolated subscapularis tendon tears. Thirteen of these participants were reviewed more than 6 months after surgery, and all of these participants but one (whose tear was irreparable) regained normal passive internal rotation, and were able to perform the lift-off test, although not yet with normal strength (Gerber & Krushell, 1991).

Attention has also focused on variations of the lift-off test in order to assess their ability to isolate the subscapularis. Greis et al in 1996 compared the activity of the upper and lower subscapularis during the non-resisted lift-off test performed at the mid-lumbar region (as described by Gerber & Krushell in 1991), and similarly performed at the height of the buttocks. Five shoulders from four participants with a mean age of 34 years participated in this study. Intramuscular electrodes were inserted into the supraspinatus and the upper and lower portions of the subscapularis. Surface electrodes were placed over the posterior deltoid, pectoralis major, infraspinatus, latissimus dorsi, teres major and serratus anterior. The subscapularis was activated significantly more than the other recorded muscles, in both lift-off positions - with the exception of the teres major which was activated the same amount as the lower subscapularis in buttocks position. There was no significant difference between the EMG activity of the upper and lower subscapularis during the lift-off test performed at either the mid-lumbar or buttock position. The upper and lower subscapularis were most activated in the lift-off test performed at the mid-lumbar region (78.4%, 66.3%), than at the buttocks position (53.9%, 43.9%), respectively. The subscapularis was more isolated from the activity of the pectoralis major during the lift-off test (2.9%) compared to internal rotation performed in front of the body (48.4%). Greis et al (1996) suggested that the since the pectoralis major contributes very little activation (2.7-2.9%) during the lift-off tests, the subscapularis is the primary muscle to provide internal rotator action when the arm is internally rotated behind the back. Kelly et al (1996a) also confirmed that the subscapularis muscle was most isolated from the pectoralis major and latissimus dorsi in the lift-off position (which was termed the Gerber push with force test in this paper).

The belly-press test has been investigated as an alternative to the lift-off test, for patients who have very limited or painful internal rotation and are not able to reach behind the back. Gerber et al (1996) developed the belly-press test, which is performed by having the patient press on the abdomen with the hand flat, while attempting to keep the arm in maximal internal rotation. If the strength of the subscapularis is impaired, maximal internal rotation cannot be maintained, and the elbow falls behind the torso. The belly-press test reliably detected subscapularis tears (8 out of 8) in patients with decreased internal rotation, who were unable to perform the lift-off test (Gerber et al., 1996). Tokish et al in 2003 performed a study to validate the belly-press test, and compare it to the lift-off test. Sixteen participants (10 males with a mean age 28.4 years, and 6 females with a mean age of 25.0 years) participated in this study. Bipolar surface electrodes were placed over the latissimus dorsi, teres major, pectoralis major (sternal insertion) and infraspinatus. Intramuscular electrodes were inserted into the supraspinatus and upper and lower portions of the subscapularis. The EMG activities of the upper and lower portions of the subscapularis were significantly higher (>57% MVC) than that of the other five muscles tested (<23% MVC) during both the lift-off and the belly-press test (Tokish et al, 2003). There was no difference between the activation of the upper and lower portions of the subscapularis within test. However, although both tests activated upper and lower portions of the subscapularis muscle, the belly-press test elicited a greater response from the upper portion, whereas the lift-off test posed a greater challenge to the lower portion of the subscapularis. The findings of Tokish et al (2003) support the use of either the lift-off or the belly-press test in the evaluation of the subscapularis muscle. Due to the range of findings in the literature, further research is required to compare the belly-press and lift-off tests, as well as examine other MMTs, to identify exertions which maximally isolate the subscapularis.

4.1.5 Previous investigations of the isolation of supraspinatus during MMTs:

Both the full can and empty can MMTs are recommended for assessment of supraspinatus strength. In 1982 Jobe & Moynes advocated a test to isolate the supraspinatus muscle, which is commonly known as the empty can test. The empty can test is performed by having the seated or standing patient abduct the shoulder to 90° with the elbow extended, arm horizontally flexed to 30° and humerus internally rotated so that the thumb points downward (as if emptying a can). However, the internal rotation of the humerus in the empty can position between 70 - 90° of arm elevation can decrease the subacromial space, resulting in pain, and impingement on the supraspinatus tendon (Burke el al, 2002). Therefore, the full can test is an alternative to the empty can test for assessing the supraspinatus muscle. The full can test is performed by having the patient extend the elbow, elevate the arm in the scapular plane, and externally rotate the arm so that the thumb points upward.

Comparisons between the empty can and full can tests exist, in which an evaluation of their ability to assess and isolate the supraspinatus muscle occurred. Jobe &

Moynes (1982) showed that the supraspinatus was the predominant muscle activated in the rotator cuff (compared to the infraspinatus, teres minor and subscapularis) during the empty can test. Itoi et al (1999) evaluated the accuracy of the full can test in comparison with the empty can test in detecting a full tear in the supraspinatus tendon. One hundred and sixty shoulders from 149 patients (mean age 53 years) were investigated in this study. Rotator cuff tears involved the supraspinatus in 130 shoulders. The full can and empty can MMTs were performed to assess the strength of the supraspinatus muscle, which was graded on a scale of 0 to 5. Muscle weakness implied a muscle tear, which was confirmed with arthroscopy. The sensitivity of the two tests was assessed to determine the percentage of time the tests would have a positive result (identify weakness) in patients who had supraspinatus tears. The full can test had a sensitivity of 80%, slightly higher than the empty can test with a sensitivity of 78%. Accuracy, the percentage of the time the tests showed a positive result (identified weakness) in patients with tears, and a negative result in patients without tears was also assessed. Both tests were equivalent in accuracy, with the accuracy decreasing as the muscle demonstrated more weakness (Grade 3 = 24% accuracy – Grade 5 = 79% accuracy). Kelly et al (1996a) compared the ability of the full and empty can tests in isolating the supraspinatus. Six tests (out of a total of 29) produced significantly greater activation of the supraspinatus muscle. The empty can and full can tests were both included in these six test positions. Once the activation of the synergist (infraspinatus) was considered, these six tests were rank ordered and Kelly et al (1996a) concluded that the full can test position best achieved isolation of the supraspinatus muscle (maximal activation of the supraspinatus and minimal activation of the infraspinatus). Townsend et al (1991) compared the activation of the supraspinatus in the full and empty can tests during 17 dynamic exercises used in a professional baseball club rehabilitation program. Fifteen male participants (23 – 34 years) were tested. Intramuscular electrodes were inserted into the infraspinatus, supraspinatus, teres minor, subscapularis, pectoralis major, latissimus dorsi and the anterior, middle, and posterior aspects of the deltoid. Exercises were decided to significantly challenge a muscle if it promoted greater than 50% MVC over at least three consecutive arcs of motion. Dynamic scaption with humeral internal rotation, while prone (similar to the empty can position) significantly challenged the supraspinatus muscle (peaked at 74% MVC). Elevation (flexion) in the sagittal plane and dynamic scaption with humeral external rotation while prone (similar to the full can position), also significantly activated the supraspinatus at a peak of 67% and 64% MVC, respectively. However, the scaption with internal rotation exercise also produced significant activation in the subscapularis (62%), middle deltoid (83%) and anterior deltoid (72%). Similarly, elevation in the sagittal plane and scaption with external rotation exercise also produced significant activations in other surrounding muscles. The findings of Townsend et al (1991) suggest that although the supraspinatus is challenged in these exercises, these are not positions of maximal isolation. Past studies demonstrate inconsistent conclusions about the ability of the empty and full can tests in isolating and assessing the supraspinatus. Further research is needed to examine the empty and full can tests, as well as consider other exertions, to conclude which MMT truly isolates the supraspinatus.

4.1.6 Previous investigations of MMTs used to assess the teres minor and infraspinatus:

The teres minor and infraspinatus are both assessed during similar exertions of external rotation, during which they have similar lines of action. Otis et al (1994) studied the behavior of the moment arms (by measuring muscle excursions) of the rotator cuff of 10 cadavers during abduction and rotation of the glenohumeral joint, and found that the teres minor yielded a moment arm in external rotation comparable with that of the infraspinatus. However, at neutral rotation, the infraspinatus demonstrated moment arms for abduction that were 73% (superior portion), 38% (middle portion) and 23% (anterior portion) of those for external rotation. These values increased at 60º abduction and 45º internal rotation, showing that the infraspinatus contributes to abduction and is less of an external rotator during abduction and internal rotation (Otis et al, 1994). These findings suggest that muscle function changes as posture changes.

Many studies have assessed the ability of MMTs to maximally activate the infraspinatus and teres minor, but few have considered other muscle contributions during these exertions. Townsend et al (1991) studied 17 dynamic shoulder exercises, and found the infraspinatus and teres minor to be maximally activated in two similar exercises. The authors found the infraspinatus to be most activated during horizontal abduction as the participant lay prone with the elbow extended and the humerus externally rotated (peak 88% MVC). The infraspinatus was also significantly activated during external rotation when the patient was lying on the opposite side as tested, and the elbow was flexed to 90° (peak 85% MVC). The teres minor was most activated during side-lying external rotation (peak 80% MVC), but also was significantly activated during horizontal abduction as the participant lay prone with the elbow extended and the humerus externally rotated (peak 74% MVC) (Townsend et al, 1991). Similarly, Ballantyne et al (1993) recruited 40 participants (mean age 28 years) and evaluated the effect of the dynamic empty can, prone external rotation and side-lying external rotation exercises on the activation of the supraspinatus, infraspinatus, teres minor and lower trapezius. Ballantyne et al (1993) concluded that the prone external rotation and side-lying external rotation were both equally effective in activating the infraspinatus and teres minor. Dark et al (2007) studied the activation of the infraspinatus on the non-dominant shoulders of 15 participants (mean age 27 years). Intramuscular electrodes were inserted into the infraspinatus, supraspinatus, subscapularis, pectoralis major and latissimus dorsi. Two surface electrodes were placed over the posterior deltoid. Internal and external rotation (arm at side, elbow flexed to 90º) exercises were performed at low (10-20% maximum strength), medium (45-55% maximum strength) and high (60-70% maximum strength) intensities. Results indicated that infraspinatus was more significantly activated than supraspinatus or posterior deltoid during external rotation, and that activation of infraspinatus increased as intensity increased (40-70% concentrically, and 11-25% eccentrically). Results also indicated that during external rotation (at all intensities) the subscapularis, pectoralis major and latissimus dorsi were minimally activated (<6%) (Dark et al, 2007). Maximal activation of the teres minor and infraspinatus occur in exertions of external rotation.

Few studies have evaluated the ability of MMTs to isolate the teres minor and infraspinatus from other contributing muscles. Kelly et al (1996a) identified exertions which isolated the infraspinatus from the supraspinatus and posterior deltoid. The infraspinatus was most isolated when the patient externally rotated the humerus against resistance at 45° of internal humeral rotation and 0° scapular elevation. However, Kelly et al (1996a) did not record or consider the contributions of the teres minor muscle, which may have acted in synergy with the infraspinatus, as indicated by Otis et al (1994). Although many authors have determined that the infraspinatus and teres minor have lines of action that provide external rotation and are maximally activated in these postures, these may not be postures of isolation since generally contributions from other muscles were not considered.

4.1.7 Isolation techniques previously used:

Although several studies claim to have found postures which isolate rotator cuff muscles, their definition of and therefore methodology of finding isolation, challenge the usefulness of these results. Suenaga et al (2003) claimed to isolate the subscapularis muscle in the lift-off position, as this position produced a maximal percent MVC in the subscapularis. Similarly, other authors have attempted to selectively activate muscles, but their isolation techniques entailed choosing a posture which produced a maximal percent MVC, when the activity and contributions of the other muscles were not considered (Townsend et al, 1991; Greis et al, 1996; Dekker et al, 2003; Tokish et al, 2003). Jenp et al (1996) used a different technique to isolate the four muscles of the rotator cuff: from 29 test postures, the postures that produced the largest EMG activity for the muscle(s) of interest were identified as potential postures. The muscle activity of the other surrounding muscles (pectoralis major, anterior/middle/posterior deltoid and other three rotator cuff muscles) was then assessed from only these potential postures. Postures which were found to have the least amount of activity from the other muscles were determined to be postures of isolation for the muscle of interest. Although this paper provides important findings, it is possible that due to the primary selection of these postures, optimal isolation postures were missed. Initial selection of postures - postures that produced the maximal EMG activity - may have eliminated other potential isolation postures, since a muscle may not have to be in a state of maximal activation to be isolated.

The review of literature demonstrates that there is still limited knowledge regarding isolation exertions of the rotator cuff. Identification of muscle isolation – true (if it exists) or functional (highest ratio of activation of muscle of interest to activation of other muscles) is crucial as it will enable more meaningful functional assessment of the rotator cuff muscles, and will allow clinicians and researchers to make precise diagnoses and treatment regimes for injuries. The lack of literature in this area and the limitations found in the existing studies demonstrate the need for a thorough EMG study of MMTs to identify exertions that isolate individual rotator cuff muscles.

4.2 Literature review of electromyography

The recording of myoelectric signals is a common means by which to estimate muscle force related to physical activities performed by humans, since direct measurement of muscle force requires the invasive insertion of a force transducer within the muscle. The presence of a force transducer would likely affect the performance of the task, as well as cause potential discomfort and pain.

4.2.1 Surface electrodes:

Surface electrodes (Figure 3) are the most common type of electrode used in EMG studies. Although surface electrodes are relatively inexpensive, easy to use and apply, and are non-invasive to the participants being tested – they are limited in the fact that they primarily detect superficial muscle activity. Surface electrodes have a large pick-up volume, in that they will record electrical activity from all muscles within this volume, which can result in cross-talk contamination of the signal of interest. Winter et al (1994) predicted the pick up range of surface electrodes to be 1.8 cm from the surface of the skin (with an assumed fat layer of 2 mm). Surface electrodes can also be problematic during dynamic movement as the muscle moves underneath the skin while the surface electrode stays affixed to a spot on the skin's surface. This may result in failure to record a consistent signal from the same muscle.

Figure 3: Bipolar surface electrode: lead connectors (left) and adhesive underside (right)

4.2.2 Intramuscular electrodes:

Intramuscular electrodes consist of a hypodermic needle (available in different lengths and gauges) that contains one or two tiny wires within it (Figure 4). The needle is inserted into the muscle, and the wires are barbed at the end, allowing them to hook and remain in the muscle, once the needle is removed. These barbed wires discourage and limit some movement of the wires within the muscle. These wires have a smaller pick-up volume and are much

Figure 4: Intramuscular needle electrodes of two lengths

more specific to the activity of the fibers within a specific muscle of interest, compared to surface electrodes. Intramuscular electrodes are able to detect myoelectric signals from deeper muscles, however these electrodes are more costly, difficult to use and are more invasive to the participants. Without standardizing the exact location and depth of each insertion of an intramuscular electrode, a different signal may be obtained as the distribution and number of fiber types varies within a muscle. Intramuscular wire electrodes can migrate within the muscle and pull in and out through the skin. Basmajian & De Luca (1985) recommended the use of barbed wires for intramuscular EMG, and suggested that participants perform 6 – 8 maximal contractions of the muscle in which the wire is inserted, to set the barb and limit wire movement.

4.2.3 Cross-talk and reliability of surface and intramuscular electrodes:

Cross-talk contamination occurs when electrodes record electrical activity from other sources within the pick-up volume, besides the signal of interest. Etnyre and Abraham (1988) compared the activity of the tibialis anterior and soleus muscles during dorsi and plantar flexion. Activity of these muscles was recorded with both surface and intramuscular electrodes on five male participants. Results suggested co-contraction of these antagonistic muscles, as the surface electrode indicated activity of the soleus (the wire electrode did not) during dorsiflexion. Cross-correlation analysis indicated that the soleus EMG signal originated in the tibialis anterior muscle. The authors concluded that cross-talk was occurring in the surface electrode during dorsiflexion (Etnyre & Abraham, 1988). Kamen & Caldwell (1996) described how electrodes are non-discriminative in their pick-up volume, as they will pick up signals from underlying and adjacent muscles, whether they are synergists or antagonists, as well as any electrical noise present. These authors suggested performing MMTs that would primarily activate the muscle of interest, to confirm electrode placement and test for cross-talk of nearby muscles. Winter et al (1994) similarly recommended that MMTs be performed to assess for cross-talk, and furthermore recommended that surface electrodes with a smaller surface area and closer bipolar spacing be used to minimize the overlap between adjacent pairs of electrodes.

The reliability of signals from surface and intramuscular electrodes has been compared. Giroux & Lamontagne (1990) compared the same day and between day test-retest reliability of surface and intramuscular wire electrodes of the upper trapezius, anterior and middle deltoid. Six males were tested while performing two lifting tasks; one dynamic and one static task. Giroux & Lamontagne (1990) reported that same day test retest reliability was good for both surface and wire electrodes, and that there was no significant difference of same day reliability between these two electrode types, for any muscle or either task (isometric or dynamic). When between-day test-retest reliability was compared, the results indicated that the surface electrodes were significantly more reliable than the wire electrodes (0.806 vs 0.018). Giroux and Lamontagne (1990) concluded that either surface or wire electrodes are suitable for several testing trials during the same session, but that repeatability of wire signals on between-day testing is limited, likely because of the difficulty in repeating wire location and depth during insertion.

The muscles of the rotator cuff are close together, small and deep, and not easily accessible for recordings from surface electrodes. The depth and location of the subscapularis makes it an impossible candidate for surface recording. Some studies have used surface electrodes to record activity from the infraspinatus (Happee & Van der Helm, 1995; Tokish et al, 2003; Dickerson et al., 2007; 2008), but rotator cuff muscle activity is most commonly recorded from intramuscular electrodes. Intramuscular electrodes were used in the present study to record signals from the rotator cuff muscles.

4.2.4 Placement of intramuscular electrodes:

The placement of intramuscular electrodes must be standardized (location, depth and technique) in order to obtain a reliable and accurate signal. Absolute measures have been used to describe the location of intramuscular electrode insertion into the supraspinatus and infraspinatus (Basmajian & De Luca, 1985). Alternatively, proportional measures have been used to describe indwelling electrode placement into the supraspinatus, infraspinatus and teres minor (Delagi & Perotto, 1980). To allow for anthropometric differences between participants, this research study generally followed proportional instructions for electrode placement rather than absolute measures.

To standardize insertion depth in the infraspinatus and supraspinatus, studies recommend inserting the electrode until contact is made with the fossa of the scapulae (Basmajian & De Luca, 1985; Kelly et al, 1997). A 1.5-inch, 27-gauge hypodermic needle would be ideal to reach this depth (Barden et al, 2005). Placement of fine-wires into the subscapularis is more difficult and dangerous than reaching the other muscles of the rotator cuff. If indwelling electrodes are inserted in an improper location, there could be a risk of pneumothorax, brachial plexus and/or arterial injuries. A safe and reliable method to reach the subscapularis with fine-wire electrodes is through insertion under the scapulae in the posterior axillary line, until reaching the costal surface of the scapula (Figure 5) (Nemeth et al., 1990). In this study of 24 shoulders, no complications were seen with this technique, and others have since used this technique successfully (Kronberg et al, 1991; Laursen et al, 1998; Morris et al, 1998).

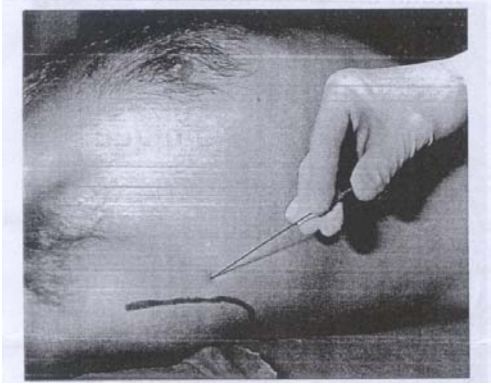


Figure 5: Intramuscular insertion site for subscapularis
(Nemeth et al, 1990)

4.2.5 Paired and single hook-wire electrodes:

There are mixed reviews in the literature regarding which electrode type are better used for intramuscular insertions: paired or single hook-wire electrodes. Paired hook-wire electrodes are intramuscular electrodes that have two fine wires within the hypodermic needle, whereas single hook-wire electrodes contain only one wire. Basmajian & De Luca (1985) suggested that a dual-needle insertion technique (one wire per needle) be used to insert the wires to ensure a standardized inter-electrode spacing of 1 cm for the bipolar configuration. However, this technique relies on the researcher to accurately measure and insert the second needle 1 cm away from the first, which is often difficult to do with muscles such as the subscapularis. The single hook-wire technique was shown to produce EMG signals with greater voltage, less variation and higher correlation for the integrated EMG area with force, compared with the paired hook-wire technique (Kelly et al, 1997). Proper electrode spacing with independent insertion of the wire minimizes the risk of signal loss caused by two leads touching and short-circuiting (Kelly et al, 1997).

However, the paired hook-wire electrodes are commonly used in the literature (Perry et al, 1981; Gowan et al, 1987; Giroux & Lamontagne, 1990; Nemeth et al, 1990; Ballantyne et al, 1993; Ruwe et al, 1994; Hintermeister et al 1998; Morris et al 1998). Bipolar configurations are advantageous to single configurations in the fact that these electrodes detect two pick-up volumes of which a differential amplifier eliminates any similarities in these signals (Kelly et al,1997). Hereby, unwanted electrical signals (such as 60 Hz noise) from sources other than the muscle being investigated will be excluded. Due to the difficulty in inserting electrodes in a precise location, distance, and depth apart, the paired hook-wire electrodes allow the wires to be kept apart at a standard distance, with only one needle insertion required. The comfort of the participants must also be considered, as it is more invasive to insert twice the number of needles. In order to standardize inter-electrode spacing and minimize the amount of discomfort imposed upon the participants, paired hook-wire electrodes were used in this study.

5.0 Methodology:

Intramuscular electrodes were inserted in the four muscles of the rotator cuff, and surface electrodes were placed over 12 shoulder muscles. Participants performed 29 specified maximal isometric exertions against a stationary force transducer. During the exertions, muscle activation and force generated at the hand were measured.

5.1 Participants:

Twelve right-hand dominant male students from the University of Waterloo within an age range of 18 - 29 years participated (Table 2). Participants were recruited with posters and verbally as described in Appendices A and B. Only one gender was recruited from a narrow age range to enhance the possibility that study results could be generalized to a similar population. Participant exclusion criteria included:

- an allergy to iodine, latex, nickel or isopropyl alcohol
- blood clotting disorders
- viral infections: HIV, Hepatitis A, B, or C
- chronic pain lasting longer than 6 months
- upper limb or lower back injury within the past 6 months
- known difficulty with or slowness of healing

Table 2: Participant anthropometric data

Participant	Height (cm)	Weight (Kg)	Age (years)
S1	183.0	83.9	24
S2	180.0	65.5	20
S3	167.6	75.0	18
S4	165.1	49.0	18
S5	181.6	78.0	22
S6	185.4	79.5	19
S7	187.9	83.0	21
S8	180.3	88.2	19
S9	182.9	72.7	29
S10	185.4	79.5	21
S11	175.3	79.5	19
S12	193.1	86.4	18
Mean	180.6	76.7	20.7
Std Dev	8.0	10.7	3.2

The purposes, methods, risks and benefits of the study were explained to the participants, and they signed a form of consent prior to participation (Appendix C). Participants received financial compensation for their participation in the study at a rate of $50.00 per participant. Participants received a feedback letter after participation including study details and researcher contact information (Appendix D). This study was reviewed by, and received clearance through, the Office of Research Ethics, University of Waterloo.

5.2 Intramuscular Electromyography:

Simultaneous EMG was recorded from intramuscular and surface electrodes (on two muscle sites), to allow for signal comparison between the two electrode types (this research was outside the scope of this current thesis work). Before insertion of intramuscular electrodes, the hair from this area was shaved. The participant lay on a clinical bench and the skin area over the muscle was thoroughly cleaned with Betadine solution containing 10% providone-iodine.

Four sterile single-use hypodermic needles (VIASYS^{TM} Healthcare, Wisconsin, USA) were inserted through the skin into the four muscles of the rotator cuff (supraspinatus, infraspinatus, teres minor and subscapularis). These stainless steel needles had been sterilized by gamma irradiation. The bipolar single-needle insertion technique (using paired hook-wire electrodes) was used, as described by Basmajian & De Luca (1985). Each of these needles contained two very thin insulated nickel alloy wires (44 gauge, 10 cm long) of similar size to a strand of hair. The ends of these wires were positioned so that 2 mm of the first wire and 5 mm of the second wire exited at the end of the needle. The first wire was stripped 2 mm, while the second wire was insulated for 3 mm after it exited the needle, and then was stripped 2 mm. This arrangement prevented the two un-insulated ends from touching, and allowed for a standardized inter-electrode spacing. The three needles that were inserted into the supraspinatus, teres minor and infraspinatus muscles were 27 gauge and 30 mm in length. The needle inserted into the subscapularis muscle was 25 gauge and 50 mm in length. The total depth of the needle into the tissue varied from participant to participant depending on the amount of subcutaneous fat overlying the muscle. It was estimated that the needles were inserted approximately 1 cm subcutaneously into the supraspinatus, infraspinatus and teres minor. The needle for the subscapularis was inserted subcutaneously approximately 4.5 cm deep.

The needles were immediately removed, but the 8 wires remained in the muscles for the duration of testing (approximately 2.5 hours). The wire within the needle was bent at the end forming a barb, so that once the needle was removed from the skin the thin wire remained in the muscle during testing. The wire extended by approximately 7 cm beyond the surface of the skin and was coiled (to allow movement of the wire through the skin) and then taped down to prevent accidental withdrawal. In order to set the hooks of the intramuscular wire electrodes firmly in the muscles and help prevent migration, participants performed 6 - 8 maximal contractions and relaxations of the supraspinatus, infraspinatus, subscapularis and teres minor before data collection as recommended by Basmajian and De Luca (1985).

Once testing was completed, the wires were removed easily with a gentle tug on the end of the wire that was lying outside the skin. This removal was painless because each wire was so pliable that the barb straightened out on traction and offered little, if any, palpable resistance (Basmajian & De Luca, 1985). Upon removal of the wires, the skin area was cleaned with isopropyl alcohol, and a bandage was placed over the area if needed. After removal, hypodermic needles and wires were disposed of in a sharps container labelled biohazardous waste.

The needle insertion procedures were carried out by Linda McLean, PhD. Dr. McLean is an Associate Professor at Queen's University in the department of Rehabilitation Therapy and is an expert at inserting intramuscular electrodes. Dr. McLean has over six years of experience and has performed numerous intramuscular insertions into the muscles of the rotator cuff, as well as into many other muscles. Dr. McLean has not once experienced any form of complication during or as a result of her needle insertions. All needle handling was performed by Dr. McLean while using latex gloves. Insertion and confirmation of electrode placement followed standard guidelines (Delagi & Perotto, 1980; Nemeth et al, 1990) as outlined in Table 3. No apparent complications or adverse effects were experienced by any of the participants. Refer to Appendix K for photographs of electrode placement (of surface and wire electrodes).

Table 3: Instructions for insertion of intramuscular electrodes

Muscle	Position	Electrode Insertion	MVC Test Maneuver	Pitfalls
Infraspinatus (Delagi et al, 1980)	Subject is prone with arm abducted to 90° and the elbow is flexed over the edge of the bench.	Insert needle electrode into infraspinous fossa two finger-breadths below medial portion of spine of scapula.	Subject is lying on left side. Arm is at side with elbow bent to 90°. External rotation of the arm is resisted.	If needle electrode is inserted too superficially it will be in the trapezius; if too laterally it will be in posterior deltoid.
Supraspinatus (Delagi et al, 1980)	Subject is prone with arm abducted to 90° and the elbow is flexed over the edge of the bench.	Insert into supraspinous fossa just above middle of spine of scapula.	Subject is lying on left side. Shoulder is abducted to 5° with elbow extended (thumb forward). Abduction is resisted.	If needle electrode is inserted too superficially it will be in the trapezius.
Teres Minor (Delagi et al, 1980)	Subject is prone with arm abducted to 90° and the elbow is flexed over the edge of the bench.	Insert needle one-third of the way between acromion and inferior angle of scapula along the lateral border.	Subject is lying on left side. Arm is at side with elbow bent to 90°. External rotation of the arm is resisted.	If needle is inserted too cephalad it will be in the supraspinatus, infraspinatus or the posterior deltoid. If inserted too caudally it will be in the teres major or triceps. If inserted too superficially or medially it will be in the trapezius or infraspinatus, respectively.
Subscapularis (similar to Nemeth et al, 1990)	Subject sits with arms abducted, externally rotated and hands behind their head.	Insert needle under edge of scapula in posterior axillary line, 8 cm above the inferior angle of the scapula adjacent to an underlying rib. Insert needle 10º cranial, just dorsal to scapular plane. Insert needle until it reaches the costal surface of the scapula.	Prone lift-off test: Subject lies prone in full shoulder extension and internal rotation with hand at L5 level. Subject extends shoulder and externally rotates humerus against resistance.	Use of needles in the axillary area may cause pneumothorax, brachial plexus, or arterial injuries. Proper insertion will minimize these risks.

Note: Fingerbreadths used are those of the participant, not of the examiner.

5.3 Surface Electromyography:

Twelve bipolar surface adhesive electrodes (Noraxon, USA Inc., Arizona, USA) were placed on the skin over 12 muscles, and one additional electrode was placed on the clavicle as a ground electrode. Prior to electrode placement, any hair in the placement area was shaved. The removal of hair enhanced the signal and simplified electrode removal. A new disposable razor was used for each participant. The skin areas for electrode placement were wiped with isopropyl alcohol and then the electrodes were placed on the skin.

Twelve bipolar Ag/AgCl surface electrodes (two 2 cm diameter surface electrodes with 2 cm distance between them) were placed on the following muscles of the right arm: latissimus dorsi, long head of triceps, biceps brachii, anterior deltoid, middle deltoid, posterior deltoid, pectoralis major (sternal insertion), pectoralis major (clavicular insertion), middle trapezius and upper trapezius in locations similar to past work (De Groot et al, 2004), as well as over the wire sites of infraspinatus and supraspinatus muscles (Table 4). The bipolar electrodes that were placed over the wire sites were separated with scissors very carefully to ensure equal diameter of each electrode. Then each electrode was placed as close as possible (but not touching) on either side of the wire insertion site.

Table 4: Surface electrode placement instructions

Surface Electrodes	Placement Location
Pectoralis Major (clavicular insertion)	*Electrode Placement:* Between sternoclavicular joint and the caracoidus process, 2 cm below the clavicle (on an angle down and laterally). *Test Contraction:* While sitting, flex elbow and shoulder to 90º, horizontally adduct & flex shoulder. Resist (from above) proximal to elbow joint in a downward and outward direction.
Latissimus Dorsi	*Electrode Placement:* 6 cm below the inferior angle of the scapula. *Test Contraction:* Sit with shoulder abducted to 90º and elbow flexed to 90º. Adduct shoulder against resistance.
Pectoralis Major (sternal insertion)	*Electrode Placement:* 6 cm above the nipple. *Test Contraction:* Subject lies supine. Shoulder is horizontally abducted to 30º with elbow flexed to 90º. Resist horizontal adduction of shoulder.
Upper Trapezius	*Electrode Placement:* 2/3 on the line between the trigonum spinae and the 8th thoracic vertebrae, 4 cm from muscle edge, at approximately a 55° oblique angle. *Test Contraction:* Subject is prone with head turned to right side. Resist shoulder abduction at 90º with elbow extended, thumb down to floor.
Middle Trapezius	*Electrode Placement:* 2 cm vertically above the trigonum spinae. *Test Contraction:* Subject is prone with head turned to right side. Subject abducts shoulder to 120º with elbow extended and thumb pointing up to ceiling. Subject pushes up to ceiling against resistance.
Anterior Deltoid	*Electrode Placement:* 2-4 cm below the clavicle, parallel to muscle fibers. *Test Contraction:* Subject sits and forward flexion at 90° is resisted.
Middle Deltoid	*Electrode Placement:* 3 cm below the lateral rim of the acromion, over muscle mass, parallel to muscle fibers. *Test Contraction:* Subject sits with elbow extended and thumb pointing forward. Abduct of the shoulder at 90° is resisted.
Posterior Deltoid	*Electrode Placement:* 2 cm below lateral border of scapular spine, oblique angle toward arm (parallel to muscle fibers). *Test Contraction:* Subject is prone with head turned to right side. Resist shoulder extension when shoulder is abducted to 90º, elbow flexed to 90º and thumb points up to ceiling.
Biceps	*Electrode Placement:* Above the centre of the muscle, parallel to the long axis. *Test Contraction:* Subject is sitting with arm at side and elbow flexed to 90º. Forearm flexion is resisted.
Triceps Brachii (long head)	*Electrode Placement:* On the posterior portion of the upper arm, located medially. *Test Contraction:* Subject is supine with shoulder and elbow flexed to 90º. Forearm extension is resisted.
Infraspinatus	*Electrode Placement*: Parallel to spine of scapulae, approximately 4 cm below, over the infrascapular fossa. *Test Contraction:* Subject is lying on left side. Arm is at side with elbow bent to 90°. External rotation of the arm is resisted.
Supraspinatus	*Electrode Placement:* Midpoint and 2 finger-breadths superior to scapular spine* *Test Contraction:* Subject is lying of left side. Shoulder is abducted to 5° with elbow extended (thumb forward). Abduction is resisted.
	Similar to Daniels & Worthingham (1986); Cram & Kasman (1998)
	*similar to Hintermeister et al (1998) Note: Neck held neutral (looking straight ahead) in all conditions unless otherwise indicated.

Each set of bipolar electrodes was connected to a 16 channel Noraxon Telemyo 2400T G2 (Noraxon, USA Inc., Arizona, USA) electromyography wireless transmitter. All channels had analog band pass filters set at 10 – 1500 Hz. EMG active lead specifications included a differential amplifier common mode rejection ratio of >100 dB and input impedance of >100 mΩ. The gain was set at 500. The transmitter data acquisition system had 16-bit resolution on all analog inputs. In order to satisfy the Nyquist theorem, the sampling rate was set to 4000 Hz. Each trial was collected for 6 seconds. The raw EMG was sent from the transmitter to the receiver, and was transferred to a personal computer for analysis. The wireless capabilities of this system allowed for participants to move freely, without impeding their actions. This system allowed for simultaneous recording from 16 channels that represented 14 muscles (both surface and intramuscular electrodes were used for the infraspinatus and supraspinatus).

5.4 Hand Force Transducer:

Due to the subjective nature of MMT grading scales, superior strength measures and differences in strength are obtainable with a dynamometer rather than by subjective tester MMT grading. A major goal of this study was to relate quantifiable measures of force associated to isolation exertions. Therefore, it was beneficial to use a force transducer to generate force measures rather than a nonspecific grading scale. A clinician typically manually applies resistance applied during MMTs. However, the resistance that is applied must be isometric for the measurement of accurate and repeatable values. Due to strength differences between the tester and patient, it is possible that the tester would be unable to resist the strength of the patient, and fail to hold the resistance constant. This could result in underestimated or inaccurate force measures. Furthermore, failure to provide static resistance could allow for postural changes to occur, and the exertions under study would not be valid (as isolation may occur in undefined postures). For these reasons, obtaining reliable results was prioritized over direct clinical relevance. Thus, participants exerted force against a firmly mounted force transducer that provided resistance, which allowed participants to perform repeatable exertions.

The participants pressed the hand or wrist against a square frame attached to a force transducer, which was firmly mounted to a vertical steel beam (Figure 6). The 3-axial transducer measured continuous forces in the X, Y and Z directions and transmitted these values through an amplifier (with a gain of 1000) to the computer through an A/D board. This transducer was preferred over a transducer that measures in only one direction (push and pull), because there was no way to prevent participants from pushing in other directions. Using a tri-axial transducer allowed for consideration of each force magnitude in the X, Y and Z directions, and then this information was used to calculate a resultant force produced (Eq. 1). Force transducer data was sampled at 50 Hz. The force was synchronized in time with EMG recordings during each 6 second trial.

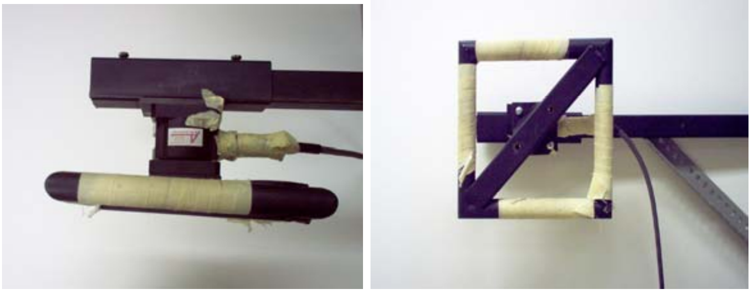


Figure 6: Force transducer and steel frame
(Left = force transducer is between square frame and support arm, Right = Square frame that participants push against)

$$\text{Resultant Force} = \sqrt{\sum (\text{Force}_x)^2 + (\text{Force}_y)^2 + (\text{Force}_z)^2} \qquad (1)$$

5.5 Photographs and Video Recording:

Photographs and video recordings were taken during the study, if consent was given by the participant. These photographs and video recordings were focused on the upper body and arm. These photos and recordings may be helpful in teaching purposes such as when presenting the study results in a scientific presentation or publication. Any facial features or other distinguishing features that were visible in photos or recordings used for these above mentioned purposes were blotted out to maintain participant confidentiality.

5.6 Testing Protocol:

Intramuscular and surface electrodes were inserted into and placed over 16 muscle sites. Participants performed maximal voluntary contractions, followed by 29 isometric exertions. EMG and force values were analyzed, and isolation ratios were calculated Total set-up and experimental testing time was approximately 2.5 hours (Table 5).

Table 5: Timeline for each experimental session
1. **Subject Preparation:** a. Clean skin and insert 4 intramuscular electrodes b. Remove intramuscular electrodes and leave behind 8 wires c. Clean skin and place 12 bipolar surface electrodes
2. **Experimental Protocol:** a. Subjects perform 2 sets of 6 second MVCs b. Subjects perform randomized exertions (6 seconds each, with 2 minute rest between each) c. During exertions, subjects push against (and are resisted by) force transducer d. Time synchronous EMG and force are captured
3. **Analysis:** a. EMG data: biases are subtracted, EMG is full-wave rectified, filtered and normalized b. Maximal isolation ratios are identified for each rotator cuff muscle c. Force outputs synchronous with the EMG during exertions which produced maximal isolation ratios are identified

5.6.1 Maximal voluntary contractions:

EMG was normalized to allow for comparisons of muscle activity levels between muscles and participants. Each participant performed 13 isometric MVCs twice, for a total of 26 MVCs for the 16 recorded muscles. MVC exertions used for the 12 muscles recorded with surface electrodes are outlined in Table 4. Since there were both surface and intramuscular electrodes recording the activity of the supraspinatus and infraspinatus, their MVC exertions were identical for both wire and surface channels. Due to the similar lines of action of the teres minor and infraspinatus (as shown by Otis et al in 1994), the MVC exertion used for infraspinatus was shared for the normalization of teres minor as well. The 13th MVC exertion was for the subscapularis which was recorded with intramuscular electrodes, and is outlined in Table 3. Six seconds were allowed for the participant to ramp up and then reach a momentary maximal voluntary contraction. MVCs were repeated twice, and if the peak voltage levels differed more than 20% or if the recording did not visually appear to ramp up to a peak, a third MVC was performed. Two minutes of rest was given between each MVC exertion.

5.6.2 Isometric exertions:

Participants performed a total of 29 rotator cuff MMTs against the manual resistance of a firmly mounted tri-axial dynamometer (conceptually similar to Michener et al in 2005). The exertions were organized into 7 groups, depending on their primary action (Table 6). The division of these 29 exertions into 7 groups was confirmed with a one-way analysis of variance test (ANOVA), which confirmed that there was no statistical difference ($p<0.05$) between the means of the isolation ratios between exertions within these 7 groups (Appendix E). The order in which the MMTs were performed was randomized within and between groups. This means that exertions were randomized within each of the 7 groups, and one exertion was performed from one group at a time (and that group order was also randomized). Participants were allowed 2 minutes of rest between each contraction, as recommended by De Luca (1997). Exertions were performed on either a bench (prone exertions) or stool (sitting exertions); the height of both the stool and bench were adjustable. Total testing time, including set-up was approximately 2.5 hours.

Table 6: Exertion groups for randomization purposes

Group 1 (Internal Rotation Tests)	**Group 2** (External Rotation Tests)	**Group 3** (Abduction Tests)	**Group 4** (Palmar Force Tests)	**Group 5** (Dorsal Force Tests)	**Group 6** (Radial Force Tests)	**Group 7** (Ulnar Force Tests)
Prone Subscapularis	Prone Infra. & T.M.	Empty Can	Neutral 0º	Neutral 0º	Neutral 0º	Neutral 0º
Lift-Off Test	Sitting Infra. & T.M.	Blackburn	Flex 45º	Flex 45º	Flex 45º	Flex 45º
Belly Press Test		Full Can	Flex 90º	Flex 90º	Flex 90º	Flex 90º
		Supra. Neutral Abduct	Abduct 45º	Abduct 45º	Abduct 45º	Abduct 45º
			Abduct 90º	Abduct 90º	Abduct 90º	Abduct 90º

5.6.2.1 Clinical manual muscle test exertions:

The instructions for performing nine of the isometric MMTs that are commonly seen in the literature and used by clinicians are listed below:

MMTs for the subscapularis:

i) Prone subscapularis test (Exertion 16):

The participant was prone with the shoulder abducted to 90º and the elbow flexed to 90º. The arm proximal to the elbow was resting on the bench (the forearm was hanging over the edge of the bench). The head was turned towards the right side. The participant internally rotated the shoulder to 65º by moving the palm of the hand towards the ceiling. Resistance was applied against the force transducer proximal to the wrist joint in the direction of shoulder external rotation (Figure 7). (Clarkson & Gilewich, 2000; and similar to Janda 1983; Daniels and Worthingham, 1986)

[redacted]

[redacted]

Figure 7: Prone subscapularis test (Exertion 16) - clinical MMT of internal rotation

ii) Lift-off test (Exertion 2):

The participant was prone and brought the arm passively behind the body into full shoulder extension and internal rotation at the level of L5 (Gerber et al, 1991). The head was turned towards the right side. Resistance was applied to the force transducer proximal to the wrist joint in the direction of shoulder external rotation (Figure 8).

Figure 8: Lift-off test (Exertion 2) - clinical MMT of internal rotation used to assess the subscapularis

iii) Belly-press test (Exertion 9):

The participant sat with the head facing forwards, and pulled against the force transducer towards their abdomen (just below the xyphoid process) with the palm of the hand (fingers extended). Participants attempted to keep the arm in maximum internal rotation (Figure 9). The researcher ensured that the participant did not let the elbow drop backward behind the trunk. (Gerber et al, 1996)

Figure 9: Belly-press test (Exertion 9) - clinical MMT of internal rotation used to assess the subscapularis

MMTs for the infraspinatus and teres minor:

i) Prone infraspinatus and teres minor test (Exertion 13):

The participant was prone with the head turned towards the right side, and with the shoulder abducted to 90º and elbow flexed to 90º (Figure 10). The arm proximal to the elbow was resting on the bench. The participant externally rotated the shoulder by moving the dorsum of the hand towards the ceiling until the forearm was horizontal. Resistance was applied against the force transducer proximal to the wrist joint on the posterior aspect of the forearm in the direction of shoulder internal rotation. (Clarkson & Gilewich (2000) and similar to Janda (1983); Daniels and Worthingham (1986))


[redacted]

Figure 10: Prone infraspinatus and teres minor test (Exertion 13) - clinical MMT of external rotation

ii) Sitting infraspinatus and teres minor test (Exertion 6):

The participant sat with the head facing forward and with 0º of shoulder elevation, 90º of elbow flexion and 45º of humeral internal rotation. The participant externally rotated the humerus. Resistance was applied from the force transducer on the back of the hand and applied in the direction of internal rotation (Figure 11). (Kelly et al, 1996a)


[redacted]
[redacted]

Figure 11: Sitting infraspinatus and teres minor test (Exertion 6) – clinical MMT of external rotation

MMTs for the supraspinatus:

i) Empty can test (Exertion 1):


[redacted]
[redacted]

Figure 12: Empty can test (Exertion 1) – clinical MMT of abduction used to assess supraspinatus

The participant sat with the head facing forward. The elbow was extended, and the shoulder was in full internal rotation (thumb down) with the arm in the scapular plane (30º forward flexion). The participant lifted the arm into 90º abduction. Resistance from the force transducer was applied on the ulnar side of hand and was applied in the direction of adduction (Figure 12). (Malanga et al, 1996; Jobe & Moynes, 1982)

ii) Blackburn test (Exertion 8):

The participant was prone with the elbow extended and shoulder abducted to 100º. The participant externally rotated the humerus so that the thumb was pointing up to the ceiling. The head was turned towards the right side. The participant abducted and resistance from the force transducer was applied on the back of the hand in the direction of adduction (Figure 13). (Malanga et al, 1996)

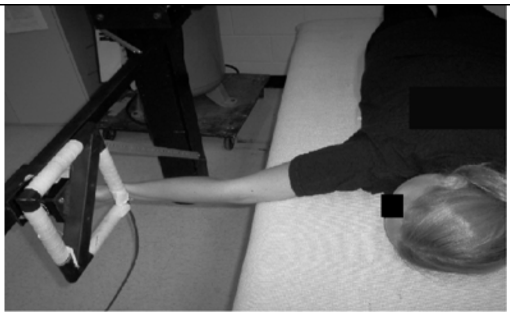


Figure 13: Blackburn test (Exertion 8) – clinical MMT of abduction used to assess supraspinatus

iii) Full can test (Exertion 21):

The participant sat with the head facing forward. The elbow was extended, and the shoulder was in the scapular plane of 30º forward flexion. The participant abducted the shoulder to 90º with 45º of humeral rotation (thumb up) against

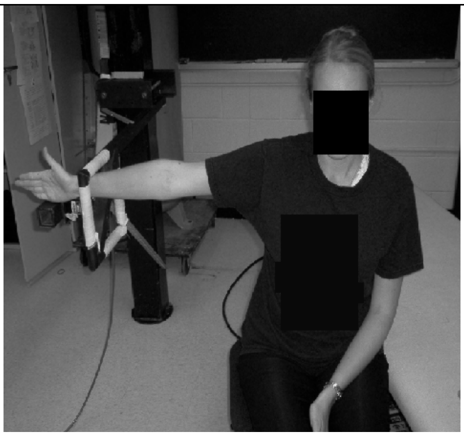


Figure 14: Full can test (Exertion 21) – clinical MMT of abduction used to assess supraspinatus

resistance from the force transducer, which was placed on radial side of the wrist (Figure 14). (Kelly et al, 1996a)

Figure 15: Supraspinatus neutral abduction test (Exertion 15) – clinical MMT

iv) *Supraspinatus neutral abduction test (Exertion 15):* The participant sat with the head facing forward and with the humerus in neutral rotation (thumb pointing forward) and the elbow extended. The participant abducted their arm to 90º. Resistance was applied proximal to elbow joint on the lateral aspect of the wrist, in the direction of shoulder adduction (Figure 15). (Clarkson & Gilewich, 2000)

5.6.2.2 Generic isometric MMT exertions:

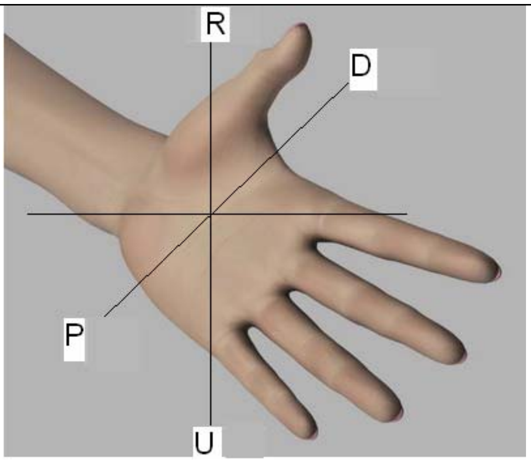


Figure 16: Dorsal (D), palmar (P), ulnar (U) and radial (R) force directions
(http://www.ravenmadness.blogspot.com/2007/05/handywork.html)

To assess further isolation exertion possibilities, an additional 20 test exertions (Table 7) were assessed: shoulder flexion and abduction at 45 and 90˚ elevation, and a neutral humeral rotation (0º), while changing the force direction at the hand in 4 directions: palmar, dorsal, radial and ulnar (Figure 16). An example of one of these 20 postures is shown in Figure 17. Twenty-nine maximal exertions were performed. Kelly et al (1996a) performed a study with the same number of maximal exertions (29). The researcher used goniometry to position the participant into each exertion testing posture. The 29 exertions in our study were numbered from 1 to 29 (format: Exertion xx) to enable comparisons during analysis. Refer to Appendices F for a complete listing of exertions with numerical names.


[redacted]
[redacted]

Figure 17: Flexion (45º) with radial resistance (Exertion 7) – generic exertion

Due to the risk of fatiguing participants as a result of the extended testing time and number of maximal exertions, it was undesirable to repeat exertions. However, the first two exertions performed by each participant were repeated at the end of testing, so that comparisons of force outputs and median and mean power frequency could be used to assess potential fatigue development. Refer to Appendix K for exertion positioning during pilot testing of a female subject.

Table 7: Twenty supplementary exertions

Exertion 3: Neutral Humeral Rotation (0º) (thumb forward) *Force Direction:* Palmar	***Exertion 25:*** Neutral Humeral Rotation (0º) (thumb forward) *Force Direction:* Dorsal	***Exertion 29:*** Neutral Humeral Rotation (0º) (thumb forward) *Force Direction:* Radial	***Exertion 28:*** Neutral Humeral Rotation (0º) (thumb forward) *Force Direction:* Ulnar
Exertion 24: Flexion at 45º (thumb up) *Force Direction:* Palmar	***Exertion 11:*** Flexion at 45º (thumb up) *Force Direction:* Dorsal	***Exertion 27:*** Flexion at 45º (thumb up) *Force Direction:* Radial	***Exertion 26:*** Flexion at 45º (thumb up) *Force Direction:* Ulnar
Exertion 22: Flexion at 90º (thumb up) *Force Direction:* Palmar	***Exertion 18:*** Flexion at 90º (thumb up) *Force Direction:* Dorsal	***Exertion 11:*** Flexion at 90º (thumb up) *Force Direction:* Radial	***Exertion 5:*** Flexion at 90º (thumb up) *Force Direction:* Ulnar
Exertion 17: Abduction at 45º (thumb up) *Force Direction:* Palmar	***Exertion 23:*** Abduction at 45º (thumb up) *Force Direction:* Dorsal	***Exertion 14:*** Abduction at 45º (thumb up) *Force Direction:* Radial	***Exertion 12:*** Abduction at 45º (thumb up) *Force Direction:* Ulnar
Exertion 10: Abduction at 90º (thumb up) *Force Direction:* Palmar	***Exertion 4:*** Abduction at 90º (thumb up) *Force Direction:* Dorsal	***Exertion 20:*** Abduction at 90º (thumb up) *Force Direction:* Radial	***Exertion 19:*** Abduction at 90º (thumb up) *Force Direction:* Ulnar

5.7 Analysis:

Raw force (volts) and EMG (milivolts) were processed, and converted into force in Newtons, and normalized muscle activity. Isolation ratios were calculated. Pre and post experimental force comparisons were made, and residual analysis was performed, to assess for muscle fatigue.

5.7.1 Force data analysis:

Force data was processed using MATLAB^{TM} 7.0.1 (Mathworks Inc., MA, USA) software. Each force trial lasted 6 seconds. To account for any direct current bias and force produced as a result of the steel frame mounted to the force transducer, force data was collected when no one was touching the force transducer. This was called the quiet force trial, and these values were considered the baseline (zero load) of force in the three directions. The quiet force trial preceded collection of each participant, and the average of this trial for forces in the X, Y and Z directions was subtracted from all respective force trials. A shunt calibration was also performed before each testing session, during which a known voltage (equal to a known value in Newtons) was sent through the transducer, which then in turn outputted a force value in volts. Once the quiet trials had been subtracted, the raw force trials (in volts) were converted to Newtons, using data from the shunt calibration. Force data was then dual pass filtered, with a 2nd order low pass filter set at a cutoff frequency of 3 Hz. The resultant force (as previously outlined in Equation 1) was then calculated for every frame of force data. It was noted that participants generally finished ramping and had reached a maximal force level around 2 seconds into each trial. Therefore, an average of the resultant force was taken in a 2 second window of the middle two seconds (from 2 – 4 seconds) of each 6 second trial. This 2 second window average was taken during the simultaneous 2 second average of normalized EMG, as will be further explained below. In some cases, participants tended to ramp more quickly or slowly, and reach a maximal force plateau before or later than 2 seconds. In these cases, the two second window was adjusted accordingly. Force comparisons were made between all participants for each exertion, resulting in average forces per exertion for the defined population under study. Forces that occurred during the two repeat trials (completed at the end of the study), were compared with initial forces in their respective exertions, to assess for force changes which may indicate fatigue.

5.7.2 EMG analysis:

EMG was processed using MATLAB^{TM} 7.0.1 (Mathworks Inc., MA, USA) software. To exclude any DC bias and bring the baseline of raw EMG about zero, the average raw EMG from each trial was subtracted from each respective trial. The raw EMG was linear enveloped (full-wave rectified and Butterworth filtered (single-pass, 2nd order) with a cutoff frequency of 3 Hz), to allow for signal analysis in the time domain (Figures 18 - 21). The single-pass of the filter produced a phase-lag that mimicked the electromechanical delay of the muscle.

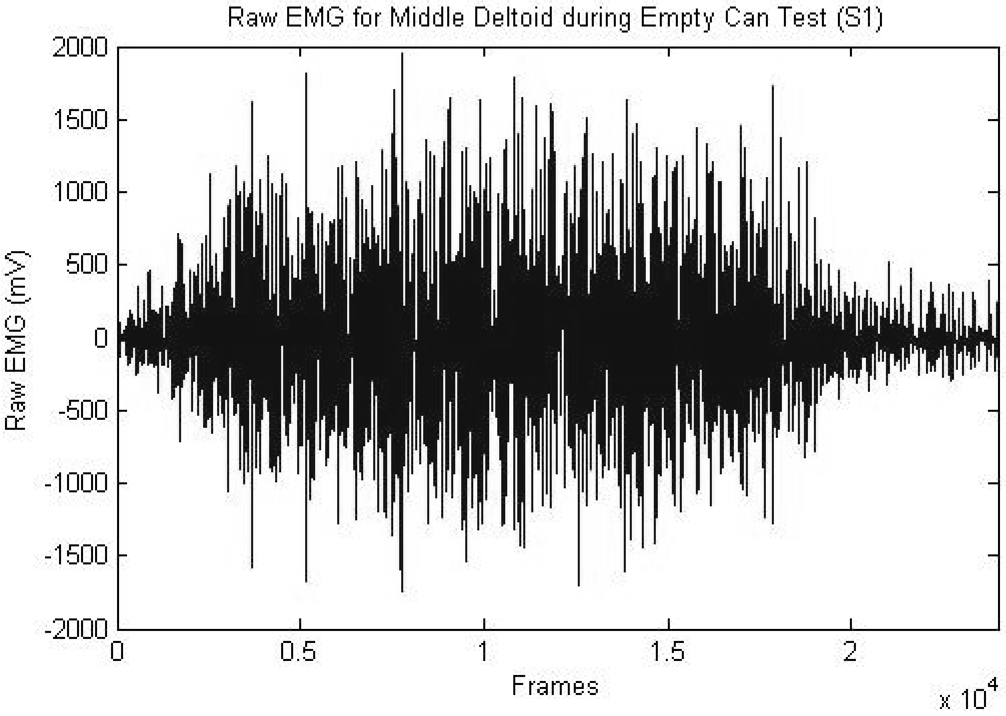


Figure 18: Raw EMG for the middle deltoid during the empty can test

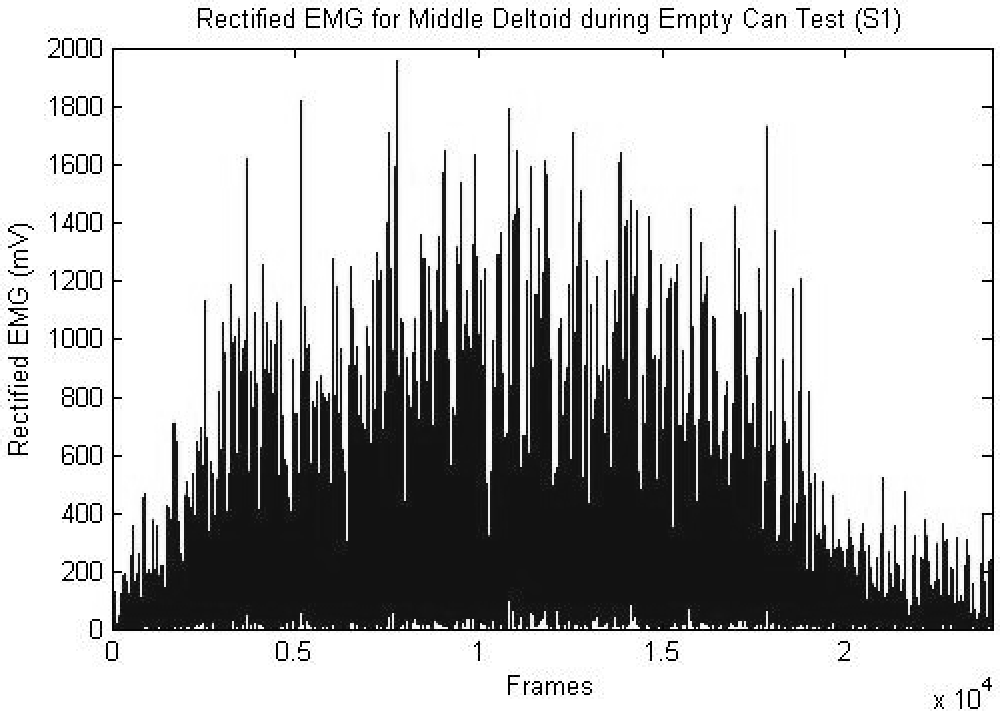


Figure 19: Rectified EMG for the middle deltoid during the empty can test

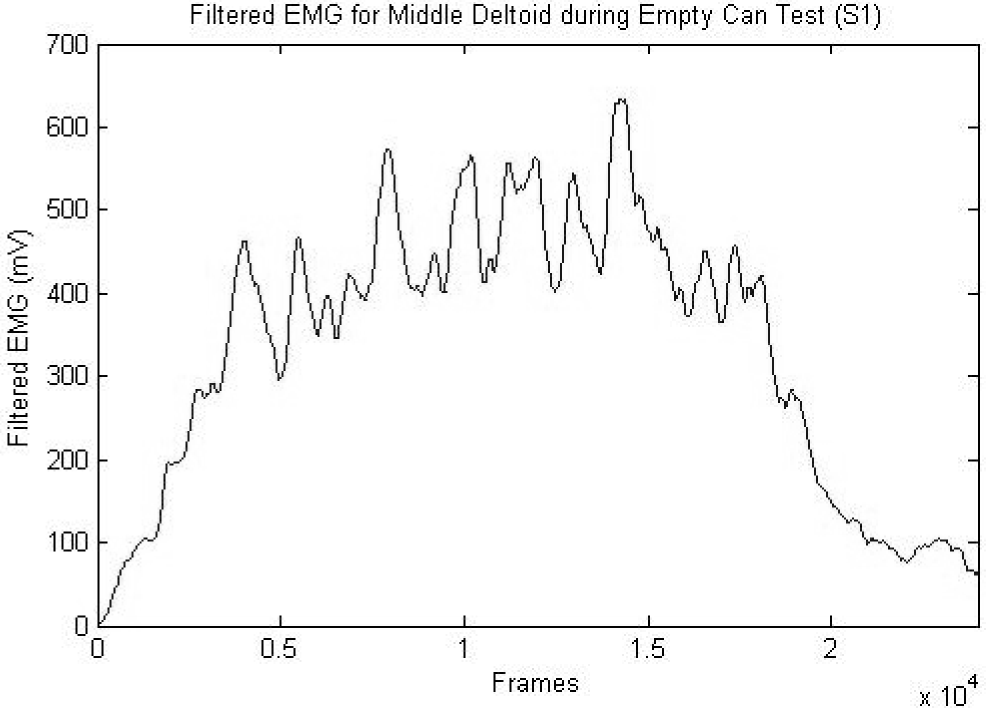


Figure 20: Filtered EMG for the middle deltoid during the empty can test

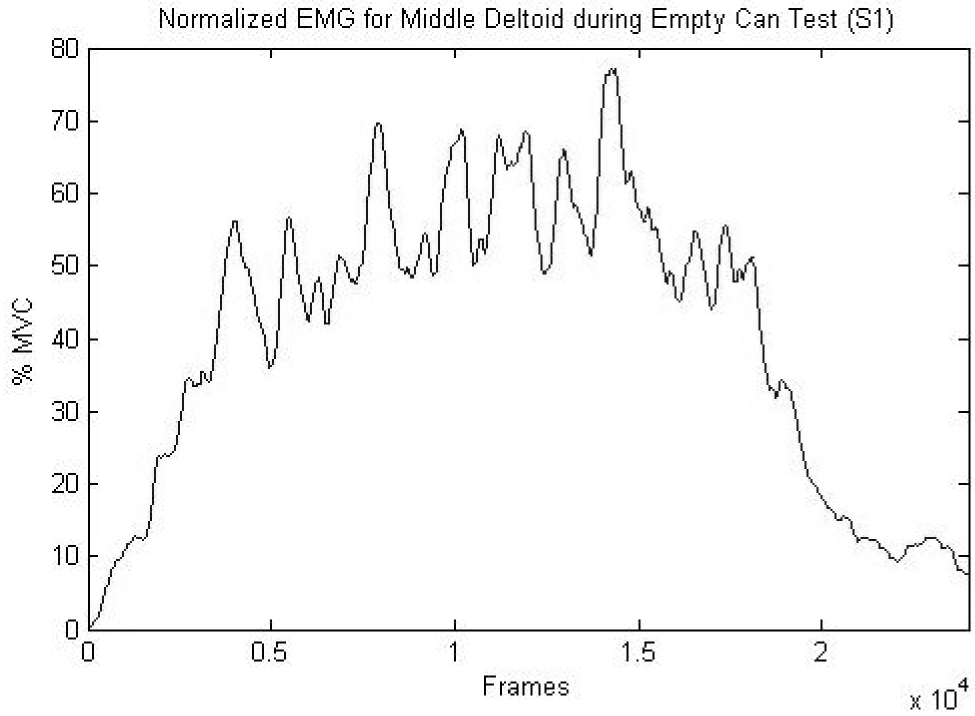


Figure 21: Normalized EMG for the middle deltoid during the empty can test

A cutoff frequency of 3 Hz was comparable to that recommended in the literature for similar recorded muscles: Dark et al (2007) used a cutoff frequency of 2 Hz for intramuscular recordings of the infraspinatus, supraspinatus, subscapularis, latissimus dorsi and pectoralis major. Winter (1990) described how the cutoff frequency (F_c) could be determined using the following (Eq. 2):

$$F_c = \frac{1}{2\pi T} \tag{2}$$

where, T is the time to peak of twitch.

Some mean T values for the upper limb were described by Buchthal & Schmalbruch (1970): 44.5 ms for the triceps, resulting in a cutoff frequency of 3.6 Hz, and 52 ms for the biceps, resulting in a cutoff frequency of 3.1 Hz (Eq. 2). Furthermore, this cutoff frequency was confirmed with residual analysis (Figure 22). Residual analysis was performed on all 12 participants at random channels and during 12 random exertions from 1 – 10 Hz at 0.5 Hz intervals, using the following (Eq. 3):

$$\text{Residual } (F_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (\text{Ai} - \hat{\text{A}}\text{i})^{2}} \qquad (3)$$

Where, N is the number of samples, Ai is the raw data and Âi is the filtered data.

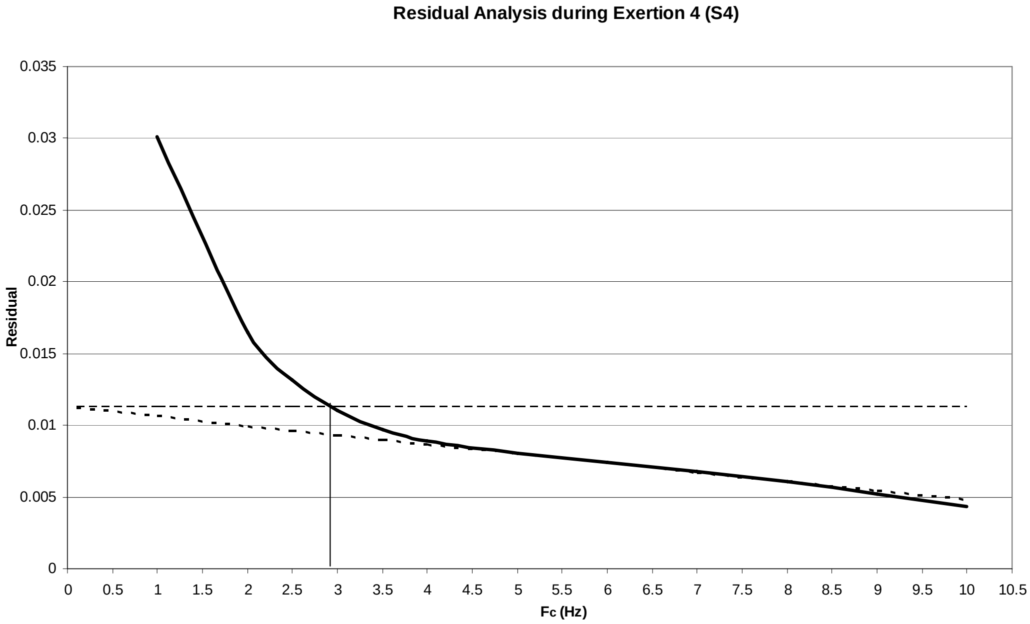


Figure 22: Residual analysis

Each MVC trial was carefully inspected visually for any data artifacts. If artifacts were present, these frames containing artifact were not considered for their peak activations. The largest (peak) activation level (mV) of filtered data was chosen as the maximal voluntary contraction (MVC). The linear enveloped trials were then normalized for each subject, and each muscle.

5.7.3 Isolation Ratios

In order to determine which exertions most isolated the muscles of interest, it was determined during what exertion there was a maximal amount of EMG activity in the muscle of interest, when the mean of all of the other muscles produced minimal EMG activity. This was determined by an Isolation Ratio calculation. The Isolation Ratio contains the EMG activity (as a % MVC) of the muscle of interest in the numerator, and the denominator contained the sum of all the EMG activities (% MVC) of the remaining muscles (Eq. 4):

$$\text{Isolation Ratio} = \frac{\dfrac{\%\text{MVC}\ \text{activity of rotator cuff muscle of interest}}{100}}{\dfrac{\sum \%\text{MVC}\text{of all other 13 recorded muscles}}{1300}} \tag{4}$$

To illustrate the meaning of an isolation ratio, consider an IR equal to zero, one and infinity: an IR equal to zero would indicate the rotator cuff muscle of interest was not activated (turned off); an IR equal to one would indicate the rotator cuff muscle of interest was activated equally as much as the mean activation of the other 13 recorded muscles; and an IR equal to infinity would indicate that the rotator cuff muscle of interest was active when all the other 13 recorded muscles were not activated (turned off), which would be indicative of true isolation. A higher IR (example 1.5) is superior as it indicates the rotator cuff muscle of interest is activated more (example 1.5 times more) than the mean activation of the other 13 recorded muscles. Isolation ratios are affected most by other active muscles, such as synergistic muscles which contribute to the main action of the rotator cuff muscle of interest. Antagonistic muscles, which act in opposition to the main action of the rotator cuff muscle of interest, would be expected to be minimally activated during rotator cuff MMTs and contribute very little to the isolation ratios.

Participants generally had reached a maximal activation level around 2 seconds into each trial. Normalized EMG was inputted into the isolation ratio within the middle two seconds (from 2 – 4 seconds) of each 6 second trial, and an average of the isolation ratios was taken from this window. This 2-second window average was taken during the simultaneous 2 second average of force. If subjects were found to ramp more slowly or quickly, the 2 second window was adjusted accordingly to accommodate for these differences.

Each trial was carefully inspected (visually) for artifact. Due to the sensitivity of the wire electrodes, changes in posture could move the wires and result in data artifacts. Most artifacts occurred at the very beginning or end of trials when the participant moved their limb during initial contraction or relaxation. Since normalized EMG was considered during the middle two seconds of the trials, these artifacts were not a problem as they were not considered in the analysis. However, there were instances during which the artifact occurred within the two second window average. In many cases, it was possible to shift the 2 second window slightly to avoid these artifacts, and still include these channels in the analysis (Figure 23). However, there were instances during which there was too much artifact to salvage the channel during a 2 second window, and these channels for those particular trials had to be excluded from analysis. When channels were excluded from the isolation ratio, the equation was adjusted accordingly so that the denominator was divided by the appropriate number (according to the number of muscles remaining in the equation).

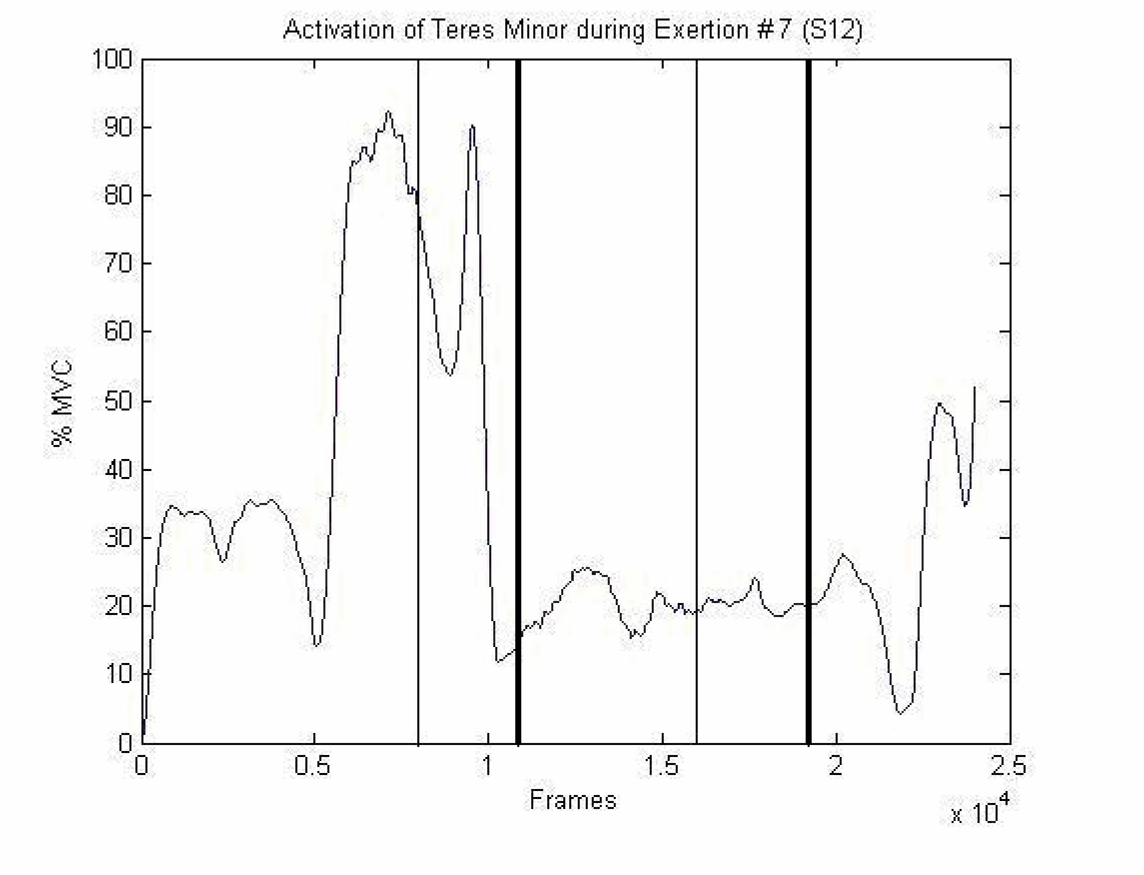


Figure 23: Window averaging around artifact

Normally EMG would be taken from 2 – 4 seconds (8000 – 16000 frames) [thin vertical lines], but in this case EMG was taken from 2.75 – 4.75 seconds (11000 – 19000 frames) [thick vertical lines] to avoid artifact.

5.7.4 Statistical Analysis:

A maximal isolation ratio indicated that the muscle of interest was most active when the average of the other 13 muscles being recorded were minimally active. This helped to identify postures that most specifically isolated the rotator cuff muscles. Isolation ratios were determined for each of the four rotator cuff muscles, for each of the 29 postures and for each of the 12 participants. This resulted in calculation of 1392 total isolation ratios. Once maximal isolation ratios were identified, the average force output produced during the point in time during which this maximal isolation occurred were examined.

Four one-way analysis of variance (ANOVA) tests (one ANOVA for each of the four rotator cuff muscles of interest) were used to compare these 1392 isolation ratios and identify if exertions were significantly different from each other. Statistical analysis was performed in JMP IN 5.1.2^{TM} (SAS Institute Inc., NC, USA). Three assumptions were made in using the ANOVA:

1) the population from which the samples were obtained was approximately normally distributed
2) the samples were independent
3) the variance within the populations were equal

A null hypothesis was made that stated that all the population means were equal (it was hypothesized that no difference would be found between the isolation ratios for the 29 different exertions). The alternative hypothesis (accepted if $p<0.05$) stated that at least one mean was different. Post hoc analysis (Student's T Test) indicated which exertions were significantly different ($p<0.05$) from each other. This process helped to identify if the muscle of interest was isolated in more than one exertion.

Initially isolation ratios (IRs) were looked at for individual exertions, and the exertions were not divided into the 7 groups. Four one-way ANOVA's were performed on isolation ratios for 12 subjects during the 29 exertions, with the responses (Y variables) as the isolation ratio for each of the rotator cuff muscles (IR infraspinatus, IR supraspinatus, IR teres minor and IR subscapularis), and the groupings (X variables) as the 29 exertions (Appendix G). Post hoc analysis (Student's T test) was performed when ANOVAs indicated that the null hypothesis was false, and there was at least one mean (exertion) that was significantly different ($p<0.05$) from the other exertions. Post hoc analysis proved to be very difficult to interpret due to the numerous levels that differentiated which exertions were the same or significantly different from others. For example, one-way ANOVA on the mean IR infraspinatus (for all subjects) indicated that there was one (or more than one) exertion that was significantly different than the other exertions ($p<0.0001$). Post hoc analysis (Student's T test) was performed to indicate which of these exertions were different from the rest. Results proved to be very complicated, as Figure 24 depicts. For this reason, the exertions were divided into seven groups of primary action: internal rotation, external rotation, abduction, palmar force, dorsal force, radial force and ulnar force groups. Four one-way ANOVAs were performed for each of the rotator cuff isolation ratios for all subjects within these seven groups. The responses (Y variables) were the isolation ratios for the four rotator cuff muscles, and the groups (X variables) were the seven groups to which the 29 exertions were divided. Post hoc analysis (Student's T test) was performed only when ANOVAs indicated there was at least one mean isolation ratio that was different within an exertion within the group under study ($p<0.05$). The ANOVA indicated if there was a difference of mean isolation ratios within exertion groups under study. The post hoc analysis then indicated which one of the exertion groups was significantly different.

Exertions that were determined to isolate the muscles of interest were identified as suitable MMTs of the rotator cuff muscles. Time corresponding force outputs with exertions found to isolate the rotator cuff muscles were reported and can be compared to muscle effort outputs.

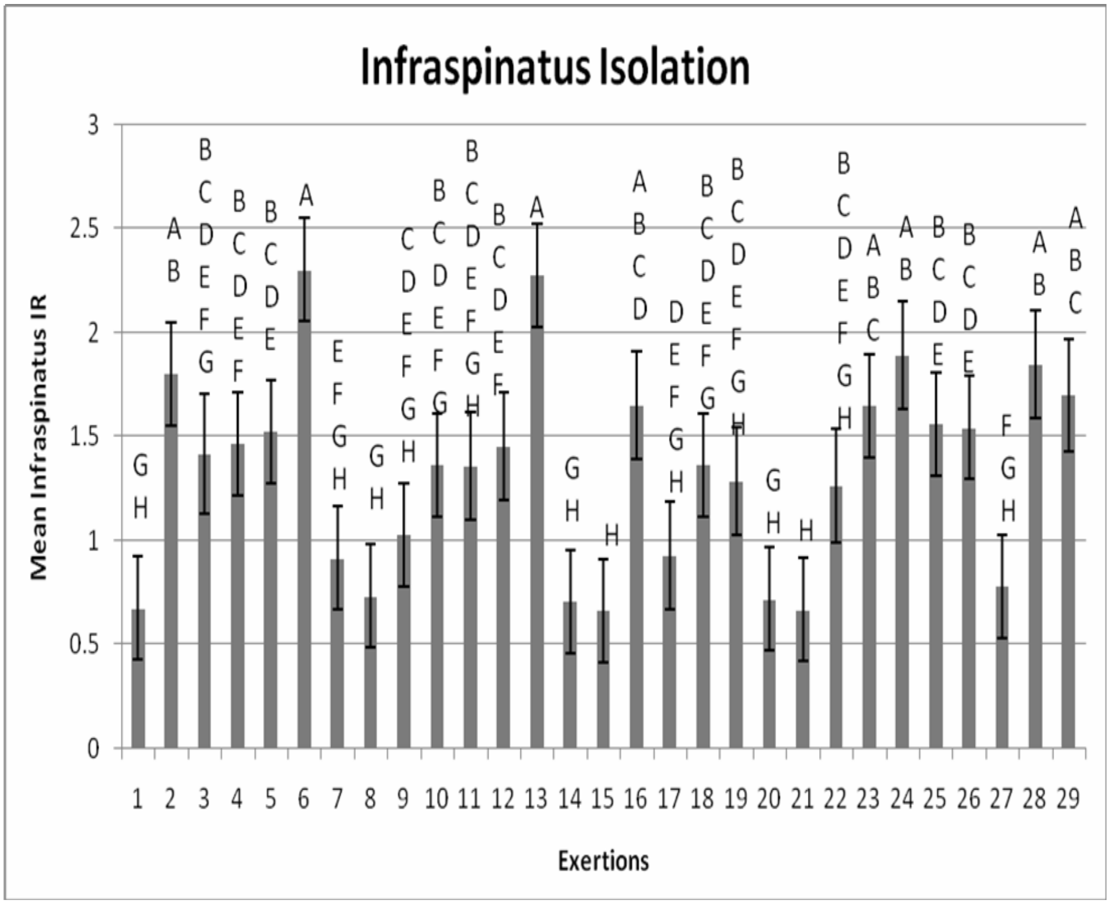


Figure 24: Infraspinatus isolation between exertions

Note: Levels not connected by the same letter are significantly different ($p<0.05$). The error bars represent ± 1 standard error.

5.7.5 Fatigue analysis:

In order to determine if results could be biased by significant muscle fatigue, force changes and median and mean power frequency (MdPF, MnPF) changes were assessed. The first two exertions performed by each participant were repeated at the end of the testing time, and these force, MnPF and MdPF values were compared. Percent difference in force values was determined using the following (Eq. 5):

$$\%\,\text{Difference} = \left[\frac{\text{Final Force - Initial Force}}{\text{Initial Force}}\right] \bullet 100 \qquad (5)$$

A paired T test (one-tailed) was used to assess if significant changes in force were displayed during initial and repeat trials ($p<0.05$).

Raw EMG, which was originally sampled at a rate of 4000 Hz, was down-sampled to 2048 Hz, and Fast Fourier Transforms (FFTs) were performed in KinAnalysis (LabView, National Instruments, USA). FFTs were performed for every channel of EMG for the first two exertions and corresponding two repeat exertions for each participant. MnPF and MdPF changes were assessed for each of the 16 channels (Appendix L). T tests (one-tailed) were used to assess if significant changes in MnPF and MdPF were displayed during initial and repeat trials ($p<0.05$). Percent difference was calculated between MnPF and MdPF for muscles that significantly decreased in frequency.

5.7.6 Secondary isolation investigations:

To further investigate isolation of the rotator cuff muscles, values for two variants of the primary isolation ratio were determined: the second isolation ratio (IR2) involved the rotator cuff muscles only, and the third isolation ratio (IR3) involved only the rotator cuff muscles and their assumed synergists.

The second isolation ratio (IR2) was used to assess the isolation of the rotator cuff muscle of interest in comparison to the other three rotator cuff muscles, which all contribute to stabilizing the humerus within the glenoid fossa. Therefore, isolation using the IR2 was defined when the rotator cuff muscle of interest was maximally activated, when the other three rotator cuff muscles were minimally activated. IR2 was calculated as follows (Eq. 6):

$$\mathrm{IR2} = \frac{\dfrac{\%\mathrm{MVC}\ \text{activity of rotator cuff muscle of interest}}{100}}{\dfrac{\sum \%\mathrm{MVC}\ \text{of 3 other rotator cuff muscles}}{300}} \tag{6}$$

The third type of rotator cuff isolation ratio (IR3) that was assessed involved only the rotator cuff muscle of interest and it's assumed synergists. This ratio (IR3) was used to assess the isolation of the rotator cuff muscles in relation to those muscles performing similar main actions. It was assumed that the function of these assumed synergistic muscles remained the same, regardless of postural change.

The assumed synergists for the infraspinatus were the supraspinatus, teres minor and posterior deltoid. The assumed synergists for the teres minor were the posterior deltoid and infraspinatus. Moore & Dalley (1999) described the main action of the infraspinatus and teres minor to be external rotation of the humerus. The supraspinatus was described as acting together with the other rotator cuff muscles and aiding the deltoid in abduction of the humerus, whereas the posterior deltoid was described as extending and externally rotating the humerus (Moore & Dalley, 1999). Townsend et al (1991) demonstrated in their findings that the infraspinatus and teres minor were maximally activated in similar exertions of abduction and external rotation. Other studies have also shown that infraspinatus and teres minor have lines of action that provide external rotation (Ballantyne et al 1993; Dark et al 2007). Kelly et al (1996a) defined the supraspinatus and posterior deltoid as synergists of infraspinatus.

The assumed synergists for the supraspinatus were the middle deltoid and infraspinatus. The main action of supraspinatus and middle deltoid is abduction (Moore

& Dalley, 1999), and infraspinatus has been shown to be maximally activated in exertions of abduction and external rotation (Townsend et al, 1991). Kelly et al (1996a) defined the infraspinatus to be a synergist of supraspinatus in their isolation techniques.

The assumed synergists for the subscapularis were the pectoralis major (clavicular insertion) and the latissimus dorsi. Internal rotation and adduction are described as main actions of the pectoralis major, latissimus dorsi and subscapularis (Moore & Dalley, 1999). Kelly et al (1996a) defined pectoralis major and latissimus dorsi to be synergists of subscapularis.

Using IR3, isolation was defined when the rotator cuff muscle was maximally activated, when the synergists of that muscle were minimally activated. IR3 was described as the following (Eq. 7-10):

$$IR3 = \frac{\frac{\%MVC_{infra}}{100}}{\frac{\%MVC_{supra} + \%MVC_{tminor} + \%MVC_{pdelt}}{300}} \tag{7}$$

$$IR3 = \frac{\frac{\%MVC_{supra}}{100}}{\frac{\%MVC_{middelt} + \%MVC_{infra}}{200}} \tag{8}$$

$$IR3 = \frac{\frac{\%MVC_{tminor}}{100}}{\frac{\%MVC_{pdelt} + \%MVC_{infra}}{200}} \tag{9}$$

$$\mathrm{IR3} = \frac{\dfrac{\%\mathrm{MVC}_{\mathrm{subscap}}}{100}}{\dfrac{\%\mathrm{MVC}_{\mathrm{pecmaj(clav)}} + \%\mathrm{MVC}_{\mathrm{latdorsi}}}{200}} \qquad (10)$$

The method of processing EMG and force for IR2 and IR3 was identical to that used to calculate the initial isolation ratio (IR). These isolation ratios (IR2 and IR3) were considered of secondary importance to the initial IR because these ratios only considered a smaller number of the muscles crossing the glenohumeral joint (compared to IR which considered 13 different muscles). The contribution of all muscles acting with or against the rotator cuff muscles must be considered when attempting to isolate the rotator cuff muscles. Secondly, the IR3 ratio type assumes synergists for each of the rotator cuff muscles, surmising that function of these muscles does not change as posture changes. This assumption has not been validated in literature, although similar principles have been used in published reports (Kelly et al, 1996a).

6.0 Results:

The largest mean isolation ratios were calculated within the clinical MMT group exertions. This trend was also seen among the secondary isolation ratios (IR2 and IR3). There were non-significant changes between pre and post-experimental force. There were non-significant changes between mean and median power frequency values, except within the infraspinatus and biceps brachii.

6.1 Isolation ratios between exertion groups

Infraspinatus Isolation:

Differences in calculated isolation ratios for the defined exertion groups existed ($p < 0.0001$), with the following order of decreasing isolation ratio magnitude:

External Rotation > [Internal Rotation, Palmar, Dorsal, Ulnar] >[Abduction, Radial]

The highest mean IR was found in the external rotation group (2.29 ± 0.18). The lowest mean IR was found in the abduction group (0.68 ± 0.12). The ratio of highest to lowest mean IR was 3.37. The results of the Student's T test are shown in Figure 25; the error bars represent ± 1 standard error. Average activation of the infraspinatus ranged from 58.0 to 82.5% MVC in the external rotation group (Exertion 13 and 6) (Appendix H). Average forces produced during these exertions were 60.2 ± 23.0 and 98.5 ± 22.9 N, respectively.

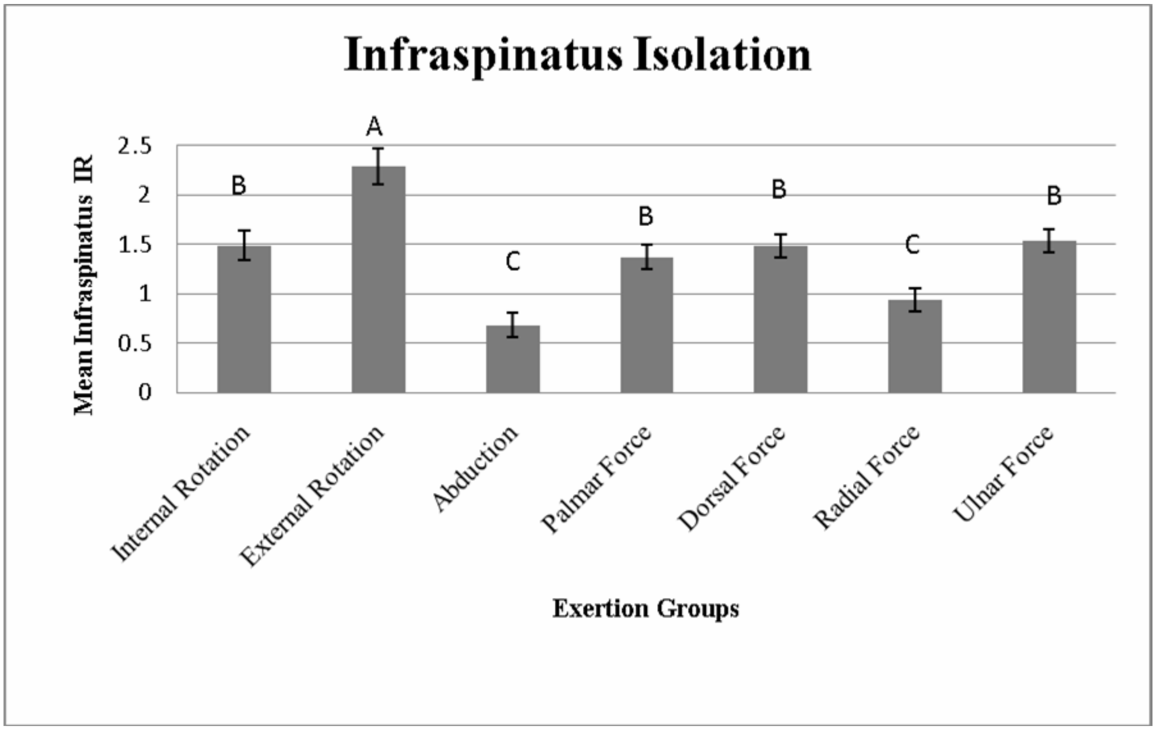


Figure 25: Isolation of the infraspinatus between groups

Supraspinatus Isolation:

Differences in calculated isolation ratios for the defined exertion groups existed (p = 0.0019), with the following order of decreasing isolation ratio magnitude:

i) Abduction > [Palmar, External Rotation, Internal Rotation, Ulnar Groups]

ii) [Dorsal & Radial] > [Internal Rotation & Ulnar]

The highest mean IR was found in the abduction group (1.74 ± 0.15). The lowest mean IR was found in the internal rotation group (0.90 ± 0.19). The ratio of highest to lowest mean IR was 1.93. The results of the Student's T test are shown in Figure 26; the error bars represent ± 1 standard error. Average activation (% MVC) of the supraspinatus ranged from 54.3 – 73.6% in the abduction group, 38.8 – 53.2% in the dorsal group and 28.5 – 59.1% in the radial force group exertions. Average forces produced during exertions within these groups ranged from 70.2 – 95.5 N in the abduction group, 62.3 – 120.2 N in the dorsal group, and 78.6 – 100.1 N in the radial force group exertions.

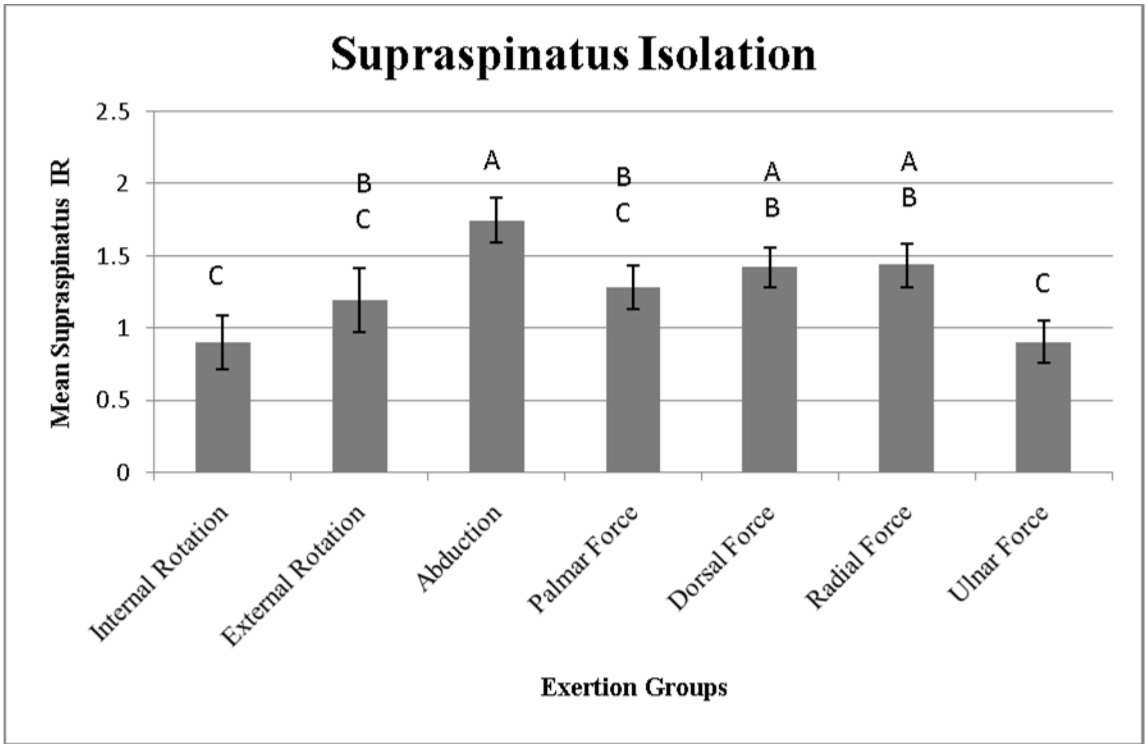


Figure 26: Isolation of the supraspinatus between groups

Teres Minor Isolation:

Differences in calculated isolation ratios for the defined exertion groups existed (p < 0.0001), with the following order of decreasing isolation ratio magnitude:

i) Ulnar > [Dorsal, Radial, Abduction]

ii) External Rotation > [Abduction & Radial]

iii) [Internal Rotation & Palmar] > Abduction

The highest mean IR was found in the external rotation group (1.67 ± 0.19). The lowest mean IR was found in the abduction group (0.74 ± 0.14). The ratio of highest to lowest mean IR was 2.26. The results of the Student’s T test are shown in Figure 27; the error bars represent ± 1 standard error. The mean activation (% MVC) of the teres minor ranged from 44.7 – 63.8% in the external rotation group, 28.7 – 42.7% in the internal rotation group, 33.9 – 48.2% in the ulnar force group, and 23.9 – 47.1% in the palmar force group exertions. The mean forces produced ranged from 60.2 – 98.5 N in the external rotation group, 85.4 – 161.1 N in the internal rotation group, 86.5 – 126.9 N in the ulnar force group, and 57.8 – 99.1 N in the palmar force group exertions.

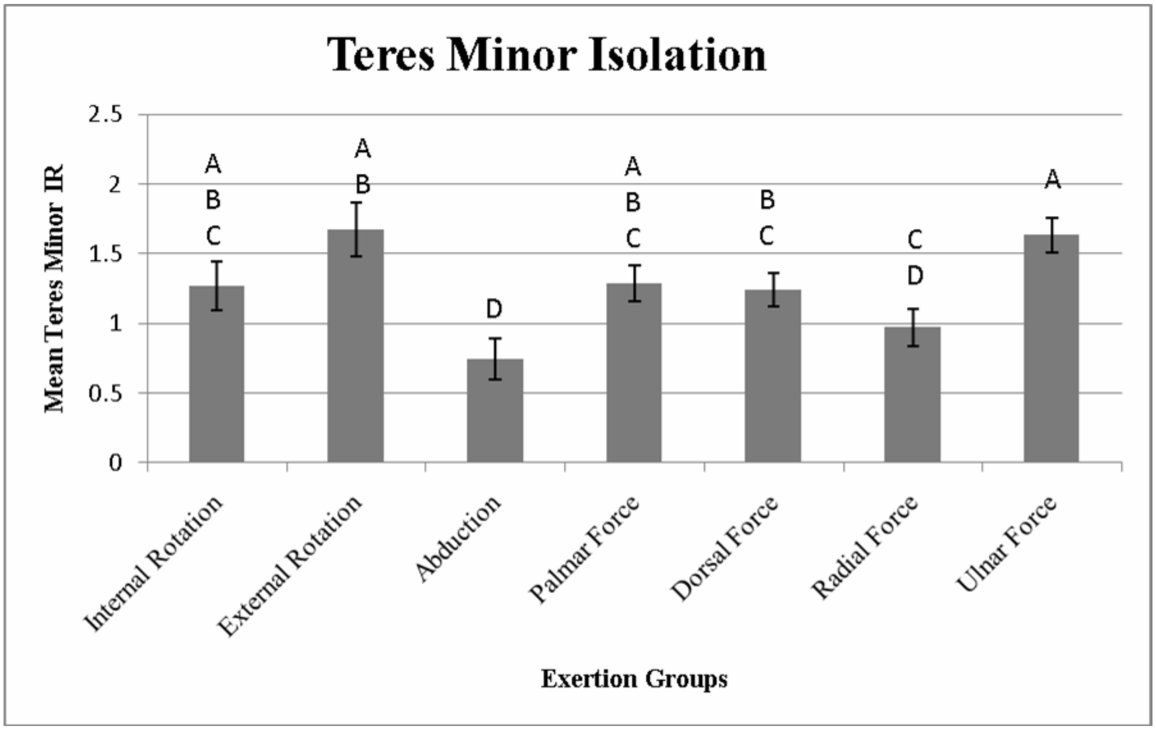


Figure 27: Isolation of the teres minor between groups

Subscapularis Isolation:

Differences in calculated isolation ratios for the defined exertion groups existed ($p < 0.0001$), with the following order of decreasing isolation ratio magnitude:

i) Ulnar > [Palmar, External Rotation, Dorsal, Radial, Abduction]

ii) Internal Rotation > [External Rotation, Dorsal, Radial and Abduction]

iii) Palmar > [Abduction, Dorsal, Radial]

The highest mean IR was found in the ulnar force group (1.93 ± 0.13). The lowest mean IR was found in the abduction group (0.43 ± 0.15). The ratio of highest to lowest mean IR was 4.49. The results of the Student's T test are shown in Figure 28; the error bars represent ± 1 standard error. The mean activation (% MVC) of the subscapularis ranged from 34.7 – 58.0% in the ulnar force group, and 33.7 – 44.8% in the internal rotation group exertions. The mean force produced ranged from 86.5 – 126.9 N during the ulnar force group, and 85.4 – 161.1 N during the internal rotation group exertions.

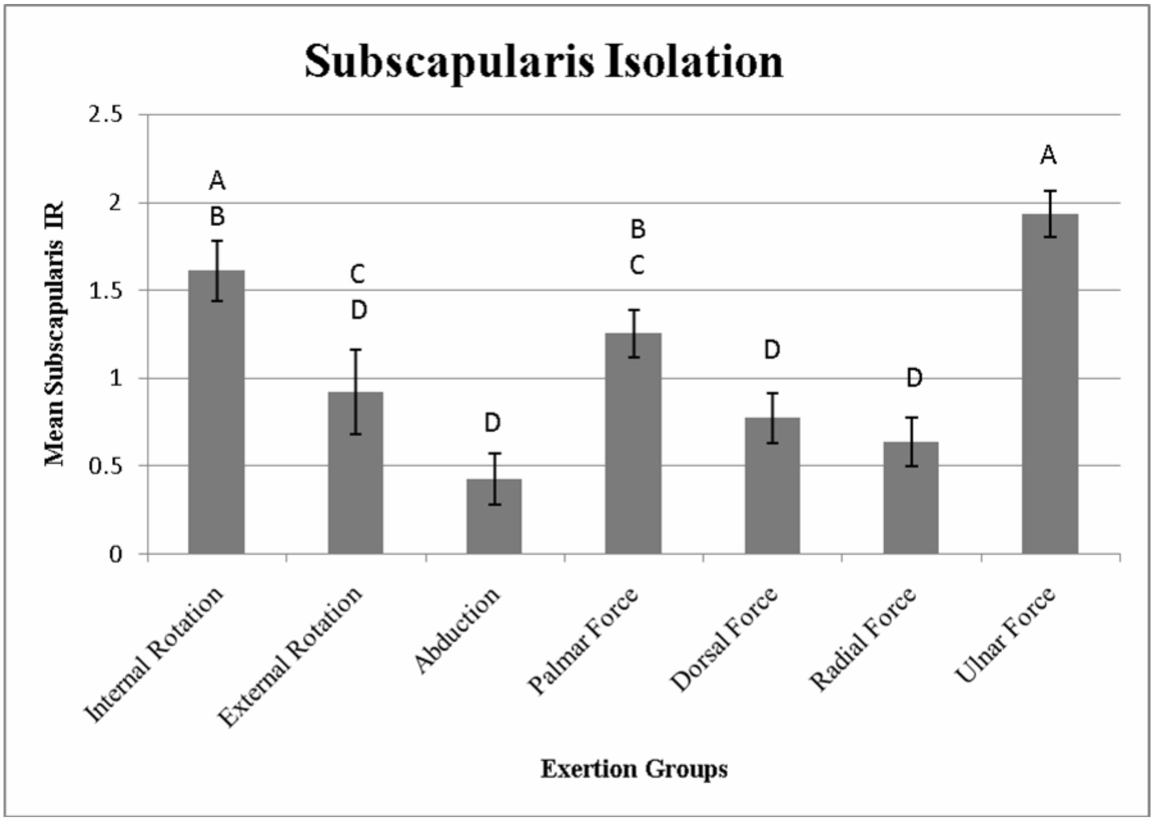


Figure 28: Isolation of the subscapularis between groups

6.2 Average force and percent activation:

The mean force (N) of all 12 participants during each of the 29 exertions was calculated during a 2 second window of 2 – 4 seconds (Figure 29). Error bars represent ± 1 standard error. On average, the largest amount of force was exerted during the belly press test

(Exertion # 9), with a mean force of 161.1 ± 25.3 N. On average, the least amount of force was exerted during abduction at 90º with palmar resistance (Exertion #10), at 57.8 ± 20.2 N.

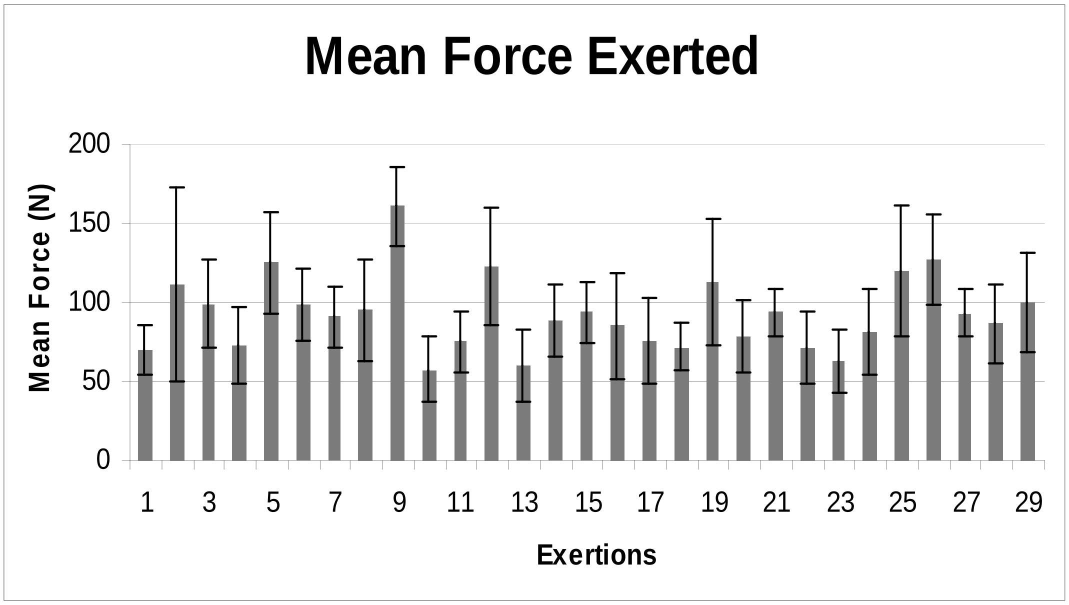


Figure 29: Mean force applied during 29 exertions

The mean percent maximal voluntary contraction (of all 12 participants) of each of the 16 recorded EMG channels was calculated during a 2 second window (from 2 – 4 seconds of each trial) for all 29 exertions. Figure 30 shows the mean percent maximal activation of the recorded muscles during the Sitting Infraspinatus and Teres Minor Test (Exertion # 6); the error bars represent +1 standard error. Refer to Appendix H for similar figures of mean percent activation for all 29 exertions, as well as a table containing mean %MVC for each muscle per exertion.

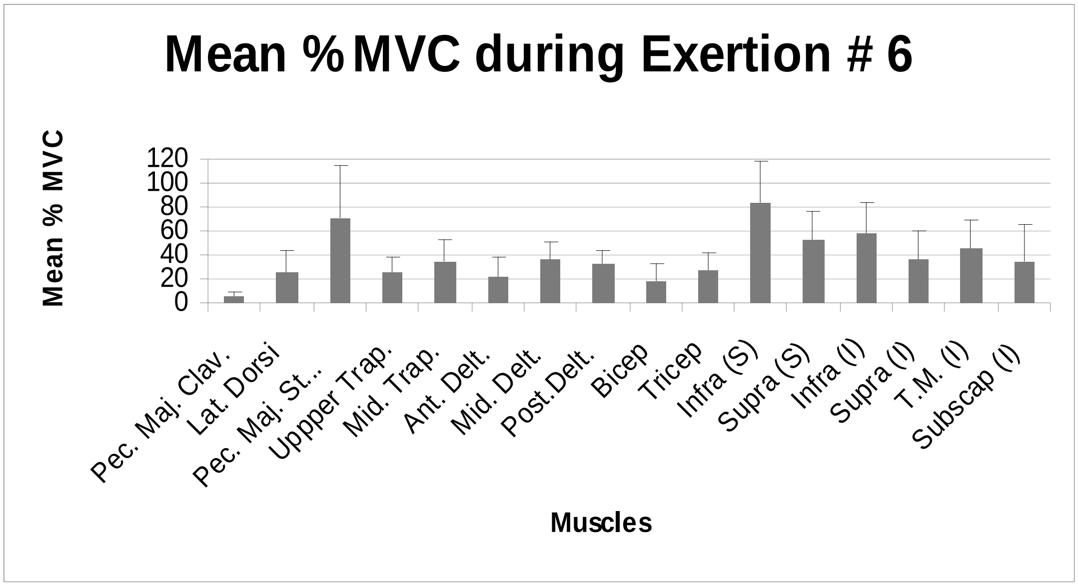


Figure 30: Mean percent activation during Exertion # 6

6.3 Fatigue analysis:

The first two exertions that were performed by each participant were repeated at the end of the experiment. Force outputted during these exertions (initial and final) were compared using a one-tailed paired T test to see if significant force changes occurred between all subjects. Results indicated that there was no significant change in initial and final force for all subjects ($p = 0.146$). The percent difference between initial and final force for all subjects was calculated (Figure 31). The average percent difference for all subjects was 2.70%. The largest percent difference occurred in Subject 12 during Exertion #19, at 157.94%. This supposed outlier was excluded from analysis, and calculations were repeated. The average percent difference in force changed to -3.8%, and the paired t test p value changed to 0.06. Refer to Appendix I for a figure which depicts each participant's initial and final forces.

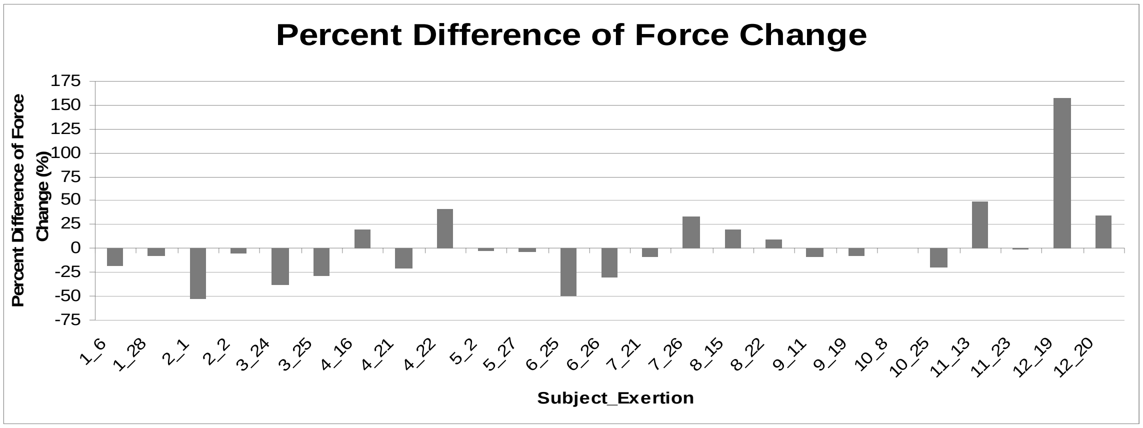


Figure 31: Percent difference of force change

Fast Fourier Transform (FFT) was performed on the raw EMG of the initial and repeat trials to assess the frequency content of the signals. Mean and median power frequency (MnPF, MdPF) were calculated (Appendix L) and one-tailed paired T tests were used to assess for significant ($p<0.05$) changes in MnPF and MdPF (Table 8). Significant changes in MnPF were seen in the wire infraspinatus channel ($p = 0.016$). Significant changes in MdPF were seen in the wire infraspinatus channel ($p = 0.022$) and in the biceps brachii ($p = 0.026$). Percent differences were calculated between initial and final MnPF and MdPF for the infraspinatus wire channel, and between MdPF for the biceps (Table 9). The averages of these percent differences were taken, and on average the MnPF and MdPF decreased by 8.27% and 11.36% in the infraspinatus (wire), respectively. On average, the bicep MdPF decreased by 5.28%.

Table 8: Paired T test results (p values) for repeated exertions

	MnPF	MdPF
Pectoralis Major (Clav)	0.218	0.061
Latissimus Dorsi	0.454	0.291
Upper Trapezuis	0.102	0.263
Middle Trapezuis	0.130	0.104
Anterior Deltoid	0.381	0.451
Middle Deltoid	0.284	0.151
Posterior Deltoid	0.099	0.089
Biceps Brachii	0.067	0.026*
Triceps (long head)	0.160	0.183
Infraspinatus (S)	0.125	0.217
Supraspinatus (S)	0.269	0.361
Infraspinatus (W)	0.016*	0.022*
Supraspinatus (W)	0.212	0.245
Teres Minor (W)	0.259	0.324
Subscapularis (W)	0.091	0.067

Note: Asterisks (*) indicates significance ($p < 0.05$).

Table 9: Percent difference in MnPF and MdPF

Subject	Exertion	MnPF % Difference (Infra W)	MdPF % Difference (Infra W)	MdPF % Difference (Biceps)
1	28	-3.72	-4.29	-7.13
1	6	-6.06	-5.15	-13.61
2	1	-8.69	-12.22	-1.44
2	2	10.40	3.37	-22.64
3	24	10.61	-12.15	-13.48
3	25	-9.00	-5.91	4.21
4	16	-21.06	-31.66	-34.21
4	21	-6.02	-12.39	5.38
4	22	-7.49	-1.75	-7.24
5	2			-1.63
5	27			-11.18
6	25	-60.58	-84.65	-4.00
6	26	17.73	-1.62	6.79
7	21	3.53	6.38	-16.15
7	26	0.49	-0.17	-33.67
8	15	-12.23	-7.01	-6.36
8	22			
9	11	28.88	25.91	42.53
9	19	-9.76	-0.71	-10.14
10	25	-29.95	-38.28	-8.83
10	8			5.63
11	13	-9.43	-20.15	9.96
11	23	10.64	58.90	7.90
12	19	-33.66	-42.48	-5.32
12	20	-38.20	-52.46	-12.18
	Average	**-8.27**	**-11.36**	**-5.28**

Note: Empty cells indicate channels that were excluded from the analysis due to artifact.

6.4 Isolation using IR2 between exertion groups:

Isolation of Infraspinatus using IR2:

Differences in calculated isolation ratios for the defined exertion groups existed ($p = 0.0196$), with the following order of decreasing isolation ratio magnitude:

External Rotation > [Internal Rotation, Abduction, Dorsal, Radial, Ulnar]

The highest mean IR2 was found in the external rotation group (2.36 ± 0.31). The lowest mean IR2 was found in the abduction group (1.12 ± 0.21). The ratio of highest to lowest mean IR2 was 2.11. The results of the Student's T test are shown in Figure 32. The error bars represent ± 1 standard error. Mean activation (% MVC) of infraspinatus ranged from 63.0 – 82.5% in the external rotation group, 24.0 – 42.6% in the palmar force group exertions. Mean force produced ranged from 60.2 – 98.5 N in the external rotation group, 57.8 – 81.3 N in the palmar force group exertions.

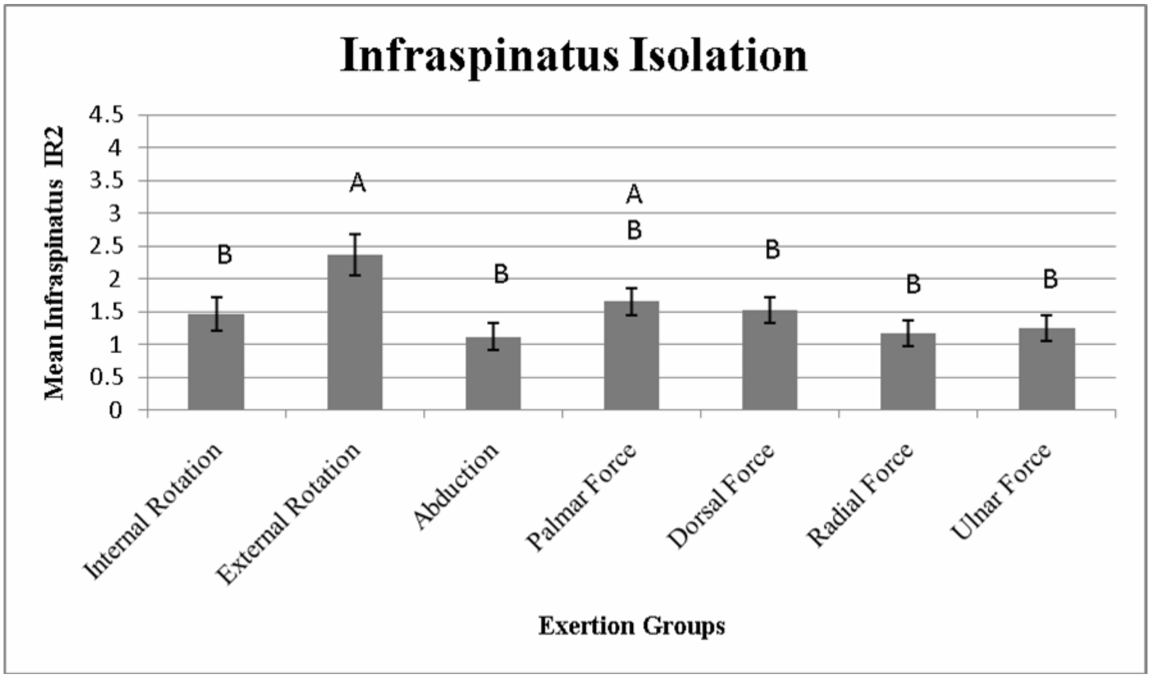


Figure 32: Infraspinatus isolation using IR2

Isolation of the Supraspinatus using IR2:

Differences in calculated isolation ratios for the defined exertion groups existed ($p < 0.0001$), with the following order of decreasing isolation ratio magnitude:

i) Abduction > Radial > [Palmar, Dorsal, Internal Rotation, External Rotation, Ulnar]

ii) [Palmar & Dorsal] > Ulnar

The highest mean IR2 was found in the abduction group (3.74 ± 0.28). The lowest mean IR2 was found in the ulnar force group (0.66 ± 0.27). The ratio of highest to lowest mean IR2 was 5.67. The results of the Student's T test are shown in Figure 33; the error bars represent ± 1 standard error. The mean activation (% MVC) of the supraspinatus ranged from 54.3 – 73.6% within the abduction group exertions. The mean force produced ranged from 70.3 – 95.1 N within the abduction group exertions.

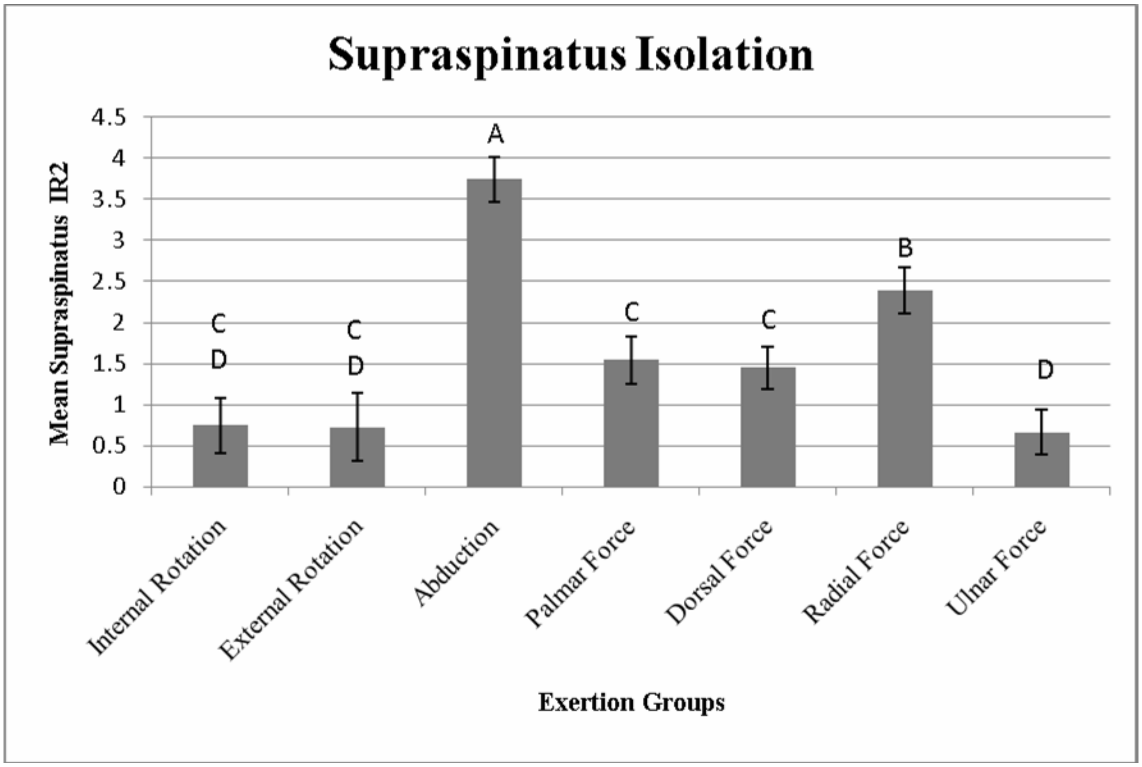


Figure 33: Supraspinatus isolation using IR2

Isolation of the Teres Minor using IR2:

There was no significant (p = 0.7259) difference between the exertion groups. The highest mean IR2 was found in the external rotation group (1.33 ± 0.22). The lowest mean IR2 was found in the abduction group (0.97 ± 0.16). The ratio of highest to lowest mean IR2 was 1.37. The mean activation of the teres minor ranged from 44.7 – 63.8% MVC within the external rotation group, and 22.9 – 28.8% MVC in the abduction exertion group. The mean force produced ranged from 60.2 – 98.5 N in the external rotation group, and 70.3 – 95.1 N in the abduction exertion group.

Isolation of the Subscapularis using IR2:

Differences in calculated isolation ratios for the defined exertion groups existed ($p < 0.0001$), with the following order of decreasing isolation ratio magnitude:

[Palmar, Internal Rotation, Ulnar] > [External Rotation, Abduction, Dorsal, Radial]

The highest mean IR2 was found in the internal rotation group (1.55 ± 0.18). The lowest mean IR2 was found in the abduction group (0.46 ± 0.15). The ratio of highest to lowest mean IR2 was 3.37. The results of the Student's T test are shown in Figure 34; the error bars represent ± 1 standard error. The mean activation (% MVC) of the subscapularis ranged from 33.7 – 44.8% in the internal rotation group, 20.1 – 44.0% in the palmar force group, and 34.7 – 58.0% in the ulnar force group exertions. The mean force produced ranged from 85.4 – 161.1 N in the internal rotation group, 57.8 – 99.1 N in the palmar force groups, and 86.5 – 126.9 N in the ulnar force group exertions.

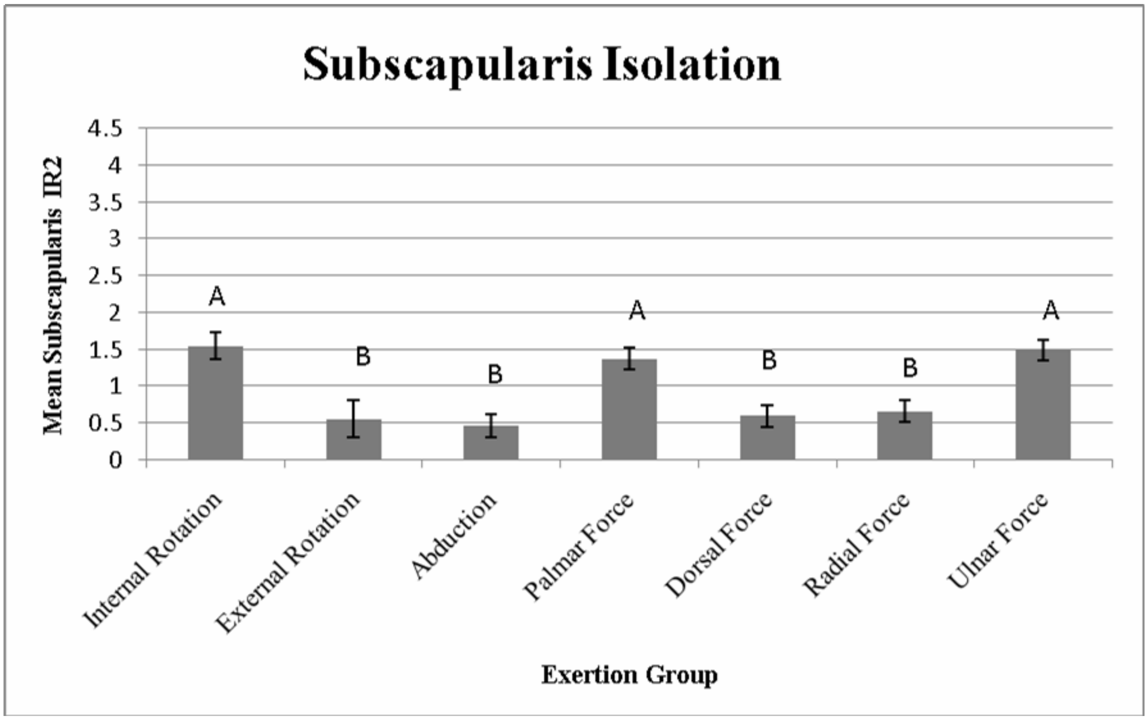


Figure 34: Subscapularis isolation using IR2

6.5 Isolation using IR3 between exertion groups:

Isolation of Infraspinatus using IR3:

Differences in calculated isolation ratios for the defined exertion groups existed (p = 0.0017), with the following order of decreasing isolation ratio magnitude:

i) Palmar > [Radial, Dorsal, Abduction]

ii) [Internal Rotation, External Rotation, Radial, Ulnar] > Abduction

The highest mean IR3 was found in the palmar force group (1.99 ± 0.21). The lowest mean IR3 was found in the abduction group (0.73 ± 0.21). The ratio of highest to lowest mean IR3 was 2.73. The results of the Student's T test are shown in Figure 35; the error bars represent ± 1 standard error. The mean activation (% MVC) of the infraspinatus ranged from 24.0 – 42.6% in the palmar group, 26.7 – 56.0% in the internal rotation group, 58.0 – 82.5 % in the external rotation group, and 37.0 – 57.3% in the ulnar force group exertions. The mean force produced ranged from 57.8 – 99.1 N in the palmar group, 85.4 – 161.1 N in the internal rotation group, 60.2 – 98.5 N in the external rotation group, and 86.5 – 126.9 N in the ulnar force groups.

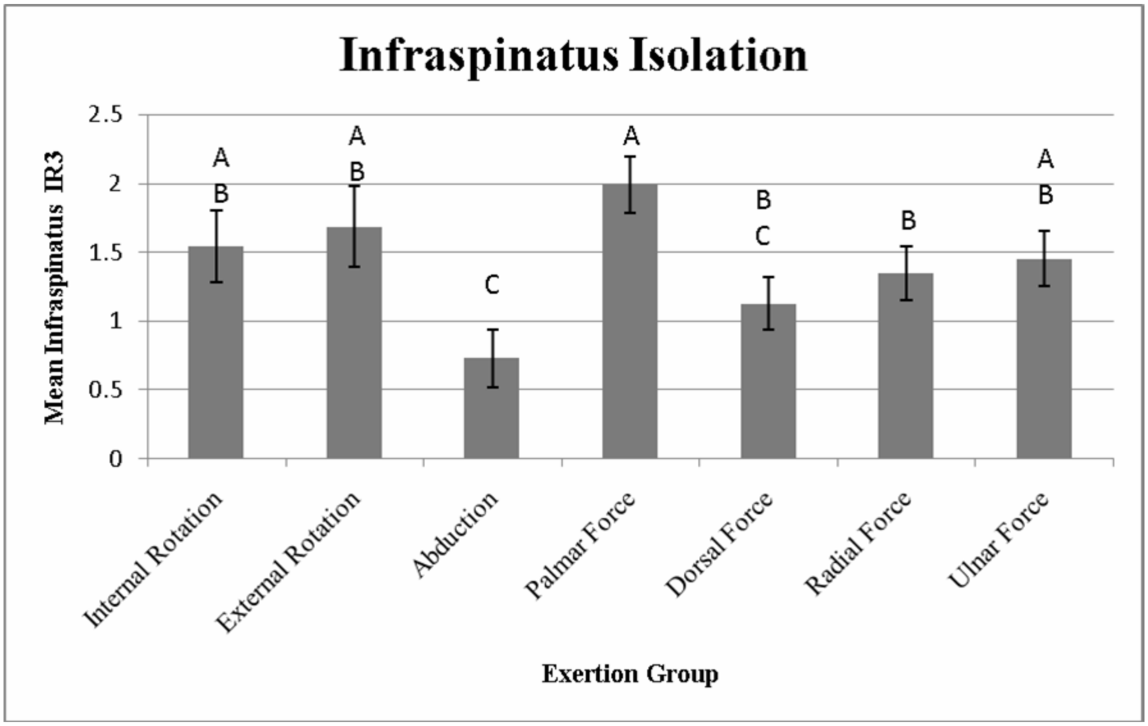


Figure 35: Infraspinatus isolation using IR3

Isolation of Supraspinatus using IR3:

Differences in calculated isolation ratios for the defined exertion groups existed (p = 0.0015), with the following order of decreasing isolation ratio magnitude:

i) Palmar > [Internal Rotation, External Rotation, Dorsal, Radial, Ulnar]

ii) Abduction > [Internal Rotation & External Rotation]

The highest mean IR3 was found in the palmar force group (1.66 ± 0.15). The lowest mean IR3 was found in the external rotation group (0.74 ± 0.21). The ratio of highest to lowest mean IR3 was 2.24. The results of the Student’s T test are shown in Figure 36; the error bars represent ± 1 standard error. The mean activation (% MVC) of the supraspinatus ranged from 27.4 – 34.1% in the palmar force group, and 54.3 – 73.6% in the abduction group exertions. The mean force produced ranged from 57.8 – 99.1 N in the palmar force group, and 70.3 – 95.1 N in the abduction group exertions.

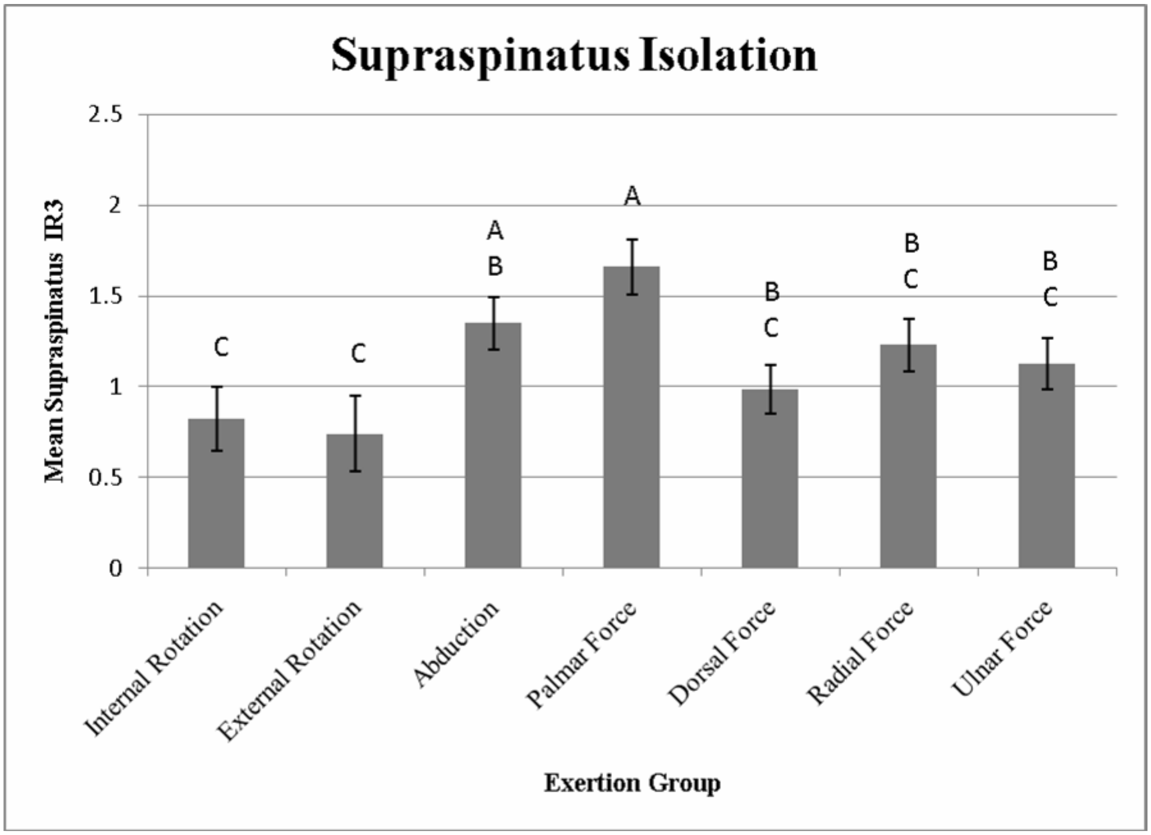


Figure 36: Supraspinatus isolation using IR3

Isolation of Teres Minor using IR3:

Differences in calculated isolation ratios for the defined exertion groups existed ($p < 0.0001$), with the following order of decreasing isolation ratio magnitude:

i) Palmar > [Internal Rotation, External Rotation, Abduction, Dorsal, Radial, Ulnar]

ii) [Radial & Ulnar] > Dorsal

The highest mean IR3 was found in the palmar force group (2.18 ± 0.17). The lowest mean IR3 was found in the abduction group (0.91 ± 0.18). The ratio of highest to lowest mean IR3 was 2.40. The results of the Student's T test are shown in Figure 37; the error bars represent ± 1 standard error. The mean activation of the teres minor (% MVC) ranged from 23.9 – 47.1% in exertions within the palmar force group. The mean force produced ranged from 57.8 – 99.1 N within the exertions of the palmar force group.

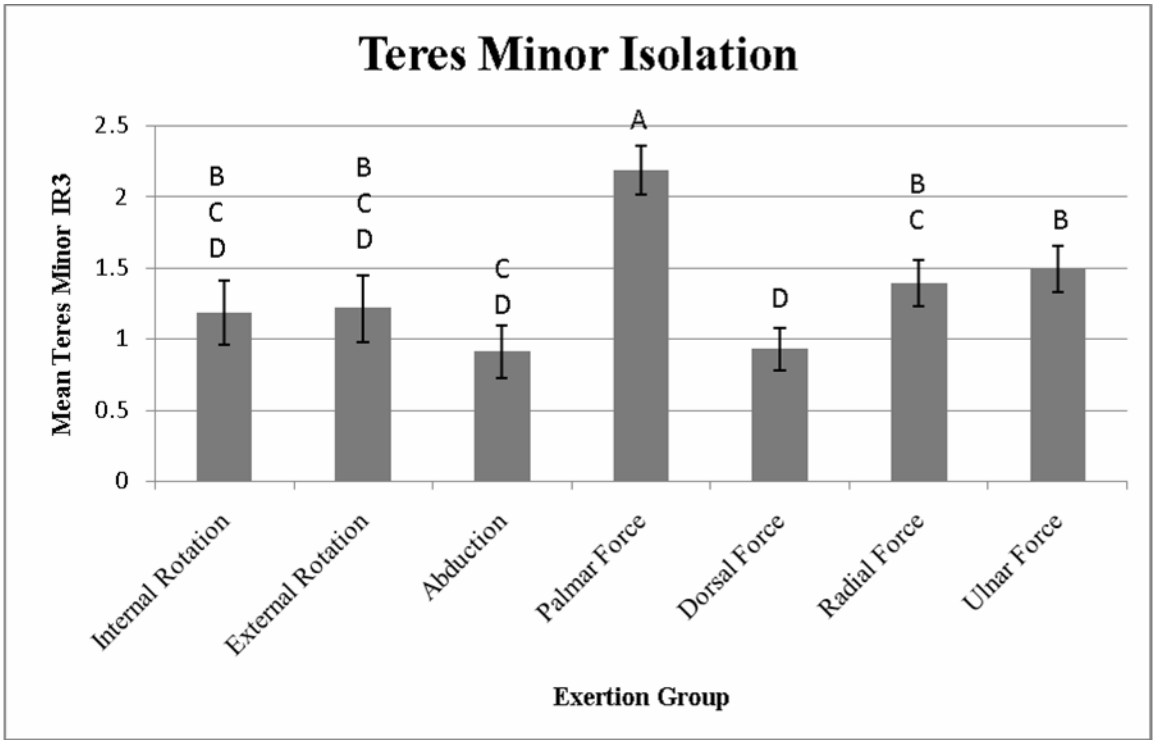


Figure 37: Teres minor isolation using IR3

Isolation of Subscapularis using IR3:

There was no significant difference between any of the exertion groups (p = 0.1501). The highest mean IR3 was found in the abduction group (2.06 ± 0.25). The lowest mean IR3 was found in the palmar force group (1.04 ± 0.23). The ratio of highest to lowest mean IR3 was 1.98. The mean activation of the subscapularis ranged from 12.2 – 19.8% MVC in the abduction group, and 20.1 – 44.0% MVC in the palmar force group. The mean force produced ranged from 70.3 – 95.1 N in the abduction group, and 57.8 – 99.1 N in the palmar force group.

6.6 Comparison of three isolation ratio types:

In order to visually compare trends between the three isolation ratios (IR, IR2 and IR3), the mean isolation ratios (three types) for each of the rotator cuff muscles for each of the seven exertion groups were plotted together (Figures 38 - 41). The asterisks (*) noted below each figure represents conditions in which the ANOVA indicated there was significant differences between one or more of the exertion groups within that isolation ratio type. The error bars represent ± 1 standard error. The maximal isolation ratios (of type IR, IR2 and IR3) determined which exertion groups maximally isolated the rotator cuff. In some cases, there was not a significant difference of mean isolation ratios (of type IR, IR2 or IR3) between exertion groups, indicating that the muscle could be isolated in a number of different exertions. A summary of these findings are displayed in Table 10. Refer to Appendix J for more detail about the ANOVA tests performed on IR, IR2 and IR3.

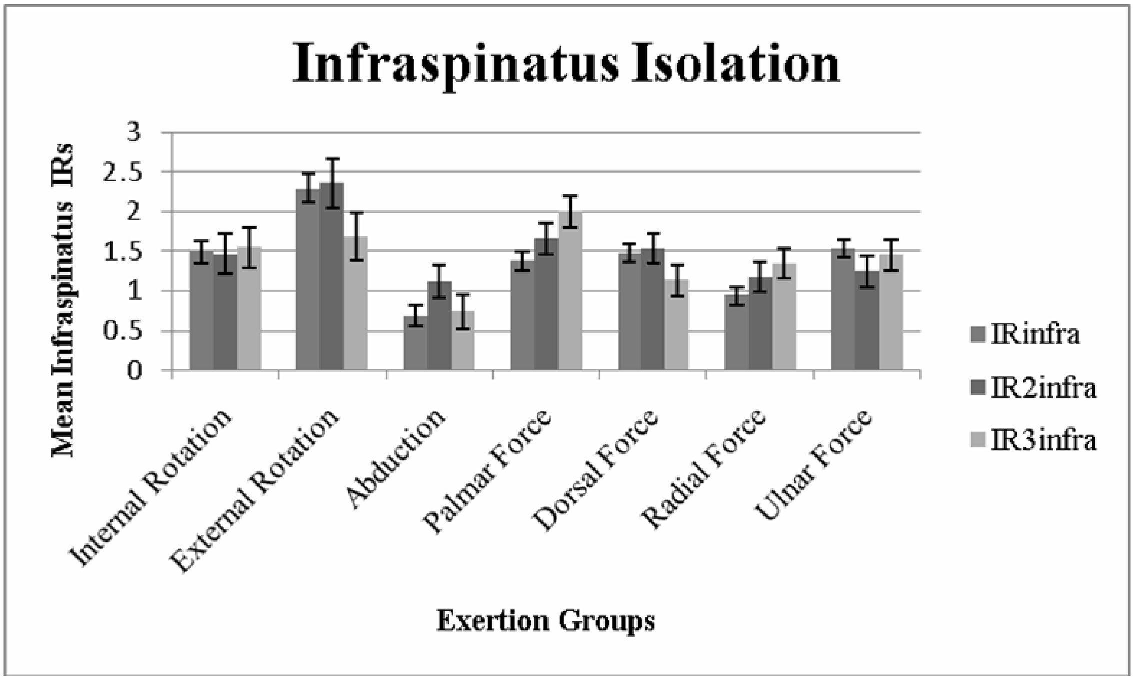


Figure 38: Infraspinatus isolation: comparisons between IR, IR2 and IR3

Note: [IRinfra*, IR2infra*, IR3infra*] The asterisks (*) represents conditions in which the ANOVA indicated there was significant differences between one or more of the exertion groups within that isolation ratio type.

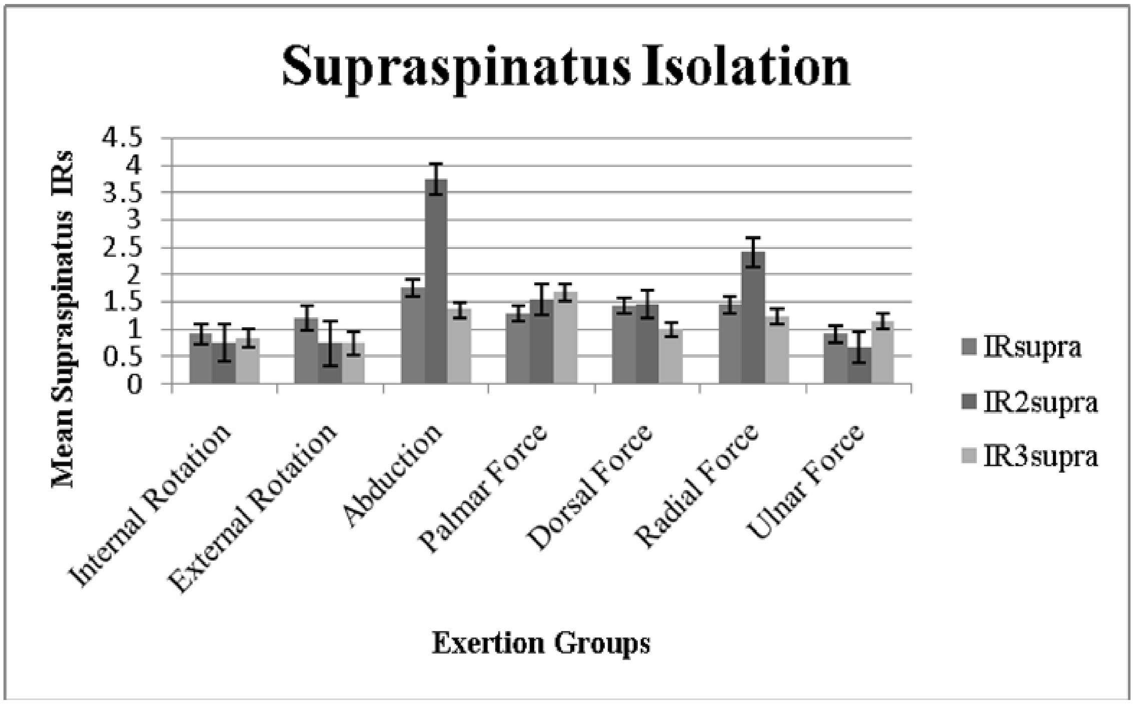


Figure 39: Supraspinatus isolation: comparisons between IR, IR2 and IR3

Note: [IRsupra*, IR2supra*, IR3supra*] The asterisks (*) represents conditions in which the ANOVA indicated there was significant differences between one or more of the exertion groups within that isolation ratio type

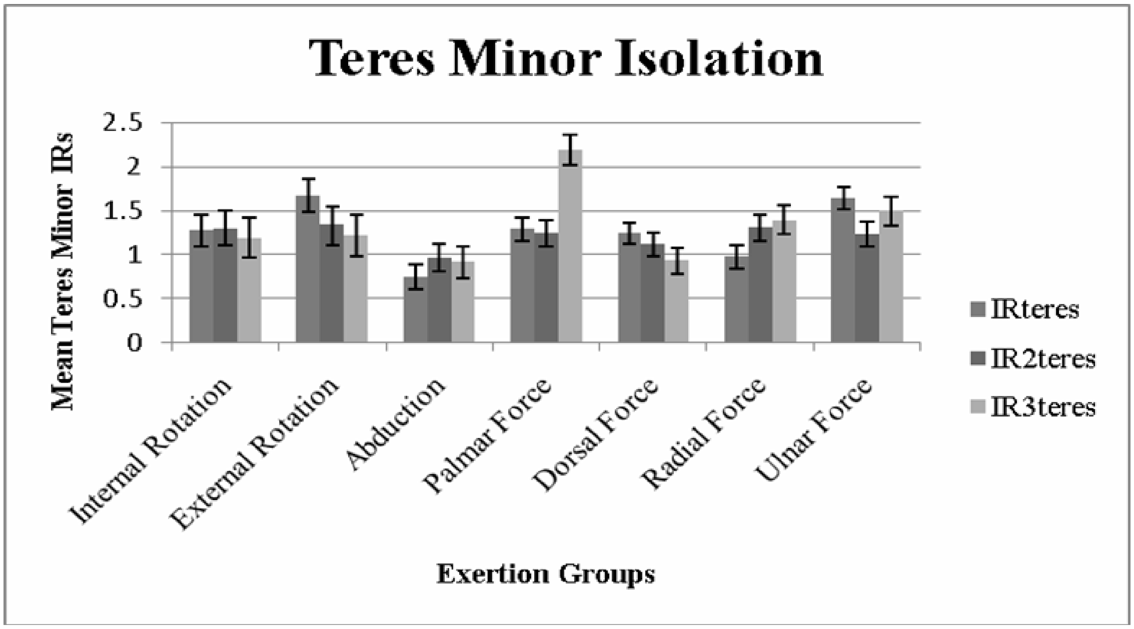


Figure 40: Teres minor isolation: comparisons between IR, IR2 and IR3

Note: [IRteres*, IR2teres, IR3teres*] The asterisks (*) represents conditions in which the ANOVA indicated there was significant differences between one or more of the exertion groups within that isolation ratio type

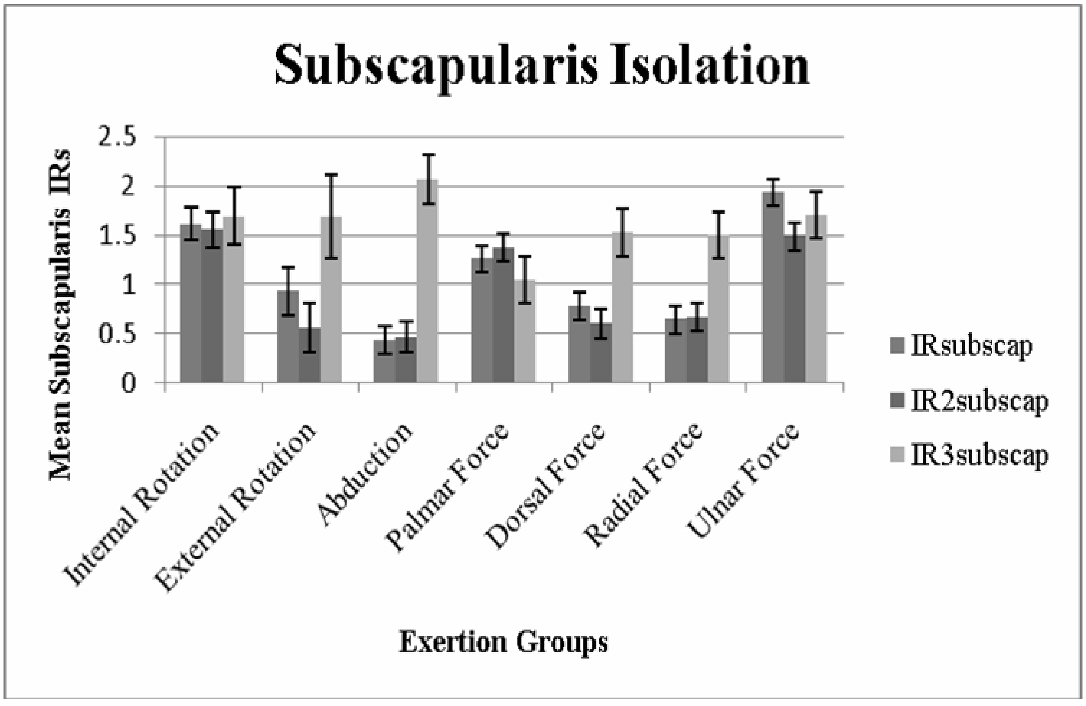


Figure 41: Subscapularis isolation: comparisons between IR, IR2 and IR3

Note: [IRsubscap*, IR2subscap*, IR3subscap] The asterisks (*) represents conditions in which the ANOVA indicated there was significant differences between one or more of the exertion groups within that isolation ratio type

Table 10: Summary of maximal isolation exertions

Ratio Type	Muscle	Isolation Exertion Group
IR	Infraspinatus	external rotation
IR	Supraspinatus	abduction = dorsal force = radial force
IR	Teres Minor	external rotation = internal rotation = ulnar force = palmar force
IR	Subscapularis	internal rotation = ulnar force
IR2	Infraspinatus	external rotation = palmar force
IR2	Supraspinatus	abduction
IR2	Teres Minor	all 7 exertion groups equal
IR2	Subscapularis	internal rotation = palmar force = ulnar force
IR3	Infraspinatus	external rotation = internal rotation = palmar force = ulnar force
IR3	Supraspinatus	abduction = palmar force
IR3	Teres Minor	palmar force
IR3	Subscapularis	all 7 exertion groups equal

7.0 Discussion:

All muscles were maximally functionally isolated (produced maximal IRs) within their respective clinical MMT groups (external rotation [for infraspinatus and teres minor], abduction [for supraspinatus] and internal rotation [for subscapularis]). Similarly, IR2 and IR3 produced maximal isolation ratios within their respective clinical MMT groups, with the exception of teres minor which had a higher IR3 within the palmar force group.

The purpose of this study was to evaluate 29 maximal isometric exertions and determine which of these exertions most functionally isolated the rotator cuff muscles. The rotator cuff muscles were not fully isolated (ratio of maximal activation of the rotator cuff muscle of interest to no activation of the other recorded muscles) in any of these 29 exertions. However, functional isolation (ratio of maximal activation of the rotator cuff muscle of interest to minimal activation of the other recorded muscles (Eq. 4)) was achieved in some exertions, suggesting that large changes in rotator cuff muscle activation can be identified within these exertions. While the results substantiate the use of these commonly used clinical MMTs, they also simultaneously suggest that other exertions are similarly effective in functionally isolating the rotator cuff muscles.

7.1 Isolation of the rotator cuff muscles and comparison of findings to past literature:

The rotator cuff muscles were maximally functionally isolated (produced maximal IRs) within their respective clinical MMT groups. Secondary isolation ratios (IR2 and IR3) were consistent in identifying effective rotator cuff isolation within these clinical MMT groups.

7.1.1 Isolation of the infraspinatus:

Isolation of the infraspinatus from the other 13 recorded muscles (using IR):

The highest mean IR for the infraspinatus occurred within the external rotation group (2.29 ± 0.18), and was significantly higher than mean IRs in all other exertion groups (Figure 25). There was no significant difference between individual IRs for the infraspinatus within each of the exertion groups (Appendix E). Therefore, the infraspinatus was most isolated (activated 2.29 times more than the other recorded muscles) during the prone and sitting infraspinatus and teres minor tests (Exertion #13 and #6, respectively). This was expected as infraspinatus is primarily an external rotator, and Exertion 13 and 6 are both exertions of external rotation. These results confirm that MMTs (Exertion #13 and #6) commonly used by clinicians to assess the strength and function of the infraspinatus are appropriate.

The infraspinatus was least isolated (mean IRs were lowest) within the abduction (0.68 ± 0.12) and radial force (0.94 ± 0.11) groups, indicating that the exertions within these two groups (abduction and flexion) should not be used to assess the function and strength of the infraspinatus. This was not surprising, because although the infraspinatus aids in abduction, it is primarily activated during external rotation.

Isolation of infraspinatus from the rotator cuff (using IR2):

The highest mean IR2 for the infraspinatus occurred within the external rotation group (2.36 ± 0.31), although this mean IR2 was not significantly higher than those within the palmar force group (1.65 ± 0.20) (Figure 32). Therefore, the infraspinatus was most isolated from the other rotator cuff muscles (the infraspinatus was activated on average up to 2.36 times more than the supraspinatus, teres minor and subscapularis) during exertions within the external rotation and palmar force groups. These exertions included external rotation (external rotation group) and horizontal adduction (palmar force group). These results confirm that MMTs commonly used by clinicians in the external rotation group (Exertions 13 and 6) are appropriate in isolating the infraspinatus from the other rotator cuff muscles. It was expected that the infraspinatus would be most isolated from the other rotator cuff muscles during its primary action: external rotation. Results also indicate the exertions within the palmar force groups are equally effective in isolating the infraspinatus from the other rotator cuff muscles.

The lowest mean IR2s occurred within the abduction group (1.12 ± 0.20), although these mean IR2s were not significantly different from those within the internal rotation, dorsal, radial or ulnar force groups. Therefore, the infraspinatus was least isolated (activated on average a minimum of 1.12 times that of the other rotator cuff muscles) during exertions within these groups. It was not surprising that the infraspinatus was least isolated in exertions of abduction from the abduction group, as the infraspinatus has been considered a synergist of supraspinatus in abduction (Kelly et al, 1996a). Therefore, it would be difficult to isolate infraspinatus from supraspinatus, since they both would be expected to be significantly activated in exertions of abduction.

Isolation of the infraspinatus from synergists (using IR3):

The highest mean IR3 for the infraspinatus occurred within the palmar force group (1.99 ± 0.21), but this mean IR3 was not significantly higher than those within the internal rotation, external rotation or ulnar force groups (Figure 35). Therefore, the infraspinatus was most isolated from synergists during exertions within the palmar, internal rotation, external rotation or ulnar force groups (maximal activation of the infraspinatus was on average 1.99 times that of the activation of supraspinatus, teres minor and posterior deltoid). These exertions included horizontal adduction (palmar force group), internal rotation (internal rotation group), external rotation (external rotation group) and extension and adduction (ulnar force group). These results confirm that commonly used clinical MMTs within the external rotation group are appropriate at isolating the infraspinatus from other muscles with the same lines of action. This finding is reasonable, as the infraspinatus would be expected to be activated highly (more so than supraspinatus and the posterior deltoid) during external rotation. However, results also indicate that the infraspinatus can be isolated from synergists just as effectively in exertions within the palmar, internal rotation or ulnar force groups. Although the infraspinatus is not expected to be significantly activated in internal rotation, neither are the other synergists, so it is reasonable to assume that the infraspinatus is isolated from the supraspinatus, teres minor and posterior deltoid in exertions of internal rotation (internal rotation group). Again, this finding suggests the constant activation of the rotator cuff muscles, even in exertions opposite to their primary movement (example internal rotation of the infraspinatus), in attempts to maintain stability of the glenohumeral joint.

The lowest mean IR3s were produced in the abduction (0.73 ± 0.21) and dorsal force (1.13 ± 0.19) groups. Therefore, the infraspinatus is isolated least from it’s synergists in exertions within the abduction and dorsal force group exertions. Since the supraspinatus and posterior deltoid are expected to be highly activated in exertions of abduction and horizontal abduction, it is not surprising that the infraspinatus is not isolated from the activity of these muscles in these exertions.

Isolation of the infraspinatus compared to past findings:

The infraspinatus was most isolated within the external rotation group (Exertions 13, 6), according to maximal IRs. These findings were consistent with past findings that found infraspinatus to be most isolated from synergists (supraspinatus and posterior deltoid) during Exertion 6 (Kelly et al, 1996a). However, when the present study considered infraspinatus synergists (supraspinatus, posterior deltoid and teres minor) in IR3, isolation of the infraspinatus was equal in exertions among the external rotation, palmar, internal rotation and ulnar groups. Different methodology of isolation calculations, as well as consideration of the teres minor may have accounted for these differences.

On average, the maximal activation of the infraspinatus was 82.5%, and this occurred within Exertion 13 (which was identified as an isolation exertion). This finding suggests that infraspinatus may be isolated in some positions during which it was maximally activated, which complies with past methods of determining isolation exertions for the infraspinatus (Townsend et al, 1991; Ballantyne et al, 1993; Dark et al, 2007). However, other isolation exertions (Exertion 6) have been found to be equally effective in isolating the infraspinatus, but these did not produce maximal activation of the infraspinatus (average 58% MVC). Townsend et al (1991) found the infraspinatus to be maximally activated during horizontal abduction while prone, with the elbow extended and humerus externally rotated (peak 88% MVC). This exertion was similar to Exertion 4 (sitting) in the present study, in which infraspinatus was on average activated to 63%

MVC. Townsend et al (1991) also found the infraspinatus to be significantly activated during side-lying external rotation (peak 85% MVC), which was similar to Exertion 6 (which was identified as an infraspinatus isolation exertion in the current study) which produced an average of 58% MVC. Ballantyne et al (1993) found the infraspinatus and teres minor to be equally activated during prone and side-lying external rotation, similar to Exertion 13 (prone) and 6 (sitting), respectively, which were both identified as isolation exertions for the infraspinatus in the current study. Dark et al (2007) found the infraspinatus to be activated significantly more than the supraspinatus and posterior deltoid during external rotation.

7.1.2 Isolation of the supraspinatus:

Isolation of the supraspinatus from the other 13 recorded muscles (using IR):

The mean IR for the supraspinatus was highest within the abduction group (1.74 ± 0.15), but the mean IR within this group was not significantly higher than mean IRs within the dorsal (1.42 ± 0.14) or radial (1.44 ± 0.15) force groups (Figure 26). There was no significant difference between individual IRs for the supraspinatus within each of the exertion groups (Appendix E).Therefore, the supraspinatus was most isolated (activated 1.74 – 1.42 times more than the other recorded muscles) in the abduction, dorsal and radial force groups. These groups included exertions of abduction (in abduction and radial groups), horizontal abduction (dorsal group) and flexion (radial group). Exertion 20 within the radial force group (thumb up), was very similar to Exertion 21 (full can, thumb up) and 1 (empty can, thumb down) from the abduction group, the only difference being 30º forward flexion in Exertion 21, as well as -45º humeral rotation in Exertion 1.

These results confirm that the MMTs commonly used by clinicians within the abduction group: the empty can, full can, Blackburn and supraspinatus neutral abduction test (Exertions 1, 21, 8 and 15, respectively), are appropriate to use in assessing the strength and function of the supraspinatus. However, results also indicate that exertions within the dorsal or radial force groups (Exertions 25, 11, 18, 23, 4 and 29, 7, 27, 14, 20, respectively) are also equally effective in isolating the supraspinatus, and could also be used by clinicians in assessment of the supraspinatus. Since the supraspinatus aids the deltoid in shoulder abduction, it is not surprising that the supraspinatus is isolated in exertions of abduction or horizontal abduction. It was surprising to see the supraspinatus isolated in exertions of flexion (within the radial group). This could be a result of grouping both abduction and flexion exertions within the radial group – perhaps if they were grouped separately, a clearer distinction would be made in isolating supraspinatus in abduction exertions.

The lowest mean IRs (ranged from 0.90 – 1.28) were found within the internal rotation, external rotation, palmar and ulnar force groups, indicating that the supraspinatus was least isolated during exertions within these groups (internal rotation, external rotation, horizontal adduction, extension and adduction). These findings are reasonable, as the supraspinatus is primarily an abductor, it would not be expected to be heavily activated during exertions of rotation, adduction or extension.

Isolation of the supraspinatus from the rotator cuff (using IR2):

The largest mean IR2 occurred within the abduction group (3.74 ± 0.28) (Figure 33). Therefore, the supraspinatus was most isolated (activated 3.74 times more than the other rotator cuff muscles) during abduction exertions within the abduction group. These results confirm that MMTs commonly performed by clinicians in the abduction group are appropriate in isolating the supraspinatus from the other three rotator cuff muscles. It is reasonable that the supraspinatus be isolated in abduction exertions, of which it is a prime mover, more so than the other rotator cuff muscles that are more involved in rotation than abduction.

The lowest mean IR2 occurred within the ulnar force group (0.66 ± 0.27), although mean IR2s from this group were not significantly different from those within the internal rotation or external rotation groups. Therefore, the supraspinatus is least isolated (activated on average only 66% of that of the other rotator cuff muscles) in exertions within these exertion groups. These findings make sense as the supraspinatus (a primary abductor) would not be expected to be heavily activated in exertions of adduction and extension from the ulnar force group or internal or external rotation.

Isolation of the supraspinatus from synergists (using IR3):

The highest mean IR3 for the supraspinatus occurred in the palmar force group (1.66 ± 0.15), although this mean IR3 was not significantly greater than that of the abduction group (Figure 36). Therefore, the supraspinatus was isolated most from it's synergists during exertions within the abduction and palmar force groups (the supraspinatus was maximally activated at an average of 1.66 times that of the middle deltoid and infraspinatus). These exertions included horizontal adduction (palmar force group) and abduction (abduction group). These results confirm that commonly used clinical MMTs in the abduction group are appropriate in isolating the supraspinatus from its synergists. However, results also indicate that the supraspinatus can be isolated equally as well in the palmar force group exertions. Since the horizontal adduction exertions of the palmar force group involve shoulder elevation, it was expected that the supraspinatus would be highly activated in these exertions.

The supraspinatus was least isolated from the infraspinatus and middle deltoid during exertions within the external rotation group (0.74 ± 0.21). This finding is reasonable, as the supraspinatus would not be expected to be heavily involved in external rotation of the humerus, but the infraspinatus would be.

Isolation of the supraspinatus compared to past findings:

Maximal IRs confirmed that the supraspinatus was most isolated within exertions of the abduction group (Exertions 1, 21, 8, 15), but that the supraspinatus could also be equally isolated within the dorsal and radial force groups. Past literature has also recommended Exertions 1 and 21 (empty and full can tests) be used to assess the supraspinatus (Jobe & Moynes, 1982; Itoi et al, 1999; Kelly et al, 1996a). These tests are very similar to Exertion 20 within the radial force group. Jobe & Moynes (1982) showed that the supraspinatus was the predominant muscle active in the rotator cuff during Exertion 1. This is consistent with the present study’s findings: isolation of the supraspinatus was compared to the other rotator cuff muscles in IR2, and it was shown that the supraspinatus was isolated most from the other rotator cuff muscles in exertions within the abduction group (including Exertion 1). Itoi et al (1999) found that Exertions 1 and 21 were equivalent in accuracy for detecting supraspinatus tears.

Kelly et al (1996a) considered the synergist (infraspinatus) of supraspinatus, and compared isolation of six exertions (including Exertion 1 and 21). Kelly et al (1996a) concluded that Exertion 21 best isolated the supraspinatus. Results from the present study showed that there was no significant difference between IRs of Exertion 1 and 21, indicating the ability of both exertions to equally isolate the supraspinatus.

The supraspinatus was maximally activated an average of 73.6 % in Exertion 1, which was identified as an isolation exertion in the present study. This finding supports past work that claimed isolation of the supraspinatus occurred within exertions of maximal activation (Townsend et al, 1991). Townsend et al (1991) found the supraspinatus to be significantly challenged in exertions similar to Exertions 1 and 21 of the present study. However, other exertions (within the abduction, dorsal and radial force groups) also effectively isolated the supraspinatus, and these were not exertions of maximal activation.

7.1.3 Isolation of the teres minor:

Isolation of the teres minor from the other 13 recorded muscles (using IR):

The highest mean IR for the teres minor was found within the external rotation group (1.67 ± 0.19), but the mean IR within this group was not significantly higher than those within the internal rotation, ulnar or palmar force groups (Figure 27). There was no significant difference between individual IRs for the teres minor within each of the exertion groups (Appendix E). Therefore, the teres minor was most isolated (activated 1.67 – 1.26 times more than the other recorded muscles) in exertions within these four groups. These groups included exertions of external rotation (external rotation group), internal rotation (internal rotation group), extension and adduction (ulnar force group), and horizontal adduction (palmar force group). These results confirm that MMTs commonly used by clinicians (external rotation group – Exertions 6 and 13) are appropriate in assessing the teres minor. However, the results also suggest that other exertions from within the internal rotation, ulnar or palmar force groups, (Exertions 16, 2, 9; 28, 26, 5, 12, 19; 3, 24, 22, 17, 10), are equally effective in isolating the teres minor and can be used in the assessment of it. The teres minor is primarily an external rotator, so it was expected that it would be isolated in exertions of external rotation. The teres minor originates on the infraspinous fossa of the scapula and inserts on the greater tubercle of the humerus, so it was also not surprising that the teres minor be isolated in exertions of extension and adduction (ulnar force group), and horizontal adduction (palmar force group). It was, however, surprising to find that the teres minor was also isolated in exertions of internal rotation (internal rotation group), during which the muscle would not be expected to be very active. It is possible that the teres minor is activated in these exertions of internal rotation to help stabilize the glenohumeral joint and prevent anterior dislocation.

The lowest mean IRs were found in the abduction group (0.74 ± 0.19), indicating that the teres minor was least isolated (activated only about 74% of that of the other recorded muscles) during abduction exertions within the abduction group (Exertions 1, 8, 21, 15). This makes sense because the teres minor is primarily an external rotator - it would not be expected to be heavily activated during abduction exertions.

Isolation of the teres minor from the rotator cuff (using IR2):

The highest IR2 occurred within the external rotation group (1.33 ± 0.22), although this mean IR2 was not found to be significantly higher than any of the other six exertion groups. Therefore, the teres minor was not found to be isolated from the other rotator cuff muscles more in any one of the exertion groups. It makes sense that the highest isolation ratio occurred within the external rotation groups, when teres minor would be expected to be most activated. However, this activation was not significant compared to the activation of the other 3 rotator cuff muscles to isolate the teres minor, demonstrating that these muscles work in concert to stabilize the glenohumeral joint.

Isolation of the teres minor from synergists (using IR3):

The highest mean IR3 for the teres minor occurred within the palmar force group (2.18 ± 0.17), indicating that the teres minor was most isolated from its synergists in horizontal adduction exertions within this group (Figure 37). On average, the teres minor was activated 2.18 times more than the posterior deltoid and infraspinatus. Therefore, these results suggest that exertions within the palmar force group isolate the teres minor from synergists significantly more than those commonly used clinical MMT exertions in the external rotation group. This finding is sensible, as the contributions of posterior deltoid and infraspinatus would expect to be minimized during exertions of horizontal adduction.

Isolation of the teres minor compared to past findings:

Maximal IRs confirmed that the teres minor was most isolated within exertions of the external rotation group (Exertions 13, 6), but that teres minor could also be equally isolated within the internal rotation, ulnar and palmar force groups. The teres minor was maximally activated an average of 63.8% during Exertion 13. These findings agree that identification of exertions of maximal activation of the teres minor, may identify some isolation exertions, as previous authors have suggested (Townsend et al, 1991; Ballantyne et al, 1993). However, results of the current study have identified other isolation exertions that are equally as effective in isolating the teres minor, and they are not exertions of maximal activation of the teres minor. Townsend et al (1991) found the teres minor to be maximally activated (peak 80 and 74% MVC) in exertions similar to Exertion 6 and 4 (average 44.7 and 51.1% MVC) of the present study. Ballantyne et al (1993) found the teres minor to be significantly activated in external rotation exertions similar to Exertion 13 (prone) and 6 (sitting) of the present study.

7.1.4 Isolation of the subscapularis:

Isolation of the subscapularis from the other 13 recorded muscles (using IR):

The highest mean IR for the subscapularis was found in the ulnar force group (1.93 ± 0.13), but the mean IR from this group was not significantly higher than those from the internal rotation group (1.61 ± 0.17) (Figure 28). There was no significant difference between individual IRs for the subscapularis within each of the exertion groups (Appendix E).Therefore, the subscapularis was most isolated (the subscapularis was activated 1.93 – 1.61 times more than the other recorded muscles) within the exertions of the ulnar force and internal rotation groups. Exertions within these groups included extension and adduction (ulnar force group), and internal rotation (internal rotation group). These results confirm that MMTs commonly used by clinicians within the internal rotation groups: prone subscapularis, lift off and belly press tests (Exertions 16, 2, 9, respectively), are appropriate to use in assessment of the strength and function of the subscapularis. The results also suggest that other MMTs (Exertions 28, 26, 5, 12, 19 from the ulnar force group) are equally as effective in isolating the subscapularis, and can also be used by clinicians in the assessment of the subscapularis. The isolations exertions identified for the subscapularis seemed logical because the muscle would be expected to be heavily activated during exertions of extension, adduction and internal rotation, due to it's origin on the subscapular fossa and insertion on the lesser tubercle of the humerus.

The subscapularis was least isolated (produced lowest mean IRs) within the exertions of the abduction group (0.43 ± 0.15). This means that during exertions of abduction within the abduction group, the subscapularis was on average activated only about 43% of that of the other recorded muscles. Exertions within the abduction groups were not significantly different from exertions within the external rotation, dorsal or radial force groups, suggesting that exertions from any of these groups are not appropriate to use in clinical assessment of the subscapularis. The subscapularis is primarily an internal rotator, and also contributes to extension and adduction. Therefore, it makes sense that the subscapularis was not isolated in exertions within the external rotation, dorsal or radial force groups, as the subscapularis is not expected to be heavily activated in exertions of external rotation, horizontal abduction (dorsal force group), flexion or abduction (radial force group).

Isolation of the subscapularis from the rotator cuff (using IR2):

The highest mean IR2 occurred within the internal rotation group (1.55 ± 0.18), although the mean IR2 was not significantly higher than those within the palmar or ulnar force groups (Figure 34). Therefore, the subscapularis was most isolated from the other rotator cuff muscles (activated on average at a maximum of 1.55 times that of the other rotator cuff muscles) during exertions within the internal rotation, palmar and ulnar force groups. These exertions include internal rotation (internal rotation group), horizontal adduction (palmar group) and extension and adduction (ulnar force group). Therefore, results confirm that internal rotation exertions commonly used by clinicians in the internal rotation groups are appropriate in isolating the subscapularis from the other rotator cuff muscles. Results also indicate that exertions within the palmar and ulnar force groups are just as effective at isolating the subscapularis from the other rotator cuff muscles. Since the subscapularis is an internal rotator, it is expected to be most isolated in exertions of internal rotation from the internal rotation group, and similarly isolated in exertions of (horizontal) adduction and extension.

The subscapularis was least isolated from the other 3 rotator cuff muscles in the abduction group (0.46 ± 0.15). This is a reasonable finding, since the subscapularis is an internal rotator involved in adduction and extension – it would not be expected to be isolated in exertions of abduction.

Isolation of the subscapularis from synergists (using IR3):

The highest mean IR3 for the subscapularis occurred in the abduction group (2.06 ± 0.25), but this mean IR3 was not significantly different in any of the other six exertion groups. The subscapularis was on average maximally activated 2.06 times more than the pectoralis major (clavicular) and latissimus dorsi. Therefore, the subscapularis was isolated from synergists the same amount in all of the exertion groups. These findings seem reasonable, since these muscles are activated in similar exertions of internal rotation, adduction and extension – it would be difficult to clearly separate the subscapularis from them.

Isolation of the subscapularis compared to past findings:

Maximal IRs confirmed that the subscapularis was most isolated within exertions of the internal rotation group (Exertions 16, 2 and 9), but that the subscapularis could also be equally isolated within the ulnar force group exertions. The subscapularis was maximally activated an average of 58% during Exertion 28 (from ulnar force group), which was identified as an isolation exertion. Results of the current study found there was no difference between isolation of the subscapularis in Exertion 2 or 9 (lift off and belly press tests). These findings support past work of Tokish et al (2003), who found there was no difference in the ability of Exertion 2 or 9 to evaluate the subscapularis. Other authors have concluded that Exertion 2 is superior to Exertion 9 (Greis et al, 1996; Kelly et al, 1996a). Greis et al (1996) found the subscapularis was more isolated from the pectoralis major during Exertion 2, compared to Exertion 9. Kelly et al (1996a) found the subscapularis to be most isolated (from the pectoralis major and latissimus dorsi) during Exertion 2, compared to Exertion 9.

7.2 Average force during isolation exertions:

The force values are important because they represent the amount of muscle force that is exerted during exertions in which the rotator cuff muscles are found to be maximally isolated. The size of the active muscles within the isolation ratios should be considered when interpreting theses forces, as larger muscles may contribute more to these forces than smaller muscles. For example, the supraspinatus may be maximally isolated (produce maximal a IR) during an abduction exertion, however the middle deltoid is also active during abduction, and due to its size, may contribute more to the force produced at the hand than the supraspinatus. The average force for all participants is displayed in Figure 29 for each of the 29 exertions. For example, the infraspinatus was found to be maximally isolated (activated 2.29 times more than the other recorded muscles) during Exertions 6 and 13 (Figure 25). The average forces produced during Exertions 6 and 13 were 98.5 ± 22.9 and 60.2 ± 23.0 N, respectively. These force values can be assumed to be normal force values during functional isolation of the infraspinatus in these two exertions within this population. Clinicians could compare these force values with those produced by patients performing these exertions against hand held dynamometers.

The error bars demonstrate the large variance of forces between the participants, indicating that this data can not be extrapolated for MMT use in clinical settings. This data was taken from a small population sample: 12 young males (mean age 20.7 years, range 18 – 29 years) with no history of shoulder or upper limb injury. This data should be expanded upon so that it can be generalized to a similar population sample, and used by clinicians during MMT assessments. If a database was created that included normal force values for a wide range of demographics, clinicians could use hand dynamometers during their assessment of muscle strength and function. Force values found to be below normal could be indicative of muscle weakness, dysfunction or tears. Having quantifiable methods of assessing muscle function would allow more accurate diagnoses and perhaps earlier detection of weakness (especially with current methods of grading MMTs being quite subjective). The forces obtained from this study are a good starting point of a normalized database, but need to be expanded upon to include more subjects, different age ranges and genders.

7.3 Assessment of fatigue:

Fatigue was not identified experimentally during the course of this experiment. There was no significant change in force values performed pre and post experimental testing, as indicated by the paired T test ($p = 0.146$). Participants were still able to produce similar levels of force. If participants were fatigued, it was expected that force levels would decline as participants would not be able to exert maximal effort. The percent difference of force change was +2.7%, indicating that force levels exerted at the end of testing were slightly higher than initial forces. However, it was noted in Figure 31 that Subject 12 had a large increase in force (percent difference of 157.9%) during Exertion 19. It is possible that this participant was not producing maximal effort during the initial task. This large increase could have skewed the average percent difference of force change, so for this reason this data was excluded and the paired t test was re-run, and average percent difference in force was re-calculated. When data from this assumed outlier was excluded, the average percent difference changed from 2.7% to -3.8%, and the paired T-test indicated a p value of 0.06. The re-calculated results indicated that there was a slight decrease in post experiment force values, but that this decrease was not significant. These results suggest that participants were given sufficient rest in between exertions, as they displayed no signs of exertion fatigue.

Although there was no decrease in force, it is possible that some muscles were fatigued, and muscle substitution occurred to help maintain maximal force levels. Mean and median power frequencies (MnPF and MdPF) were assessed during initial and final repeat exertions. Literature suggests that a shift of MdPF to lower frequencies is indicative of fatigue (Allison & Fujiwara, 2002). Paired T-test results indicated that there were significant changes in the MnPF ($p = 0.016$) and MdPF ($p = 0.022$) of the infraspinatus (wire) channel, and in the MdPF ($p = 0.026$) of the biceps brachii. These results indicate that significant differences in frequency are occurring between initial and final exertions, but do not indicate what direction the frequencies are shifting. For this reason percent differences of MnPF and MdPF were calculated for the infraspinatus (wire) and biceps between initial and final exertions. The average percent differences of MnPF and MdPF for the infraspinatus (wire) were -8.27 and -11.36%, respectively. The average percent difference of the MdPF for the biceps was -5.28%. Therefore, it was concluded that the MnPF and MdPF decreased (shifted to lower frequencies) post experiment. These decreases in frequency may suggest fatigue in the infraspinatus (wire) and bicep. However, Robertson et al (2004) cautioned interpretation of MnPF and MdPF as a decrease in frequency does not necessarily indicate an increase in motor unit synchronization, but may mean there is a decrease of active motor units, a decrease in firing rate or slowing of conduction velocity. There was no indication that any of the other 12 recorded muscles were fatigued. Since force levels were not significantly reduced post experiment, and 14 out of 16 muscle sites indicated no significant changes in MnPF and MdPF, it was concluded that the rest given between exertions was sufficient, and fatigue had no or minimal effect on the participants.

7.4 Study limitations:

The largest challenge in this study was to obtain EMG signals from the wire electrodes without artifact. Although wire movement was limited (isometric exertions, careful insertion and taping down of the wires), the slightest movement produced artifact. Artifact of the subscapularis was a particular concern during exertions during which the arm was close to the body. Since the insertion of the subscapularis wire was in the axilla, the arm sometimes brushed against the wire, resulting in artifact. Meticulous analysis was performed on each channel of EMG, and artifact was identified and avoided as much as possible. In the event that artifact was missed and this data was included in analysis, the muscle activation used in the isolation ratios would be inaccurate and therefore, the identified isolation exertions may not be representative. Isolation ratios could similarly be affected by the exclusion of channels containing artifact, which were not salvageable. Further research should consider arm position during exertions when intending to use the axillary insertion for the subscapularis.

The grouping of the 29 exertions into 7 groups may have been a limiting factor in the analysis. Firstly, there were an unequal number of exertions within groups. Also, exertions within a group did not all require the same posture. Although ANOVAs confirmed that isolation ratios between exertions within a group were not statistically different, it is possible that some exertions would have better fit into other groups. Grouping these exertions may have inflated or deflated mean isolation ratios, which would have affected which groups most isolated the muscle of interest. Some MMT exertions were very similar to the generic exertions, but they were separated in to different groups. Exertion 20 from the radial exertion group (90º abduction, thumb up), was very similar to Exertion 21 (90º abduction, thumb up at 30º forward flexion), Exertion 1 (90º abduction, thumb down, 30º forward flexion) and Exertion 15 (supraspinatus neutral abduction) from the abduction exertion group. If exertions had been grouped more distinctly, there may have been better separation of isolation ratios between groups, and therefore a clearer distinction between isolation exertions.

There were only subtle differences (45º) between many of the exertions tested. This level of similarity may have limited the straightforward determination of exertions that significantly isolated the rotator cuff muscles better than others did. For example, there was no significant difference between isolation ratios for the teres minor in IR2, or the subscapularis in IR3. If the exertions had been more varied, or other exertions were selected and tested, more definite distinctions between isolation exertions may have been possible.

Results may not be truly representative of rotator cuff isolation because of the assumptions of the isolation ratios used. The initial isolation ratio (IR) considered the contributions of 13 surrounding shoulder muscles. It is possible that other muscular contributors were not recorded (for example, the serratus anterior and coracobrachialis). The secondary isolation ratios (IR2 and IR3) were considered of secondary importance to the initial IR because these ratios only considered a smaller number of the muscles crossing the glenohumeral joint (compared to IR which considered 13 different muscles). Furthermore, the IR3 ratio type assumed synergists for each of the rotator cuff muscles, surmising that function of these muscles does not change as posture changes, contrary to Liu et al (1997).

Additional experimental equipment limitations may have also influenced the results. A further limitation of this study was that pectoralis major (sternal insertion) was unable to be collected on 9 subjects due to equipment failure, and was therefore excluded from the isolation ratios, which affected their magnitude.

In clinical practice, some MMTs are resisted at the elbow. In the present study, force was applied at the hand or wrist for all exertions. This difference in procedure may have resulted in different recruitment of muscles, or affected the level of muscle activation, which in turn would have affected the magnitude of the isolation ratios.

7.5 Future work:

Since this is the first study to consider the activation of 13 surrounding shoulder muscles in the isolation of the rotator cuff, future studies should continue to investigate the contributions of these muscles, and should also include a larger population sample which includes females, symptomatic populations, and other age groups. This research should investigate the MMTs from the present study, as well as additional exertions, to confirm and identify rotator cuff isolation consistency within different populations. Further research should also measure force production during exertions to expand on results of this present study, and to enable the creation of a normalized database of arm strength that includes diverse populations. Clinicians will then be able to refer to normalized force values, and make more qualitative assessments by using dynamometry during rotator cuff MMTs.

The data from this study and its analogs can also be examined with shoulder biomechanical models (such as Dickerson et al, 2008). Our current experimental results (muscle activation, position and force production), which represent a large set of unique exertions and multiple muscle recordings, can be used to validate these models, which predict muscle force based on exertion position and anthropometric data. Validation of such models is pertinent to their effective use in industry during job assessment, and the prediction of muscle injury or fatigue risks. As risk is often associated with high demand tasks, this data can serve to evaluate model performance in strenuous exertions.

8.0 Conclusion:

The purpose of this study was to identify exertions which maximally isolated the rotator cuff muscles. This study has demonstrated that attempts to fully isolate the rotator cuff muscles are not possible, however exertions exist that functionally isolate the rotator cuff muscles and can detect large changes in rotator cuff muscle activation. Results indicated that the rotator cuff muscles were maximally functionally isolated from all other recorded muscles in exertions within the following groups:

- Infraspinatus:
    - External rotation group
- Supraspinatus:
    - Abduction, dorsal force and radial force groups
- Teres Minor:
    - External rotation, internal rotation, ulnar force and palmar force groups
- Subscapularis:
    - Internal rotation and ulnar force groups

These results generally confirmed the appropriateness of currently used clinical MMTs in assessing individual rotator cuff muscle status, and identified further exertions that are equally functionally isolated these muscles. Secondary isolation ratios (IR2 and IR3) were consistent in identifying effective rotator cuff functional isolation within the clinical MMT groups.

Two of the three hypotheses of this study were confirmed. Firstly, the clinical MMTs were generally most effective in maximally functionally isolating the rotator cuff muscles, although other exertions were also found to be equally as effective. Secondly, the rotator cuff muscles were functionally isolated within exertions based on their primary action, however in some instances, alternative exertions (and actions) were found to similarly isolate the rotator cuff muscles. It was thirdly hypothesized that all muscles were isolated by multiple exertions. This hypothesis was not confirmed because individual exertions were not analyzed, but were rather considered in 7 exertion groups. However, the isolation ratios calculated for each grouping of exertions often were similar, which suggests that multiple exertions can also yield similar isolations.

This study verified the appropriateness of commonly used clinical MMTs in isolating and assessing the muscles of the rotator cuff. Many other exertions were also defined as equally appropriate rotator cuff assessment tests, some of which may be easier for the patient to perform, or for the clinician to resist. The findings of this study will give clinicians more confidence, qualitative accuracy and flexibility in their assessments. Despite the occurrence of artifact, the intramuscular electrodes were invaluable in their assessment of rotator cuff activation, which would have been very difficult (and in the case of the subscapularis, impossible) with surface electrodes. The study results provide valuable information about the fundamental mechanics of the rotator cuff, and provide a starting point of normalized force data that clinicians can refer to when using dynamometry in their assessments. Future research should include the contributions of surrounding muscular in the identification of isolation exertions of the rotator cuff.

References:

Allison, G.T. & Fujiwara, T. (2002). The relationship between EMG and frequency and low frequency band amplitude changes at different levels of muscle capacity. *Clinical Biomechanics, 17*:464-469.

Ballantyne, B.T, O'Hare, S.J., Paschall, J.L., Pavia-Smith, M.M., Pitz, A.M., Gillon, J.F., Soderberg, G.L., Wilk, K.E., Riddle, D.L. & Lamb, R.L. (1993). Electromyographic activity of selected shoulder muscles in commonly used therapeutic exercises. *Physical Therapy, 73*(10), 668-682.

Barden, J.M., Balyk, R., Raso, V.J., Moreau, M. & Bagnall, K. (2005). Atypical shoulder muscle activation in multidirectional instability. *Clinical Neurophysiology, 116*, 1846-1857.

Basmajian, J.V. & De Luca, C.J. Muscles Alive. Their Functions revealed by Electromyography (Fifth Edition). Williams and Wilkins, Baltimore, 1985.

Bohannon, R.W. (2005). Manual muscle testing: does it meet the standards of an adequate screening test? *Clinical Rehabilitation, 19,* 662-67.

Buchthal, F. & Schmalbruch, H. (1970). Contraction times and fibre types in intact human muscle. *Acta Physiolo Scand., 79*(4):435-52.

Burke, W.S., Vangsness, C.T., & Powers, C.M. (2002). Strengthening the supraspinatus: a clinical and biomechanical review. *Clinical Orthopaedics and Related Research, 402*, 292-298.

Buschbacher, R. Shoulder Girdle Injuries. In: Lillegard WA, Rucker KS, eds. Handbook of Sports Medicine: A Symptom-Oriented Approach. Boston: Andover Medical Publ; 1993.

Clarkson, M.H. & Gilewich, G.B. (1990). *Musculoskeletal assessment: Joint range of motion and manual muscle strength.* Baltimore, Lippincott Williams & Wilkins.

Cram, J.R. & Kasman, G.S. (1998). Introduction to Surface Electromyography, Aspen, Gaithersburg, MD.

Dark, A., Ginn, K.A., Halaki, M. (2007). Shoulder muscle recruitment patterns during commonly used rotator cuff exercises: an electromyography study. *Physical Therapy, 87*, 1039-1046.

Daniels, L. & Worthingham, C. Muscle testing techniques of manual examination, WB Saunders, Philadelphia (1986).

De Luca, C.J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics, 13*:135-163.

De Groot, J., Rozendaal, L., Meskers, C. & Arwert, H. (2004). Isometric shoulder muscle activation patterns for 3-D planar forces: A methodology for musculo-skeletal model validation. *Clinical Biomechanics, 19,* 790-800.

Dekker, M. Tokish, J., Ellis, H., Torry, M & Hawkins, R. (2003). Subscapularis muscle activity during selected rehabilitation exercises. *American Journal of Sports Medicine, 31*(1), 126-34.

Delagi, E. & Perotto, A. (1980). Anatomic Guide for the Electromyographer. 2nd Ed.

Dickerson C.R., Martin B.J., & Chaffin D.B. (2007). Predictors of perceived effort in the shoulder during load transfer tasks. *Ergonomics, 50*(7): 1004–1016.

Dickerson C.R., Hughes R.E., and Chaffin D.B. (2008). Experimental evaluation of an ergonomic shoulder muscle force model. *Clinical Biomechanics*, accepted.

Etnyre, B.R. & Abraham, L.D. (1988). Antagonist muscle activity during stretching: a paradox re-assessed. *Medicine and Science in Sports and Exercise, 20*(3):285-289.

Gerber, C. & Krushell, R.J. (1991). Isolated rupture of the tendon of the subscapularis muscle. *Journal of Bone and Joint Surgery, 73B*, 389-94.

Gerber, C., Hersche, O., & Farron, A. (1996). Isolated rupture of the subscapularis tendon. Results of operative repair. *Journal of Bone and Joint Surgery, 78*:1015-23.

Giroux, B. & Lamontage, M. (1990). Comparisons between surface electrodes and intramuscular wire electrodes in isometric and dynamic conditions. *Electromyography and Clinical Neurophysiology, 30*, 397-405.

Gowan, I.D., Jobe, F.W., Tibone, J.E., Perry, J., & Moynes, D.R. (1987). A comparative electromyographic analysis of the shoulder during pitching: professional versus amateur pitchers. *The American Journal of Sports Medicine, 15*(6), 586-590.

Greis, P.E., Kuhn, J.E., Schultheis, J., Hintermeister, R., & Hawkins, R. (1996). Validation of the lift-off test and analysis of subscapularis activity during maximal internal rotation. *Am. J. Sports Med., 24*, 589.

Happee, R. & Van der Helm, F. (1995). The control of shoulder muscles during goal directed movements, an inverse dynamic analysis. *J Biomechanics, 28*(10), 1179-1191.

Herbison, G.J., Isaac, Z., Cohen, M.E. & Ditunno Jr, J.F. (1996). Strength post-spinal cord injury: myometer vs. manual muscle test. *Spinal Cord, 34,*543-548.

Hintermeister, R.A., Lange, G.W., Schultheis, J.M., Bey, M.J. & Hawkins, R.J. (1998). Electromyographic activity and applied load during shoulder rehabilitation exercises using elastic resistance. *The American Journal of Sports Medicine, 26*(2), 210-220.

Itoi, E., Tadato, K., Sano, A., Urayama, M. & Sato, K. (1999). Which is more useful the “full can test” or the “empty can test,” in detecting the torn supraspinatus tendon? *American Journal of Sports Medicine, 27*(1), 65-68.

Janda, V. Muscle Function Testing. Butterworths, Toronto, CA. 1983.

Jenp, Y., Malanga, G.A., Growney, E.S. & An, K. (1996). Activation of the rotator cuff in generating isometric shoulder rotation torque. *American Journal of Sports Medicine, 24*(4), 477-485.

Jobe, F.W. & Moynes, D.R. (1982). Delineation of diagnostic criteria and a rehabilitation program for rotator cuff injuries. *American Journal of Sports Medicine, 10*(6), 336-339.

Kamen, G. & Caldwell, G.E. (1996). Physiology and interpretation of the electrogram. *Journal of Clinical Neurophysiology, 13*(5):366-384.

Kelly, B.T., Cooper, L.W., Kirkendall, D.T., & Speer, K.P. (1997). Technical considerations for electromyographic research on the shoulder. *Clinical Orthopaedics,* 335, 140-151.

(a) Kelly, B.T., Kadrmas, W.R., & Speer, K.P. (1996). The manual muscle examination for rotator cuff strength; an electromyographic investigation. *The American Journal of Sports Medicine, 24*(5), 581-588.

(b) Kelly, B.T., Kadrmas, W.R., Kirkendall, D.T. & Speer, K.P. (1996). Optimal normalization tests for shoulder muscle activation: an electromyographic study. *Journal of Orthopaedic Research, 14*, 647-653.

Knepler, C. & Bohannon, R.W. (1998). Subjectivity of forces associated with manual muscle test grades of 3+, 4- and 4. *Perceptual and Motor Skills, 87,* 1123-28.

Kronberg M., Brostrom, L. & Nemeth, G. (1991). Differences in shoulder muscle-activity between patients with generalized joint laxity and normal controls. *Clinical Orthopaedics,* 269, 181-192.

Kuhlman, J.R., Iannotti, J.P., Kelly, M.J., Riegler, F.X., Gevaert, M.L. & Ergin, T.M. (1992). Isokinetic and isometric measurement of strength of external rotation and abduction of the shoulder. *The Journal of Bone and Joint Surgery, 74*:1320-1333.

Laursen, B., Jensen, B.R., Nemeth, G. & Sjogaard, G. (1998). A model predicting individual shoulder muscle forces based on relationship between electromyographic and 3D external forces in static position. *J Biomechanics, 31*(8): 731-739.

Liu, J., Hughes, R.E., Smutz, W.P., Niebur, G. & Nan-An, K. (1997). Roles of deltoid and rotator cuff muscles in shoulder elevation. *Clinical Biomechanics, 12*(1):32-38.

Malanga, G.A., Jenp, Y-N., Growney, E.S., Kai-Nan, A. (1996). EMG analysis of shoulder positioning in testing and strengthening the supraspinatus. *Med Sci Sports Exerc, 28*(6), 661-664.

Merrian-Webster's collegiate dictionary (10th ed.). (1993). Springfield, MA: Merriam Webster.

Michener, L.A. Boardman, N.D. Pidcoe, P.E. & Frith, A.M (2005). Scapular muscle tests in subjects with shoulder pain and functional loss: reliability and construct validity. *Physical therapy, 85*(11):1128-1138.

Mirzabeigi, E., Jordan, C., Gronley, J.K., Rockowitz, N.L. & Perry, J. (1999). Isolation of the vastus medialis oblique muscle during exercise. *American Journal of Sports Medicine, 27*(1):50-54.

Moore, K.L. & Dalley, A.F. (1999). Clinically Oriented Anatomy. Forth Edition. Philadelphia, PA: Lippincott Williams & Wilkins.

Morris, A.D., Kemp, G.J., Lees, A. & Frostick, S.P. (1998). A study of the reproducibility of three different normalization methods in intramuscular dual fine wire electromyography of the shoulder. *Journal of Electromyography and Kinesiology, 8*, 317-22.

Myers, J.B., Riemann, B.L., Ju, Y., Hwang, J., McMahon, P.J. & Lephart, S.M. (2003). Shoulder muscle reflex latencies under various levels of muscle contraction. *Clinical Orthopaedics & Related Research. 407*, 92-101.

Nemeth, G., Kronberg, M. & Brostrom, L. (1990). EMG recordings from the subscapularis muscle: description of a technique. *Journal of Orthopaedic Research, 8*,151-153.

Otis, J.C., Jiang, C., Wickiewicz, T.L., Peterson, M.G.E., Warren, R.F. & Santner, T.J. (1994). Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. *Journal of Bone and Joint Surgery, 76A*(5), 667-676.

Perry, J., Schmidt, C. & Antonelli, D.J. (1981). Surface versus intramuscular electrodes for electromyography of superficial and deep muscles. *Physical Therapy, 61*(1), 7-15.

Robertson, G.M., Caldwell, G., Hamill, J., Kamen, G. & Whittlesey, S. (2004). Research methods in biomechanics. Champaign, IL: Human Kinetics.

Ruwe, P.A., Pink, M., Jobe, F.W., Perry, J. & Scovazzo, M.L. (1994). The normal and the painful shoulders during the breaststroke: electromyographic and cinematographic analysis of twelve muscles. *American Journal of Sports Medicine, 22*(6), 789-796.

Sapega, A.A. (1990). Current Concepts Review: Muscle performance evaluation in orthopaedic practice. *The Journal of Bone and Joint Surgery, 72*:1562-1574.

Sarrafian, S.K. (1983). Gross and functional anatomy of the shoulder. *Clinical Orthopaedics and Related Research, 173*, 11-19.

Suenaga, N., Minami, A. & Fujisawa, H. (2003). Electromyographic analysis of internal rotation motion of the shoulder in various arm positions. *Journal of Shoulder and Elbow Surgery, 12*, 501-505.

Tokish, J., Decker, M., Ellis, H., Torry, M. & Hawkins, R. (2003). The belly-press test for the physical examination of the subscapularis muscle: electromyographic validation and comparison to the lift-off test. *Journal of Shoulder and Elbow Surgery, 12, 427-30.*

Townsend, H., Jobe, F.W., Pink, M., & Perry, J. (1991). Electromyographic analysis of the glenohumeral muscles during a baseball rehabilitation program. *American Journal of Sports Medicine, 19*(3), 264-272.

Winter, D.A. Biomechanics and Motor Control of Human Movement (3rd Edition). John Wiley & Sons, Inc., New York, 1990.

Winter, D.A., Fuglevand, A.J. & Archer, S.E. (1994). Crosstalk in surface electromyography: theoretical and practical estimates. *Journal of Electromyography and Kinesiology. 4*(1):15-26.

WSIB of Ontario Statistical Supplement to Annual Report (2005). (http://www.wsib.on.ca/wsib/wsibsite.nsf/Public/AnnualReports)

WSIB of Ontario Statistical Supplement to Annual Report (2006). (www.wsib.on.ca/wsib/wsibobj.nsf/Lookupfiles/Downloadablefile2006StatisticalSupplement/$File/2278AStatSupp06.pdf)

Muscle attachment sites of the four rotator cuff muscles on the scapulae (Figure 1):

(http://www.nlm.nih.gov/medlineplus/ency/images/ency/fullsize/19622.jpg)

Assessment of the supraspinatus using the empty can test (Figure 2):
(http://www.clinicalsportsmedicine.com/chapters/14d.html)

Dorsal (D), palmar (P), ulnar (U) and radial (R) force directions (Figure 17):
(http://www.ravenmadness.blogspot.com/2007/05/handywork.html)

APPENDICES

Appendix A Recruitment poster:

Department of Kinesiology
University of Waterloo

PARTICIPANTS NEEDED FOR RESEARCH IN BIOMECHANICS

We are looking for right-hand dominant male volunteers between the ages of 18 – 35 years with no history of right shoulder injury to take part in an EMG study of shoulder muscle activity during simple arm postures.

As a participant in this study, you would be asked to:

- Perform simple arm movements while the activity of the muscles surrounding your shoulder will be examined with EMG:
  - 12 bipolar surface electrodes will be placed on your skin over 12 muscles
  - 4 needles will be placed into 4 muscles in your right shoulder to allow for the recording of intramuscular EMG.
  - The needles will immediately be removed after insertion, leaving 8 tiny wires (similar in size to a strand of hair) in your muscle for the duration of the study. It is not expected that you will feel the presence of these wires.
- The study is done under sterile conditions, and the insertions are done by a member of the study team with specific training and six years of experience in performing these procedures.

Your participation would involve 1 session, which is approximately 2.5 hours.

In appreciation for your time commitment, you will receive $50.00

For more information about this study, or to volunteer, please contact:
Rebecca Brookham
Kinesiology Dept. BMH 1404 or 3044
519-888-4567 Ext. 36162
Email: *rlbrookh@ahsmail.uwaterloo.ca*

This study has been reviewed by, and received clearance through, the Office of Research Ethics, University of Waterloo.

Appendix B Verbal recruitment script:

“Hello, my name is Rebecca Brookham and I am a Master’s student in the Department of Kinesiology. I am currently working in the Biomechanics lab in BMH 1404 with Dr. Clark Dickerson and am doing my thesis. I am studying the muscle activity of the rotator cuff and surrounding muscles of the shoulder during manual muscle tests that are commonly used to assess muscle function by clinicians. This research will hopefully lead to a better understanding of the rotator cuff activity during certain postures, which may enhance clinicians’ knowledge and confidence about their methods of assessment. You will be asked to perform simple arm movements while 12 bipolar surface electrodes and 4 intramuscular electrodes record the EMG of your shoulder and back muscles. This will involve 4 needles being inserted into the muscles of your shoulder, which will immediately be removed. Two tiny wires (about the size of a strand of hair), are contained within each intramuscular electrode, which upon removal will remain in your muscles during the study while you perform these movements. It is not expected that you will feel the presence of these wires. This study is performed under sterile conditions. The insertions will be performed by a member of the study team with specific training and 6 years of experience in performing these procedures. The session should take approximately 2½ hours of your time.

You will receive $50.00 in appreciation of your time.

If I can take another 2 minutes of your time, I would like to explain and demonstrate two examples of test postures that you would be asked to perform.”

(Researcher gains consent, and presently demonstrates the following test postures on herself to the potential participant)

“1) You, the participant will sit with your right arm abducted (which means held out to the side like this) to 90º. You will push against a force transducer which will resist your arm just above the elbow joint on the outside aspect of your arm in the direction of shoulder adduction (this means you would be trying to raise your arm up towards the ceiling, while the force transducer will resist this movement. (Clarkson & Gilewich, 1989)

2) You, the participant would lay on a bench on your stomach, with your right shoulder abducted (held out to the side like this) to 90º and elbow bent to 90º. Your upper arm would be resting on the bench. You would internally rotate your shoulder by moving your palm towards the ceiling. The force transducer will provide resistance on your arm, above your wrist joint in the direction of shoulder external rotation (pushing your hand down and away from the ceiling). (Clarkson & Gilewich, 1989)

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics. However, the final decision about participation is yours.

If you are interested in participating, please come to BMH 1404 and see me. Thank you.”

Appendix C Information and consent form:

INFORMATION AND CONSENT FORM

Digital Ergonomics Laboratory
Department of Kinesiology
University of Waterloo

Title of Project: Electromyography Validation of Rotator Cuff Manual Muscle Tests and Comparison of Indwelling versus Surface Electrodes

Principal Investigator:	Clark Dickerson, PhD University of Waterloo, Department of Kinesiology (519) 888-4567 Ext. 37844
Co-Investigator:	Linda McLean, PhD Queen's University, School of Rehabilitation Therapy (613) 533-6000 Ext. 79009
Student-Investigator:	Rebecca Brookham, BSc University of Waterloo, Department of Kinesiology (519) 888-4567 Ext. 36162

Purpose of this Study:

The shoulder is a very complex joint as it has more postural flexibility than any other joint of the body. Shoulder injuries are common and costly to the Canadian society, but studies of shoulder function are limited. Also lacking are electromyographic validation and standardization of diagnostic tests of shoulder pathologies, such as rotator cuff manual muscle tests (MMTs). MMTs are frequently used in clinical settings to assess the function and strength of muscles in a simple, time and cost-efficient manner.

This study proposes to test several manual muscle tests for each muscle of the rotator cuff (supraspinatus, infraspinatus, teres minor and subscapularis) in order to validate the test's proposed functions. Evaluation of these tests will identify specific postures that allow maximal activation of rotator cuff muscles, and these findings will allow clinicians and researchers to confidently and accurately attain muscle-specific strength-based information. This information can then be utilized to plan appropriate therapeutic measures. The purpose of this research is to promote effective treatment and prevention of shoulder injuries by increasing electromyographic knowledge of shoulder function, and to validate diagnostic MMTs of the rotator cuff.

In addition, a secondary purpose of this study will be to compare myoelectric signals of the rotator cuff from surface and intramuscular electrodes. No known studies have compared rotator cuff myoelectric activation levels from surface and indwelling electrodes simultaneously, to determine whether there is significant congruity between the signals. This study will determine, for a subset of exertions, the feasibility of estimating deep muscle activity (percent maximal voluntary contraction) based upon surface activity readings. This may help in deciding whether indwelling electrodes are necessary for the future study of the rotator cuff.

It is hypothesized that surface electrodes will not be sufficient in assessing rotator cuff activity, and the reliability of the MMTs will be improved with the use of hand dynamometers by clinicians. This research will conclude what postures are proven to be valid MMTs of the rotator cuff, aiding in diagnosis, treatment and prevention of shoulder injuries.

Photographs and video recordings will be taken during the study, if consent is given by the participant. These photographs or video recordings will be focused on the upper body and arm, but will not be focused on facial features. These photos and recordings are useful to verify the movement information recorded by the researchers, and may be helpful in teaching purposes such as when presenting the study results in a scientific presentation or publication. Any facial features or other distinguishing features that are visible in photos or recordings used for these above mentioned purposes will be blotted out to remove distinguishing features and maintain participant confidentiality.

Procedures Involved in this Study

The project consists of one session amounting to approximately 2.5 hours.

1.0 Participant Preparation for Needle Electrodes

1.1 Prior to coming to the lab, you will be asked if you have an allergy to iodine, latex, nickel, or isopropyl alcohol. If you are allergic or have experienced these health issues, you cannot participate in the study.

1.2 Prior to coming into the lab, you will be asked to fill out a self report health screening checklist to assess past health problems as well as present health problems. If you report blood clotting disorders, HIV, Hepatitis A, B, or C, have had a lower back or upper limb injury within the past 6 months, suffer from chronic pain lasting longer than 6 months, or have a known difficulty or slowness healing, you will not be able to participate in the study.

1.3 You will be reminded to ask any questions whether they relate to the science of the procedure or not.

1.4 Prior to coming to the lab, you (male participants) will be advised that you will be asked to remove your shirt during experimental set-up and testing. You will lie on your stomach on a clinical bench and the skin area over the muscle will be thoroughly cleaned with Betadine solution containing 10% povidone-iodine.

1.5 Four sterile single-use hypodermic needles of 3.5 inches or less and 27 gauge or smaller will be inserted through the skin into four muscles of the shoulder. This will feel similar to the prick of a needle that would be received at the doctor's office. Each of the needles contains two very thin wires (44 gauge) of similar size to a strand of hair. Each of the 8 wires is bent at the end, so that once the needle is removed from the skin, the 8 thin wires will remain within the muscle during testing (approximately 2.5 hours). The wire extends by approximately 7 cm beyond the surface of the skin. It is unlikely that you will feel the presence of this wire within your muscle. This wire will record the electrical activity of the muscle as you perform various movements. Once the desired muscle contractions are completed, the wires will be removed easily with a gentle tug on the end of the wire that is lying outside the skin. This removal will be painless because each wire is so pliable that the barb straightens out on traction and offers little, if any, palpable resistance (Basmajian, 1985). Upon removal of the wires, the skin area will be cleaned with isopropyl alcohol, and a bandage will be placed over the area. The hypodermic needles will not be reused. After removal, hypodermic needles will be disposed of into a sharps container labelled biohazardous waste.

1.6 The total depth into the tissue will vary from participant to participant depending on the amount of subcutaneous fat present overlying the muscle. It is expected that the needles will be inserted approximately 1 cm into the supraspinatus, infraspinatus and teres minor. The needle for the subscapularis will be inserted approximately 3 cm deep. The depth will be apparent when the needles reach the surface of the scapula.

1.7 The needle insertion procedures will be carried out by Linda McLean, PhD. Ms. McLean is an Associate Professor at Queen’s University in the department of Rehabilitation Therapy and is an expert at inserting intramuscular electrodes. Ms. McLean has performed numerous intramuscular insertions into the muscles of the rotator cuff, as well as into many other muscles, and has over 6 years of experience. Throughout the years of her experience and numerous insertions, Ms. McLean has not experienced one single adverse affect or complication or injury of any kind. All needle handling will be performed by Ms. McLean while using latex gloves and by keeping the needle environment sterile prior to insertion.

2.0 Participant Preparation for Surface Electrodes

2.1 Twelve bipolar surface adhesive electrodes will be placed on the skin over 12 muscles, and one additional electrode will be placed on a bony landmark (likely the clavicle) as a ground electrode. These electrodes will also record the electrical activity of your muscles, and will be compared to the signals obtained through the wire electrodes.

2.2 Prior to electrode placement, any hair in the placement area is shaved. The removal of hair enhances the signal and makes the removal of the electrode easier. A new disposable razor is used for each participant. Over 500 participants have undergone this procedure in the Kinesiology department, and to date no participants have been cut.

2.3 The skin areas for electrode placement are wiped with isopropyl alcohol and then the electrodes are placed on the skin.

2.4 Surface electrodes are adhered to the skin overlying 12 muscles of interest. Two electrodes will be placed on each of the following muscles of interest: latissimus dorsi, long head of triceps, biceps, anterior deltoid, middle deltoid, posterior deltoid, pectoralis major (sternal insertion), pectoralis major (clavicular insertion), lower trapezius, upper trapezius, as well as over the wire sites of infraspinatus and supraspinatus muscles, all of the right arm. On occasion the electrodes can leave a mark after removal. Usually, these marks disappear within hours or within two days.

2.5 All instrumentation attached to you is electrically isolated and CSA approved.

2.6 On completion of the session the electrodes are removed.

3.0 Testing Procedures

3.1 You will be asked to perform simple hand and shoulder movements against manual resistance, in which you will push as hard as possible for approximately6 seconds against the resistance provided by the researcher. You will perform maximal contractions during approximately 29 shoulder positions, with a 2 minute rest between each test. Listed below are two of the test postures used by clinicians to activate the rotator cuff, which will be tested in this study.

Test Posture for the Subscapularis:
You will lie on your stomach with your right shoulder abducted (out to the side) to 90º and elbow bent to 90º. You will internally rotate your shoulder by moving your palm towards the ceiling. You will push against a force transducer which will resist your movement. (Clarkson & Gilewich, 1989)

Test Posture for the Supraspinatus:
You will sit with your right arm abducted (raise arm out to your side and up towards the ceiling) to 90º. You will push against a force transducer which will resist your movement. (Clarkson & Gilewich, 1989)

Personal Benefits of Participation

By participating in this study, you may further your knowledge and understanding of experimental procedures commonly used in biomechanics/ergonomics research. There are no other expected benefits to you.

Risks to Participation and Associated Safeguards

There is always a risk of muscle, joint or other injury in any physical work. However, the risks in this study are not anticipated to be greater than those required to move personal belongings from one apartment to another or those encountered in an exercise program or recreational activity that requires brief maximum muscular efforts. You are permitted to withdraw from the study at any point at your request.

1) During any of the conditions, you may experience muscular fatigue, and/or soreness. The stiffness and/or soreness may develop or persist for two or three days following the study if you are unaccustomed to this type of work. This soreness/stiffness is normal and usually disappears in a few days. If it does not go away within a few days, you should contact the researcher.
2) Some individuals may experience mild skin irritation from the surface electrodes. This is similar to the irritation that may be caused by a bandage and typically fades within 2 to 3 days. Risk of infection from the needles is minimal since the area will be cleansed with alcohol, and bleeding is not expected.
3) There is a risk of discomfort during the insertion of the needle. This discomfort will be similar to the prick of a needle that would be obtained from a doctor's office. Additional pain may be experienced due to the depth of the insertion, but this pain will only be temporary, as the needle will immediately be removed.
4) There is a minimal risk of pneumothorax (puncturing a lung), and/or brachial plexus or arterial injuries with the improper insertion of the subscapularis intramuscular electrode. Pnuemothorax resulting from a 27 gauge needle could cause shortness of breath. There have been zero incidences of pneumothorax occurring as a result of this procedure, and would occur only if the needle was inserted in an improper location and/or improper direction. Since the needles will be inserted by an expert who has performed this procedure numerous times, it is not expected that this will be a concern. Injuries of the brachial plexus or arteries resulting from a 27 gauge needle could cause a temporary tingling sensation, and/or muscle weakness. In the unlikely event that a complication did occur, researchers obtain current first aid and CPR certificates and would perform necessary first aid to stabilize the participant while waiting for 9-1-1 response teams. Figure 1 shown below indicates the location of the subscapularis muscle on the front of the shoulder blade in relation to the ribs. In order to puncture a lung, the needle would have to be inserted into the arm pit area in a direction opposite to that of the shoulder blade. Throughout over six years of experience and numerous insertions into over 15 muscles (including muscles of the rotator cuff) Ms. McLean has not once experienced any form of complication during or as a result of her needle insertions. Figure 2 demonstrates what a left punctured lung could look like.
5) There is a minimal risk of wire breakage inside your muscle. Previous authors have found that this has never occurred during thousands of intramuscular wire insertions (Basmajian, 1985). The tiny gauge of these dull wires and composition of nickel alloy cause these wires to be innocuous, so that the occurrence of a breakage is not disturbing as it would not be harmful to your body. The wires are

not degradable. It is likely that the wire would eventually work itself out of your body, as most foreign objects do (such as a wood splinter), however, on the occurrence of this incident, you would be recommended to follow-up with your family physician.

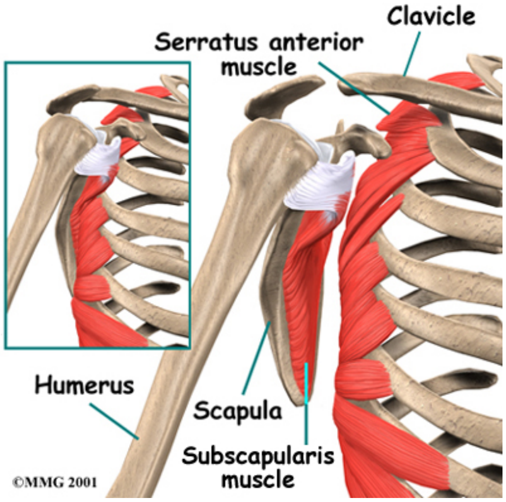


Figure 1 Subscapularis Location

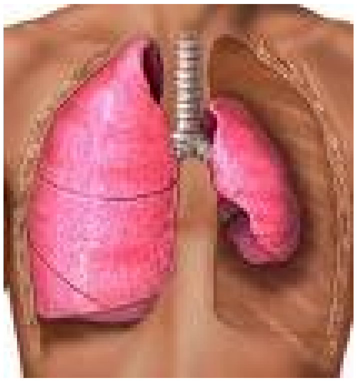


Figure 2 Left Punctured Lung

Time Commitment

Participation in this study will require approximately 2 ½ hours of your time.

Changing Your Mind about Participation

You may withdraw from this study at any time without penalty. To do so, indicate this to the researcher or one of the research assistants by saying, "I no longer wish to participate in this study".

Confidentiality and Data Retention and Security

To ensure the confidentiality of individuals' data, each participant will be identified by a participant identification code known only to the investigators and the research assistants. Videotapes and/or photographs will be stored indefinitely in a secure area, BHM 1404, in a locked cabinet in a locked office. Separate consent will be requested in order to use the videotapes and/or photographs for teaching, for scientific presentations, or in publications of this work. All paper documentation will be kept in a secured locked office (BMH 1404) for up to 3 years. All electronic files will be stored on a password-protected computer in BMH 1404, with file names that protect confidentiality. These files will be destroyed at the end of data processing (maximum 5 years).

Participant Feedback

After the study is completed, you will be provided with a feedback sheet.

Suitability for Participation

You should not volunteer for this study if you have sustained an upper limb or low back injury in the past six months, suffer from chronic pain lasting longer than 6 months, or have blood clotting disorders, HIV, Hepatitis A, B, or C, have a known difficulty or slowness healing, or are allergic to iodine, latex, nickel or isopropyl alcohol.

Concerns about Your Participation

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, you may contact Dr. Susan Sykes, Director ORE, at (519) 888-4567 ext. 36005.

Questions about the Study

If you have additional questions later or want any other information regarding this study, please contact Clark Dickerson (Faculty Supervisor) at 519-888-4567 ext. 37844 or Rebecca Brookham (Student Investigator) at 519-888-4567 ext. 36162.

Reference:

Basmajian, J.V. & De Luca, C.J. (1985). Muscles Alive Their Functions Revealed by Electromyography. Fifth Edition. Williams & Wilkins, Baltimore, USA.

Clarkson, M.H. & Gilewich, G.B. (1989). *Musculoskeletal assessment: Joint range of motion and manual muscle strength.* Baltimore, Lippincott Williams & Wilkins.

Delagi, E.F., Perotto, A., Iazzetti, J., & Morrison, D (1980). Anatomic Guide for the Electromyographer. The Limbs. 2nd Edition. Charles C Thomas (Publisher), Springfield, Illinois, USA.

Nemeth, G., Krongberg, M. & Brostrom, L. (1990). Electromyogram (EMG) Recordings from the Subscapularis Muscle: Description of a Technique. *Journal of Orthopaedic Research,* 8, 151-153.

Consent to Participate

I agree to take part in a research study being conducted by Dr. Clark Dickerson of the Department of Kinesiology, University of Waterloo.

I have made this decision based on the information I have read in the Information letter. All the procedures, any risks and benefits have been explained to me. I have had the opportunity to ask any questions and to receive any additional details I wanted about the study. If I have questions later about the study, I can ask one of the researchers (Dr. Dickerson, 519-888-4567 Ext. 37844; Rebecca Brookham, 519-888-4567 Ext. 36162; Dr. Linda McLean, 613-533-6000 Ext. 79009).

I understand that I may withdraw from the study at any time without penalty by telling the researcher.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I may contact this office (519-888-4567, ext. 36005) if I have any concerns or questions resulting from my involvement in this study.

______________________________	____________________________
Printed Name of Participant	Signature of Participant
______________________________	____________________________
Dated at Waterloo, Ontario	Witnessed

Consent to Use Video and/or Photographs

Sometimes a certain photograph and/or part of a video-tape clearly shows a particular feature or detail that would be helpful in teaching or when presenting the study results in a scientific presentation or publication. If you grant permission for photographs or videotapes in which you appear to be used in this manner, please complete the following section.

I agree to allow video and/or photographs to be used in teaching or scientific presentations, or published in scientific journals or professional publications of this work without identifying me by name. I understand that I retain the right to withdraw my consent to be videotaped or photographed at any time, and that existing video or photos may be destroyed at my request. There will be no penalty to me if I choose to refuse this consent.

____________________________	_________________________________
Printed Name of Participant	Signature of Participant
___________________________	_________________________________
Dated at Waterloo, Ontario	Witnessed

Appendix D Feedback letter:

University of Waterloo
519-888-4567 ext 36162
rlbrookh@ahsmail.uwaterloo.ca

September 1, 2007

Dear Participant,

Thank you for your participation in the study, “Electromyography Validation of Rotator Cuff Manual Muscle Tests and Comparison of Indwelling versus Surface Electrodes” conducted by Rebecca Brookham, Bask, Clark Dickerson, PhD and Linda McLean, PhD. Clark Dickerson can be contacted at (519) 888-4567 extension 37844.

The purpose of this letter is to thank you for your participation in this study, provide you with information regarding the purposes and outcomes of this work, and to ensure you that any data pertaining to you will be kept confidential.

As a reminder, the purpose of this study was to examine the muscle activity of the shoulder during various postures used by clinicians to assess the strength and function of these muscles. There are many postures that can be used to assess the four muscles of the rotator cuff, however there has been limited electromyographic validation of these tests. Without validation, clinicians do not have any evidence that they are accurately assessing the rotator cuff with these tests.

Researchers commonly choose to use surface electrodes to record signals from the small, deep muscles of the rotator cuff, rather than the more invasive indwelling electrodes. However, to our knowledge there have not been any simultaneous comparisons between surface and indwelling recordings of the rotator cuff, indicating little evidence that surface electrodes are able to obtain valid signals from the rotator cuff.

By evaluating the electromyographic signals from the rotator cuff during various manual muscle tests, it is proposed that the researchers will be able to determine the validity of several manual muscle tests. In addition, the comparison between electrode types (surface versus indwelling) will allow researchers to determine whether surface electrodes give accurate representations of the rotator cuff muscle activity that is seen from the indwelling electrodes. The results of this study will give clinicians confidence and knowledge about their practice techniques, and will in addition give researchers knowledge about collection method assumptions.

Please remember that any data pertaining to you as an individual participant will be kept confidential. Once all the data are collected and analyzed for this project, I plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. If you are interested in receiving more information regarding the results of this study, or if you have any questions or concerns, please contact me at either the phone number or email address listed at the top of the page. If you would like a summary of the results, please let me know now by providing me with your email address. When the study is completed, I will send it to you. The study is expected to be completed by April 2008.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes at 519-888-4567, Ext. 36005.

If you are interested in reading more about intramuscular EMG, please refer to:
1) Basmajian, J.V. & De Luca, C.J. (1985). Muscles Alive Their Functions Revealed by Electromyography. Fifth Edition. Williams & Wilkins, Baltimore, USA.
2) Nemeth, G., Krongberg, M. & Brostrom, L. (1990). Electromyogram (EMG) Recordings from the Subscapularis Muscle: Description of a Technique. *Journal of Orthopaedic Research,* 8, 151-153.

Thank you again for your participation.

Rebecca Brookham, BSc

Appendix E One-way ANOVA confirmation of exertion groups:

Group	IR ratio	p value
Dorsal Force	IR infra	0.7921
	IR supra	0.9559
	IR teres	0.8418
	IR subscap	0.7575
External Rotation	IR infra	0.9550
	IR supra	0.2092
	IR teres	0.3652
	IR subscap	0.1104
Palmar Force	IR infra	0.5348
	IR supra	0.8703
	IR teres	0.5686
	IR subscap	0.6624
Radial Force	IR infra	0.0521
	IR supra	0.7838
	IR teres	0.9254
	IR subscap	0.5848
Internal Rotation	IR infra	0.0570
	IR supra	0.0877
	IR teres	0.9069
	IR subscap	0.0682
Abduction	IR infra	0.9568
	IR supra	0.9054
	IR teres	0.9899
	IR subscap	0.7871
Ulnar Force	IR infra	0.4687
	IR supra	0.6393
	IR teres	0.5662
	IR subscap	0.7381

[Note: The table shows the p values for one-way ANOVAs that were performed between exertions within each of the 7 groups. Exertions within each of the 7 groups were not found to be statistically different from each other ($p<0.05$). This confirmed that the exertions were properly grouped, according to main action.]

Appendix F Listing of 29 exertions:

Flexion (0°, 45°, 90°)	**Exertion #**
Neutral, dorsal	25
Neutral, palmar	3
Neutral, ulnar	28
Neutral, radial	29
Flex 45, dorsal	11
Flex 45, palmar	24
Flex 45, ulnar	26
Flex 45, radial	7
Flex 90, dorsal	18
Flex 90, palmar	22
Flex 90, ulnar	5
Flex 90, radial	27
Abduction (0°, 45°, 90°)	**Exertion #**
Neutral, dorsal	25
Neutral, palmar	3
Neutral, ulnar	28
Neutral, radial	29
Abduct 45, dorsal	23
Abduct 45, palmar	17
Abduct 45, ulnar	12
Abduct 45, radial	14
Abduct 90, dorsal	4
Abduct 90, palmar	10
Abduct 90, ulnar	19
Abduct 90, radial	20
Subscapularis	**Exertion #**
Prone subscapularis	16
Lift-off	2
Belly-press	9
Infra/Teres	**Exertion #**
Prone infra/teres	13
Sitting infra/teres	6
Supraspinatus	**Exertion #**
Empty can	1
Blackburn	8
Full Can	21
Supra Neutral Abduct	15

Note that the ‘Exertion #’ is a method used to name the exertions (for simplicity in analysis), and is not the order in which the exertions were performed.

Appendix G

Further results of one-way ANOVAs performed on individual exertions for IR

Isolation (IR) of Infraspinatus – was shown in the methodology section, Figure 25. There were 334 total observations, and 14 missing observations.

Isolation (IR) of Supraspinatus:

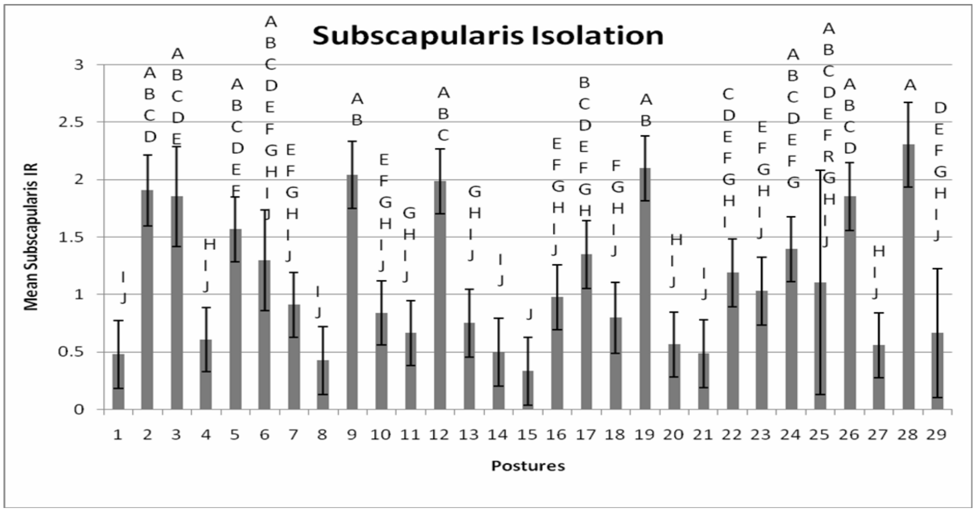
One-way ANOVA indicated that there was no statistical difference (p = 0.4059) between the mean IR of the supraspinatus of the 29 exertions. There were 249 total observations, and 99 missing observations.

Isolation (IR) of the Teres Minor:

One-way ANOVA indicated that there was no statistical difference (p = 0.567) between the mean IR of the teres minor of the 29 exertions. There were 280 total observations, and 68 missing observations.

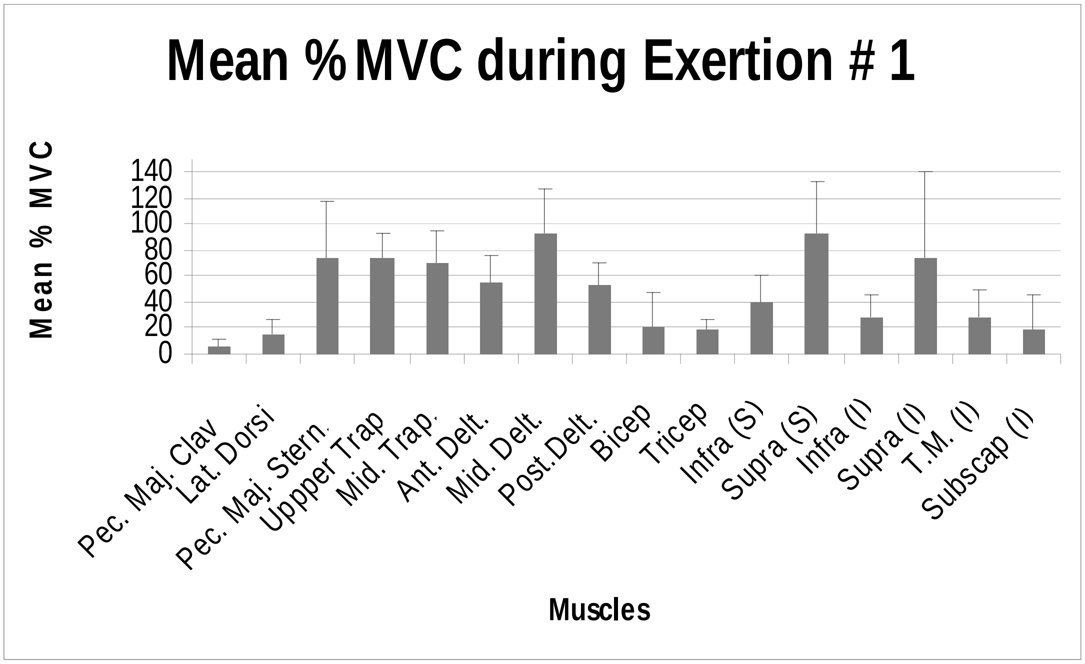
Isolation (IR) of the Subscapularis:

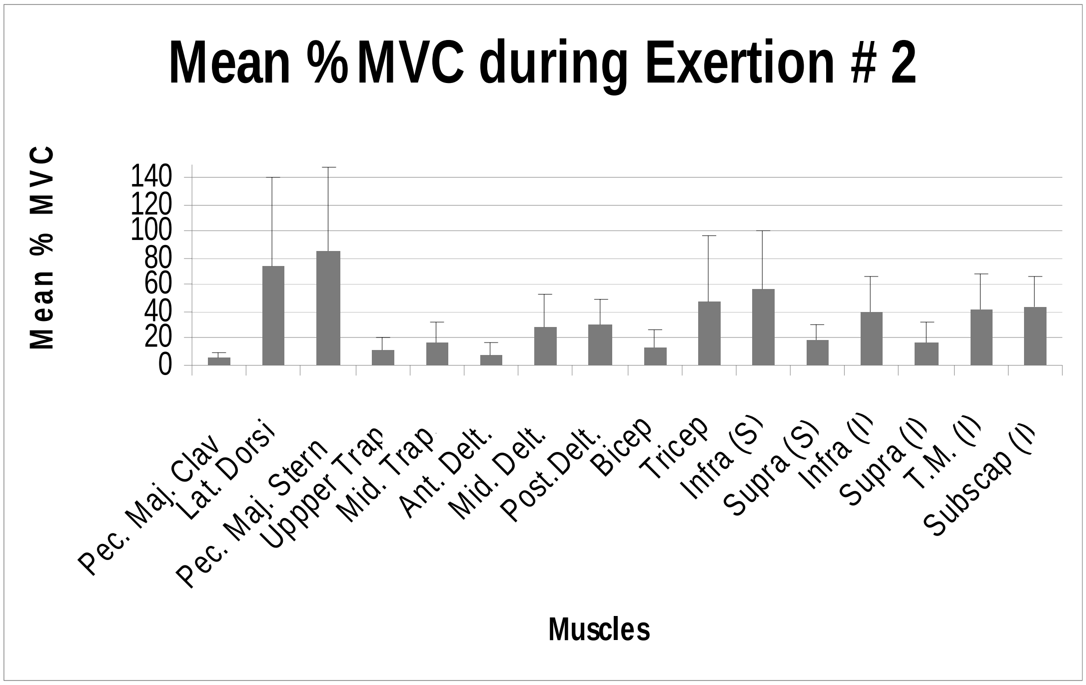
One-way ANOVA indicated that there was statistical difference (p<0.0001) between one or more of the mean IR of the subscapularis between the 29 exertions. There were a total of 294 total observation and 54 missing observations. Post hoc analysis (Student's T test) was performed to indicate the following levels between exertions (see Figure below - error bars represent ± 1 standard error):

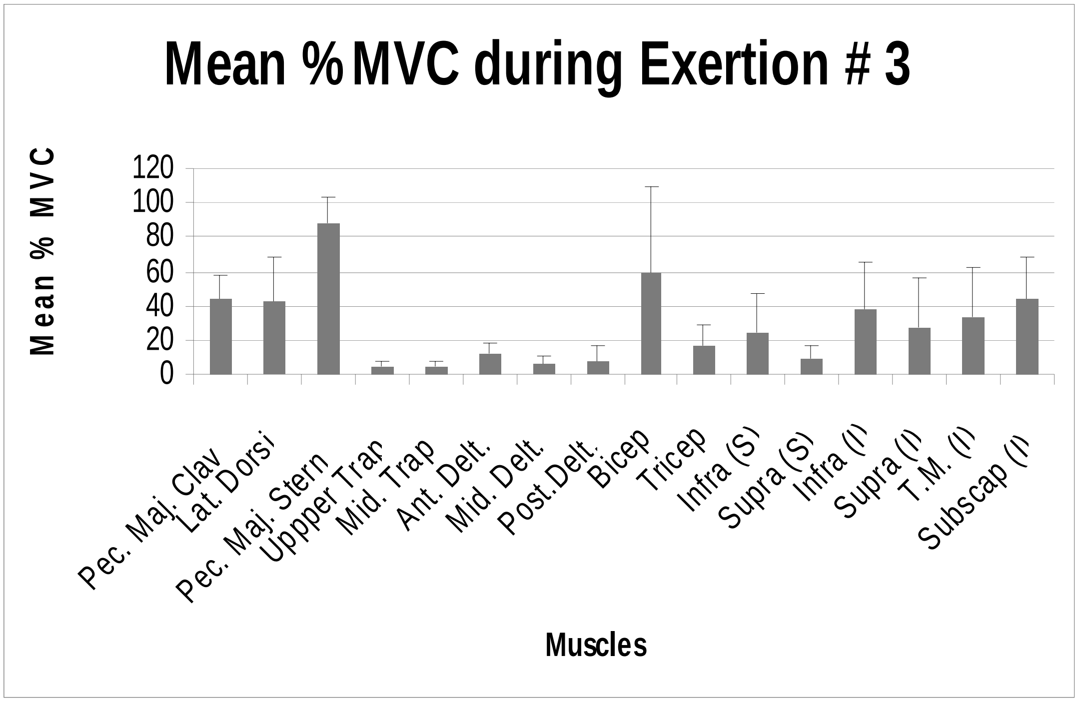


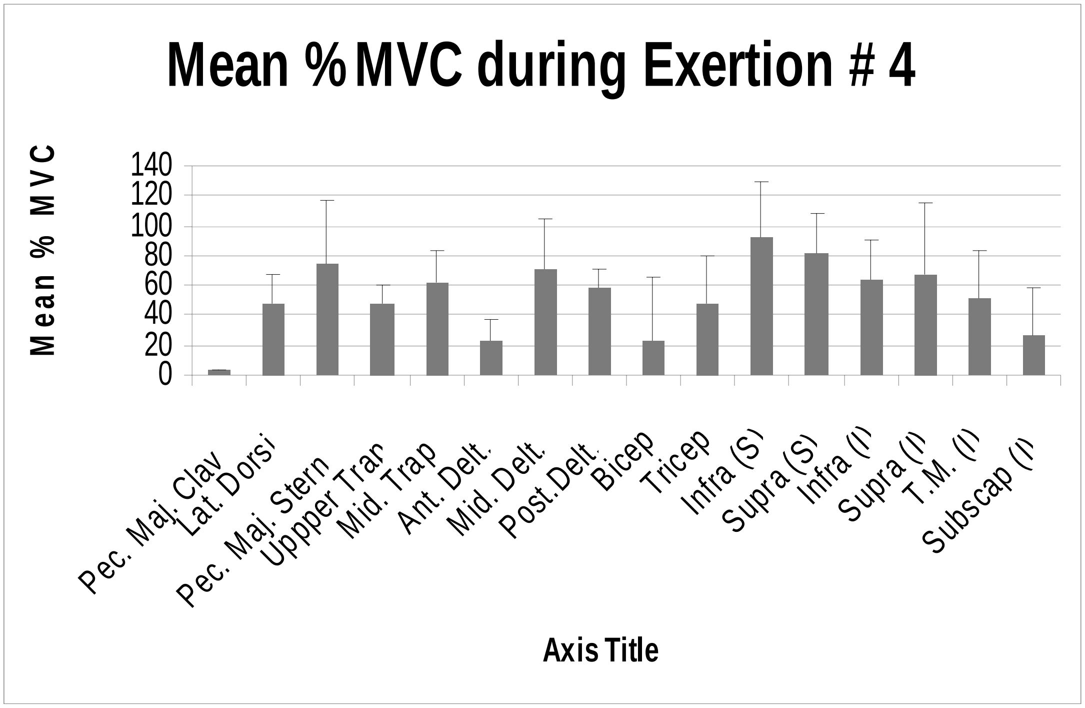
Appendix H Mean percent maximal voluntary contraction for each exertion

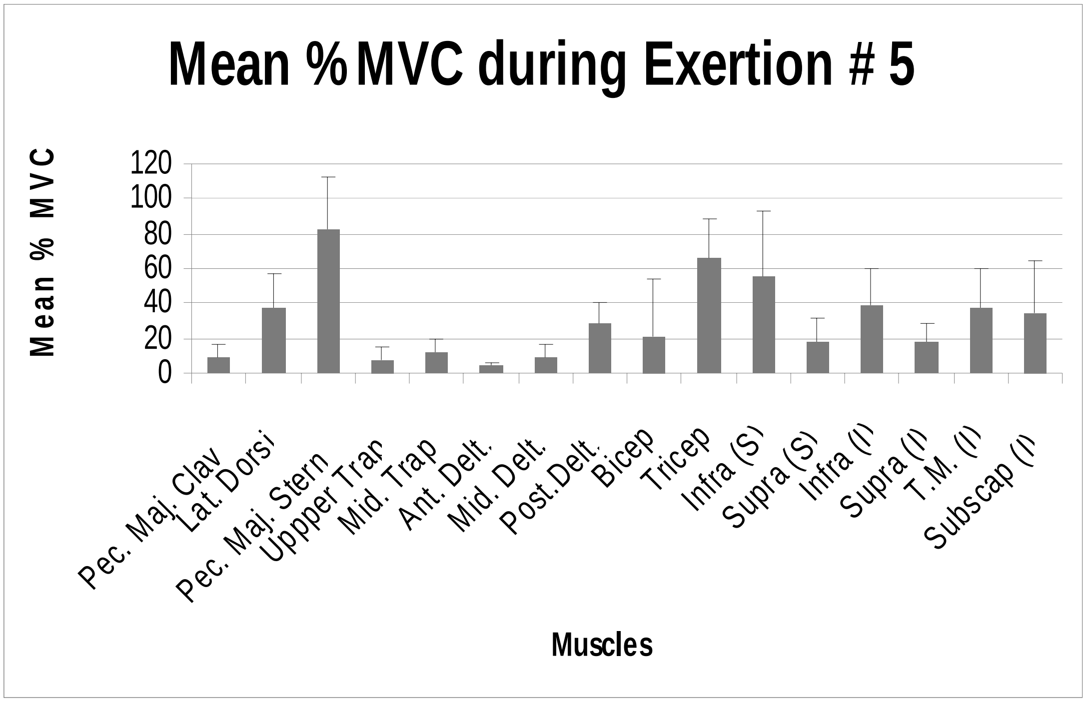
Posture	Pec Maj (clav)	Lat Dorsi	Pec Maj (stern)	Upper Trap	Mid Trap	Ant Delt	Mid Delt	Post Delt	Bicep	Tricep	Infra (S)	Supra (S)	Infra (W)	Supra (W)	T Minor (W)	Subscap (W)
1	6.1	15.4	74.5	73.3	69.3	55.2	93.7	52.3	21.1	19.5	39.6	93.3	28.4	73.6	28.8	19.8
2	6.5	73.5	85.8	10.8	17.6	8.3	29.1	30.0	13.3	47.7	57.7	18.4	40.5	17.6	42.5	42.9
3	43.7	43.0	87.6	4.1	4.1	12.6	5.6	7.8	58.9	16.9	24.4	8.7	38.1	27.4	34.1	44.0
4	2.7	48.5	73.8	48.5	62.2	23.0	70.1	58.4	22.2	47.8	92.9	80.7	63.0	68.2	51.1	26.8
5	9.7	38.2	83.2	8.0	11.6	3.9	9.2	28.3	20.9	66.1	56.1	18.0	39.1	18.3	37.8	34.7
6	4.7	25.7	71.4	25.9	34.8	22.2	36.4	33.2	17.3	26.9	83.9	52.7	58.0	36.1	44.7	34.4
7	33.4	16.0	75.9	51.7	30.8	60.9	43.5	16.0	67.2	10.2	38.3	56.8	34.2	47.2	37.5	33.1
8	11.9	15.6	77.3	60.6	55.6	51.1	55.5	30.3	67.0	9.7	25.1	87.0	22.2	63.7	22.9	13.8
9	13.4	49.5	74.4	15.5	13.2	7.1	22.4	22.2	63.9	9.6	29.3	23.8	26.7	19.1	28.7	44.8
10	28.6	14.0	76.3	24.1	23.2	30.8	22.9	12.3	40.2	9.2	18.3	32.1	33.9	29.7	29.2	20.1
11	4.9	28.3	79.2	40.3	48.7	32.3	55.9	48.7	30.8	26.5	79.7	71.8	47.2	52.4	47.7	24.5
12	18.1	60.8	78.4	4.9	9.1	6.1	7.9	17.1	30.1	61.8	39.2	13.6	38.3	23.0	33.9	50.9
13	2.7	49.6	80.8	40.2	56.1	13.1	54.1	58.9	18.2	32.2	104.6	84.1	82.5	39.8	63.8	34.0
14	6.6	14.7	69.4	61.4	49.2	45.7	57.8	30.5	55.4	10.3	33.0	75.1	24.7	55.3	25.7	17.0
15	7.1	14.3	71.8	71.0	62.3	54.2	73.7	36.0	58.7	13.8	32.7	90.7	26.7	54.3	26.4	12.2
16	3.9	80.6	87.6	19.0	35.9	11.2	56.0	55.2	8.1	37.4	69.9	37.7	56.0	36.0	42.7	33.7
17	28.9	15.9	75.4	25.6	17.2	37.0	21.0	8.5	50.1	8.9	19.6	28.1	24.0	34.1	26.5	31.4
18	5.1	40.4	75.9	42.3	43.6	33.7	61.8	61.5	25.8	35.4	85.2	74.0	51.9	49.6	45.3	30.0
19	16.2	48.6	78.7	9.1	14.2	5.4	7.3	17.7	26.5	56.2	35.9	18.1	37.7	26.7	41.0	56.6
20	8.9	15.0	72.6	61.4	49.2	49.8	59.8	27.0	57.2	14.7	28.8	73.7	23.4	35.9	26.2	16.6
21	12.1	15.7	66.9	72.6	52.1	60.7	69.6	30.1	61.9	11.7	33.2	89.6	26.9	64.2	26.3	17.2
22	55.7	15.5	84.7	24.1	16.4	45.7	13.9	5.9	72.1	11.0	15.4	27.3	34.4	33.7	23.9	31.9
23	2.5	64.4	71.2	37.1	49.8	18.8	57.2	51.4	14.6	45.8	102.9	68.3	62.6	53.2	42.2	40.7
24	48.9	16.7	83.3	9.9	6.0	30.4	8.4	3.9	53.2	10.8	14.1	9.8	42.6	22.9	47.1	35.7
25	3.3	20.5	73.8	38.9	36.9	27.7	47.5	37.4	19.1	25.0	67.8	50.7	43.1	38.8	38.8	45.4
26	7.0	49.8	77.7	5.0	7.3	3.6	11.4	30.0	7.6	71.1	57.2	17.1	37.0	18.3	38.4	48.2
27	30.9	17.6	72.1	66.0	43.9	75.5	56.1	22.9	79.3	13.8	40.8	80.2	31.9	59.1	38.2	24.7
28	3.9	88.8	69.7	8.2	20.8	5.9	24.8	41.8	4.9	71.8	89.9	30.1	57.3	26.1	48.2	58.0
29	27.4	17.5	77.8	29.2	17.6	44.7	31.3	9.5	64.6	8.7	29.5	27.3	33.9	28.5	25.4	15.8

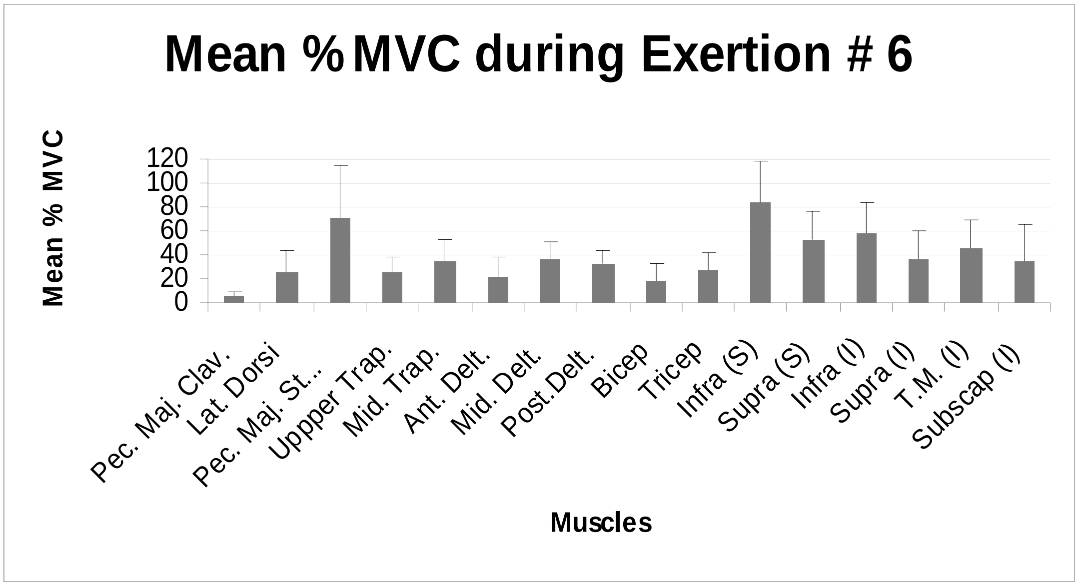

Mean %MVC during Exertion # 1
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

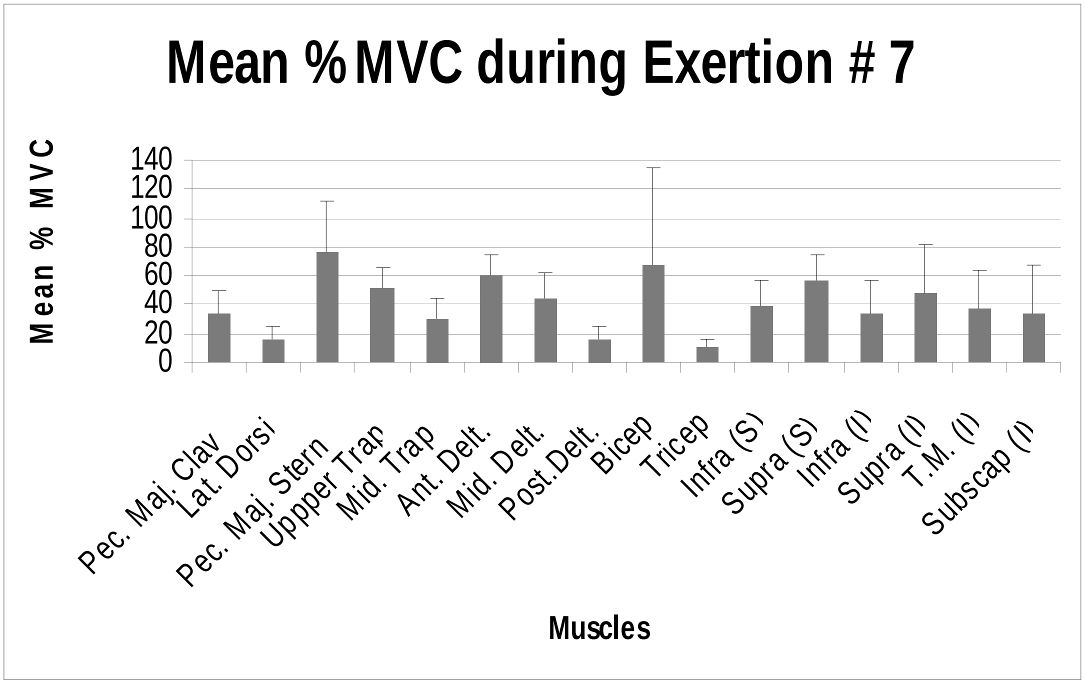

Mean %MVC during Exertion # 2
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

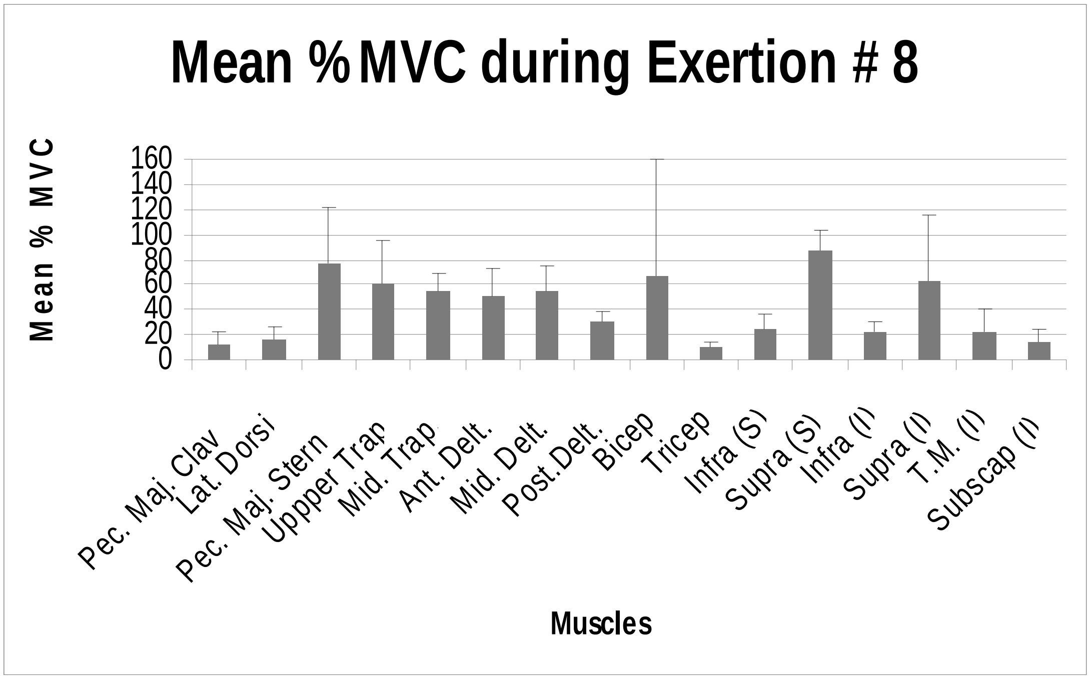

Mean %MVC during Exertion # 3
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I
Supra (I
T.M. (I
Subscap (I
Muscles

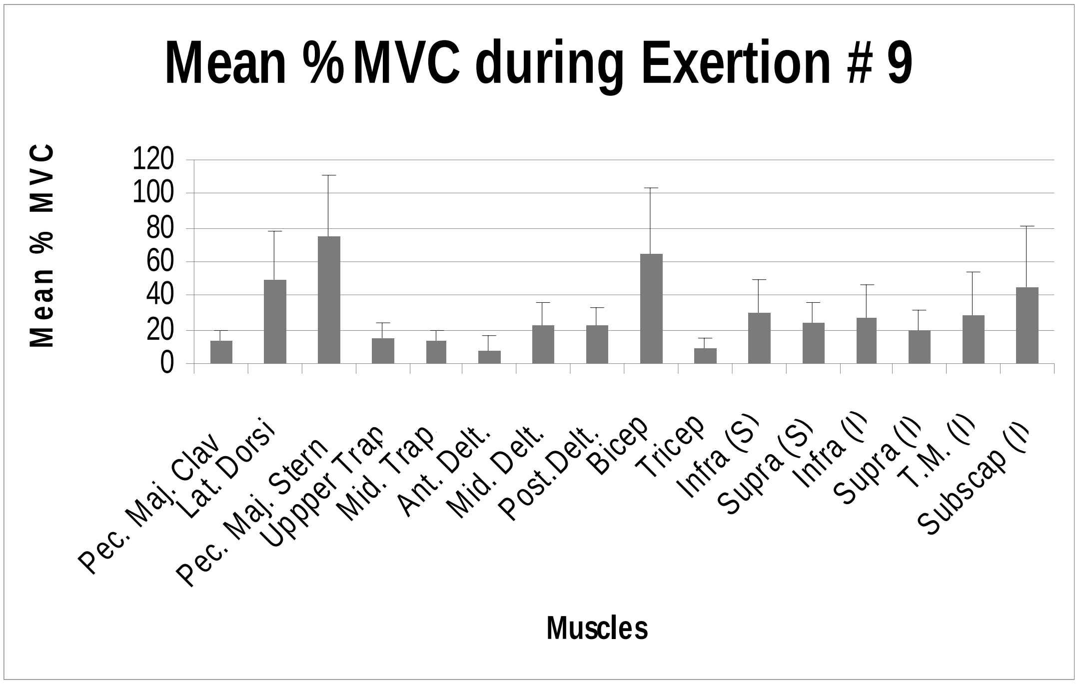

Mean %MVC during Exertion # 4
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I
Supra (I
T.M. (I
Subscap (I
Axis Title

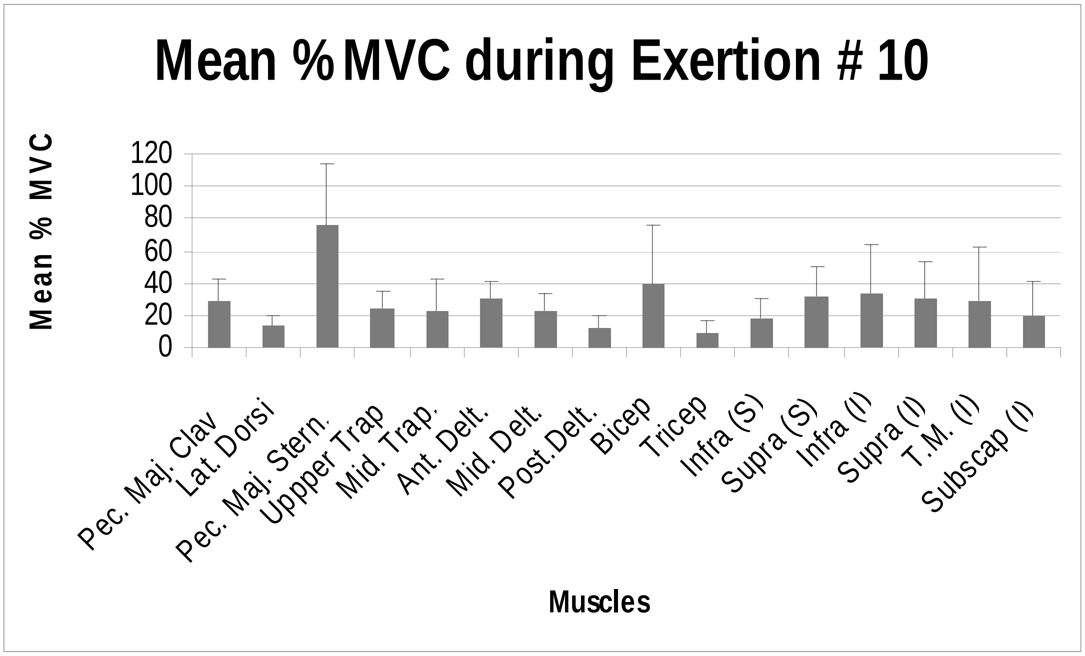

Mean %MVC during Exertion # 5

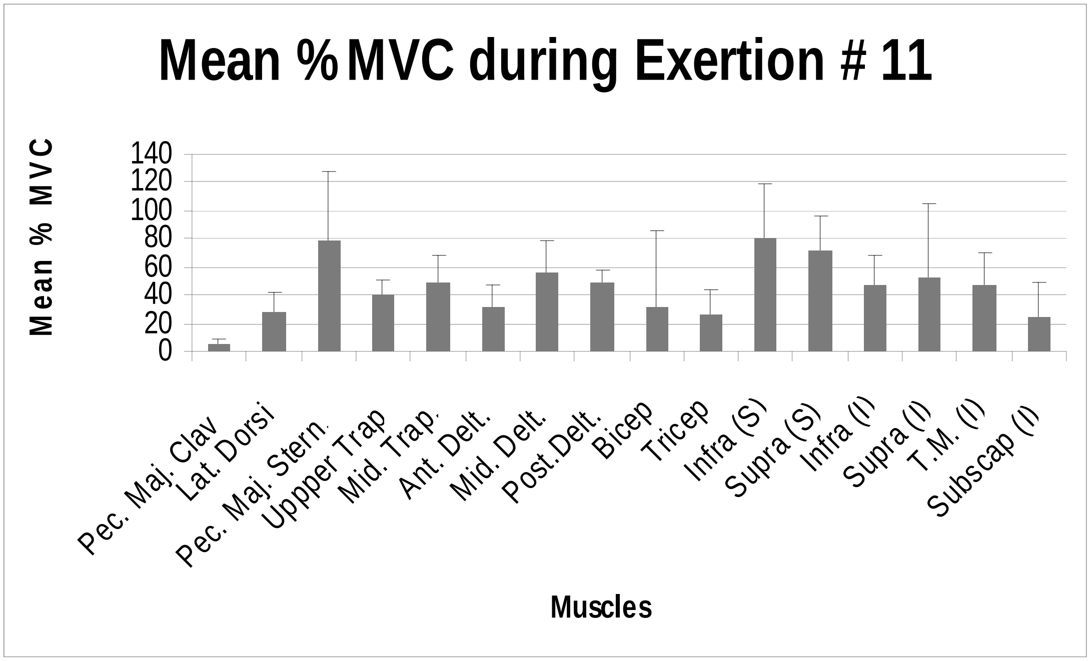

Mean %MVC during Exertion # 6

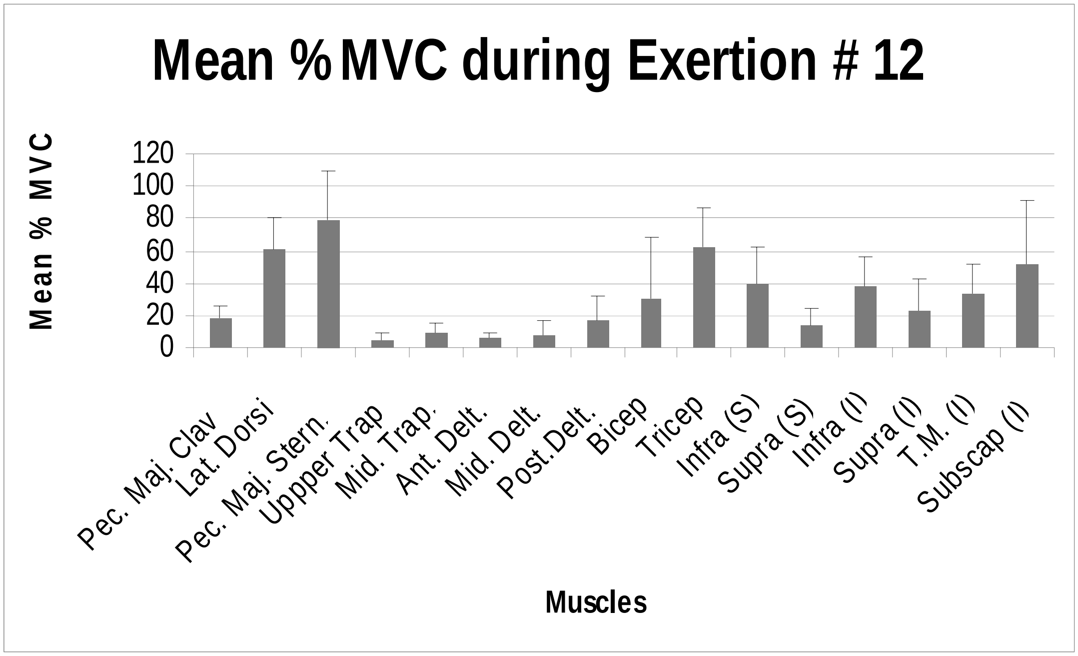

Mean % MVC during Exertion # 7
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

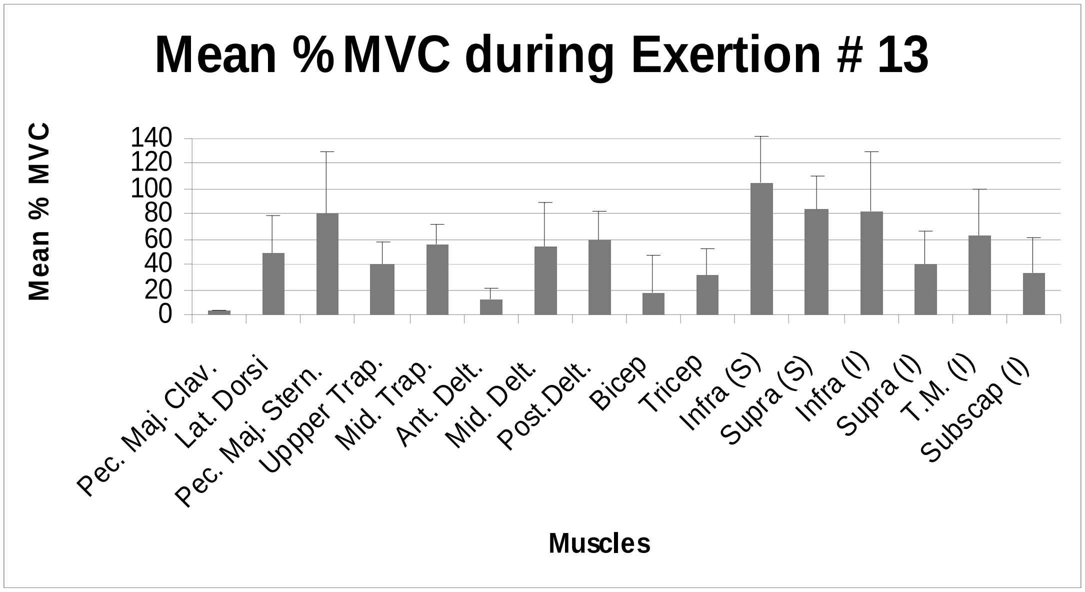

Mean % MVC during Exertion # 8
Mean % MVC
160
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

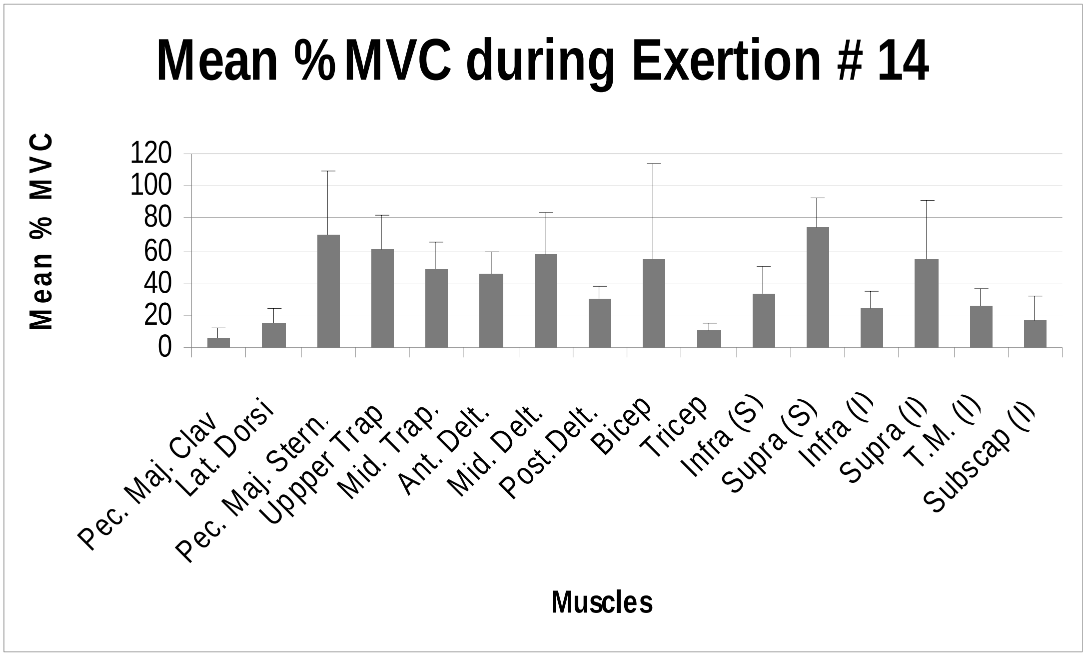

Mean %MVC during Exertion # 9
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

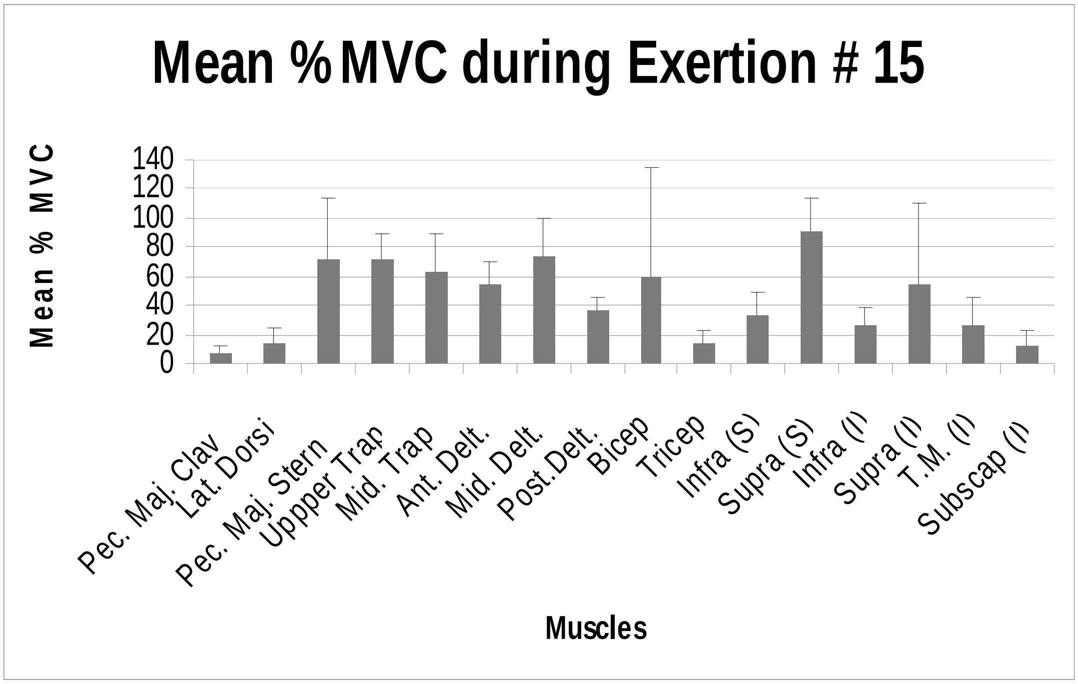

Mean %MVC during Exertion # 10
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

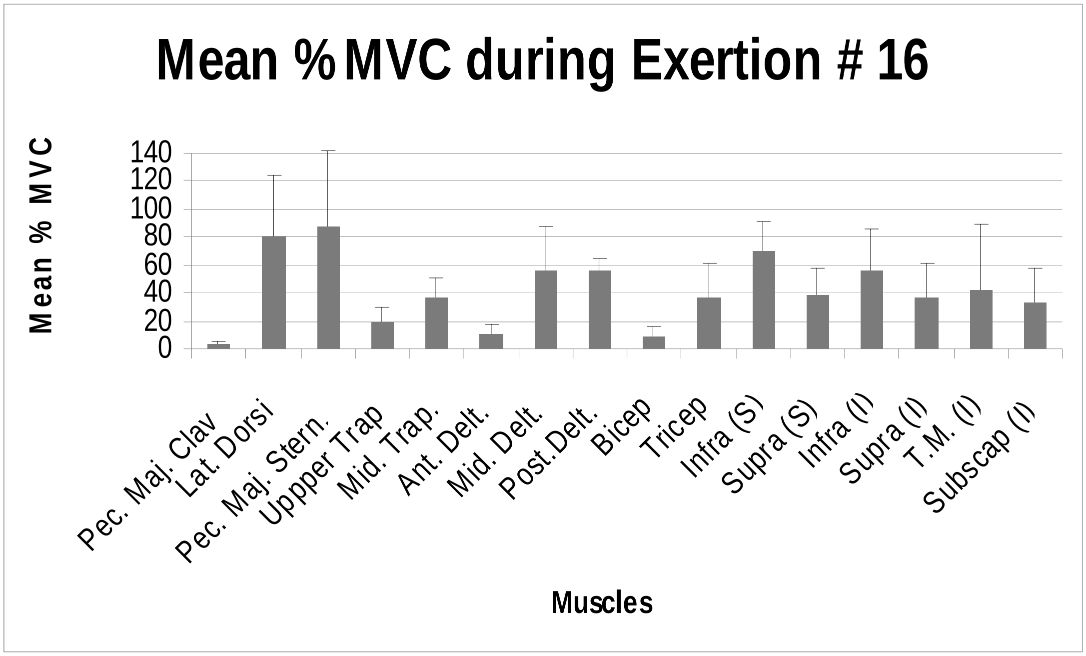

Mean %MVC during Exertion # 11
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

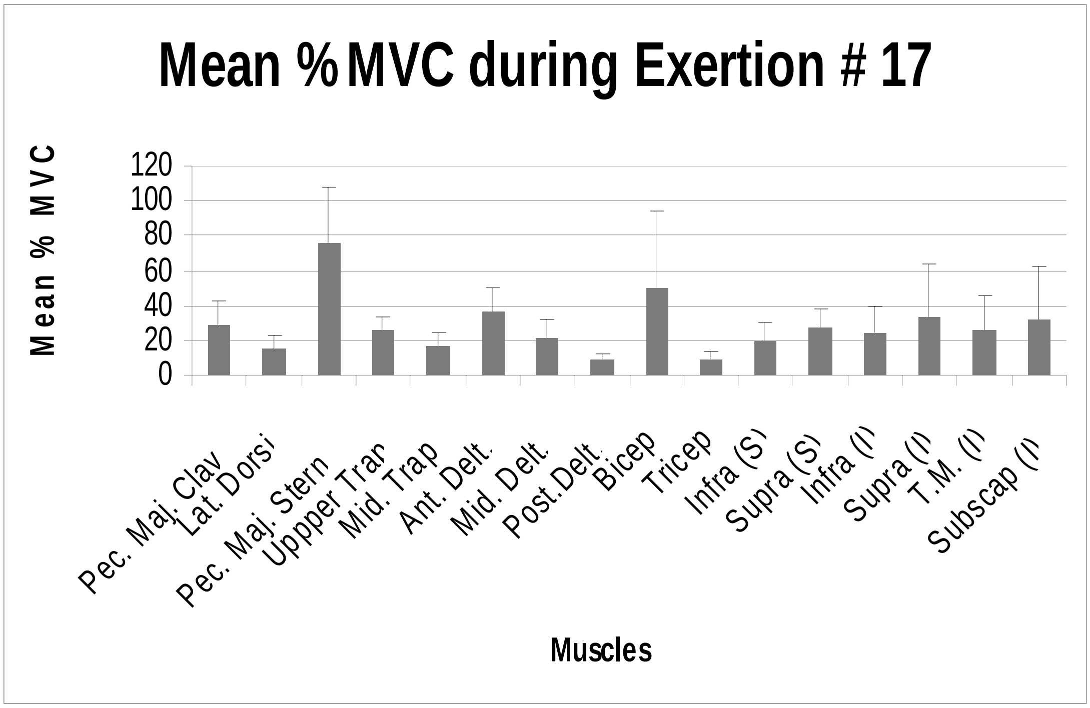

Mean %MVC during Exertion # 12
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

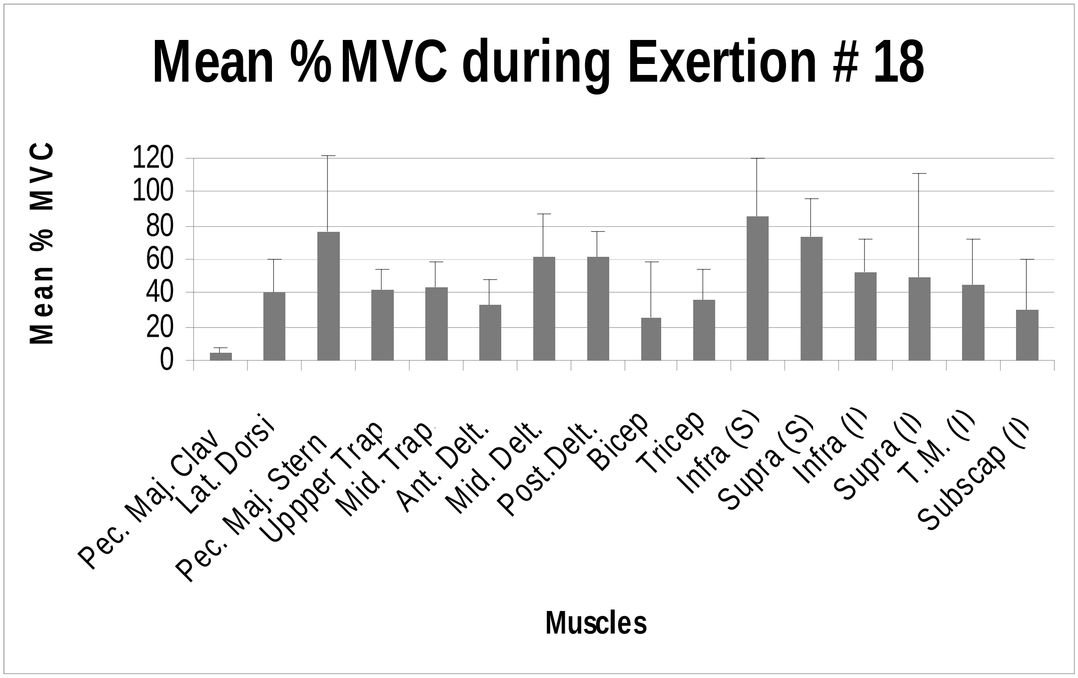

Mean %MVC during Exertion # 13
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav.
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap.
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

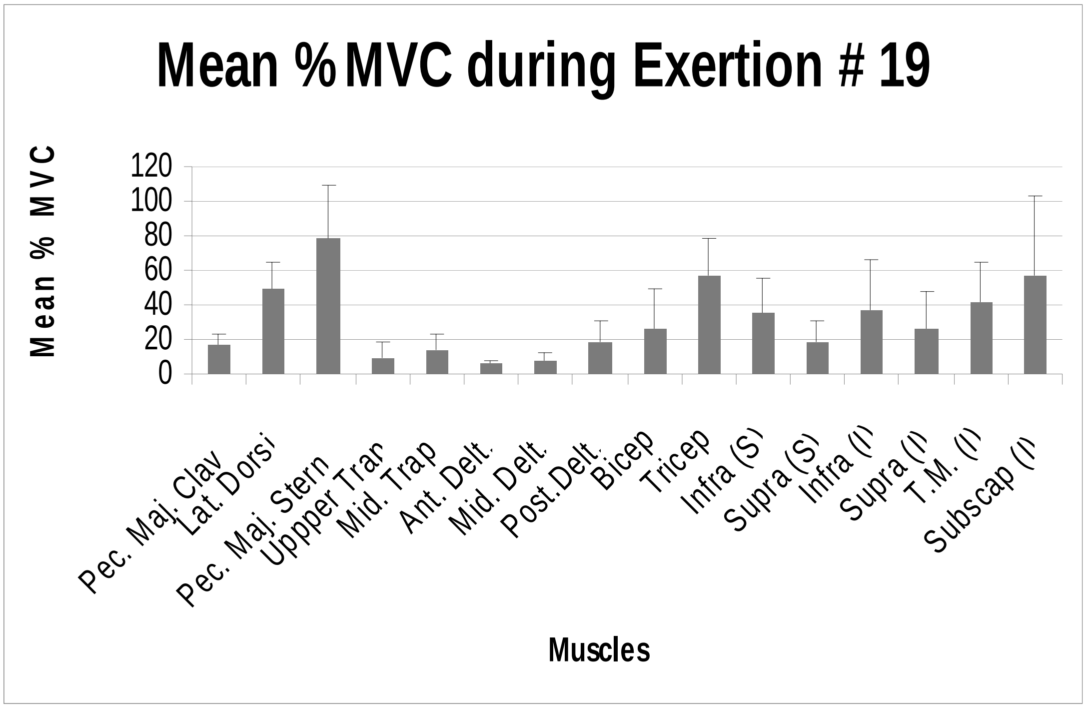

Mean %MVC during Exertion # 14
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

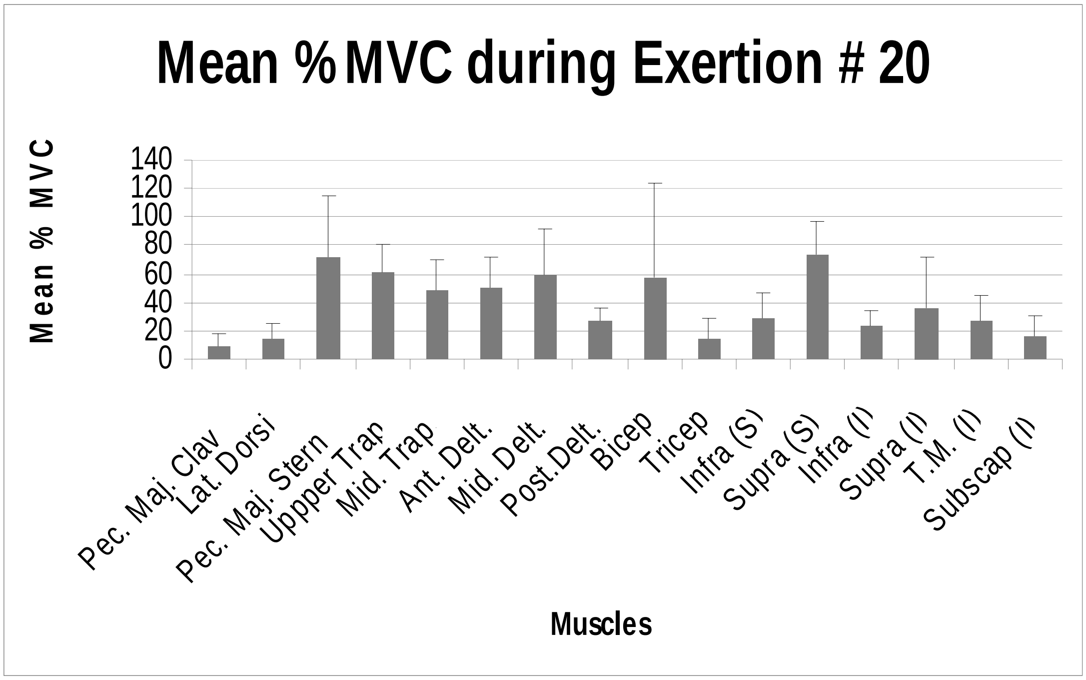

Mean %MVC during Exertion # 15
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

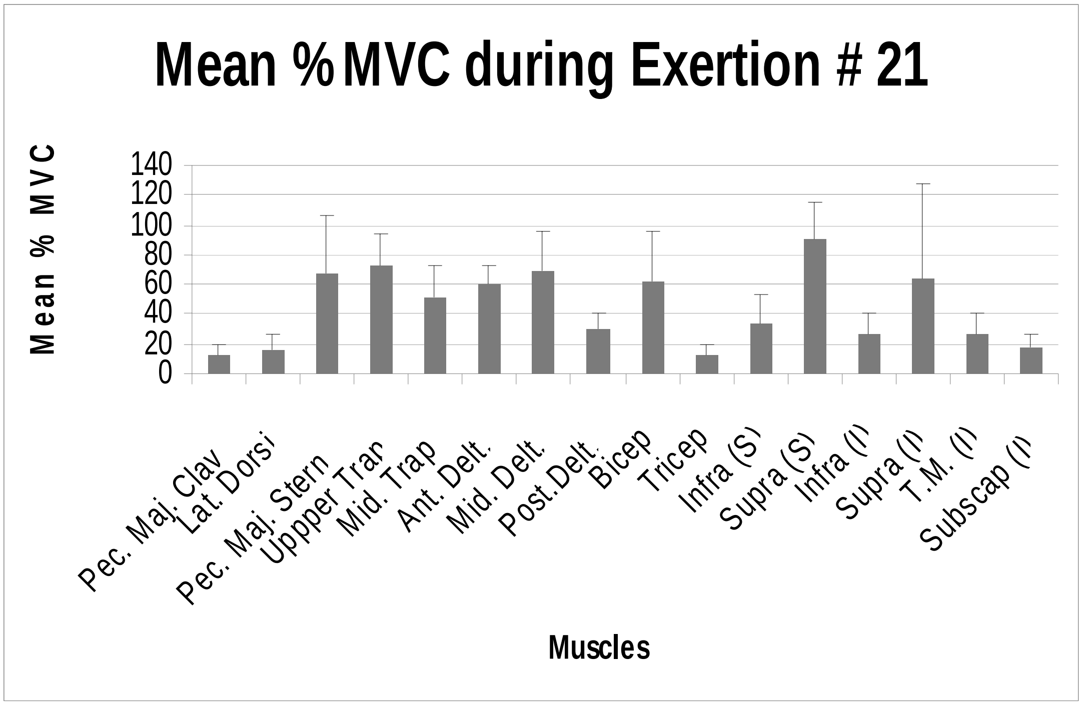

Mean %MVC during Exertion # 16
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern.
Uppper Trap
Mid. Trap.
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

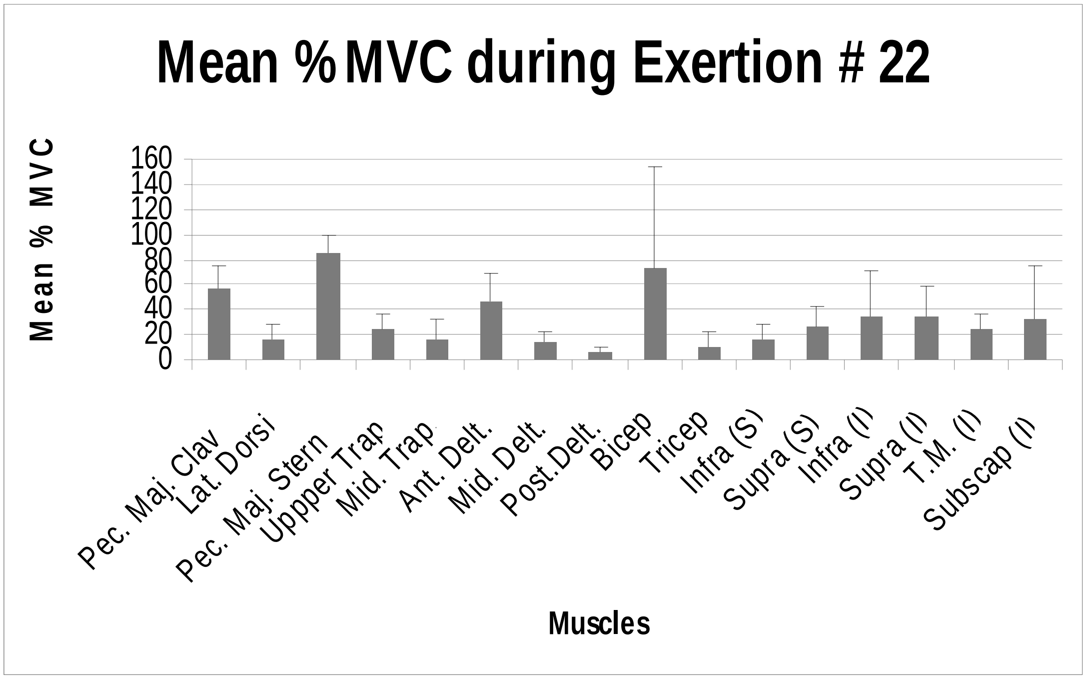

Mean % MVC during Exertion # 17
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

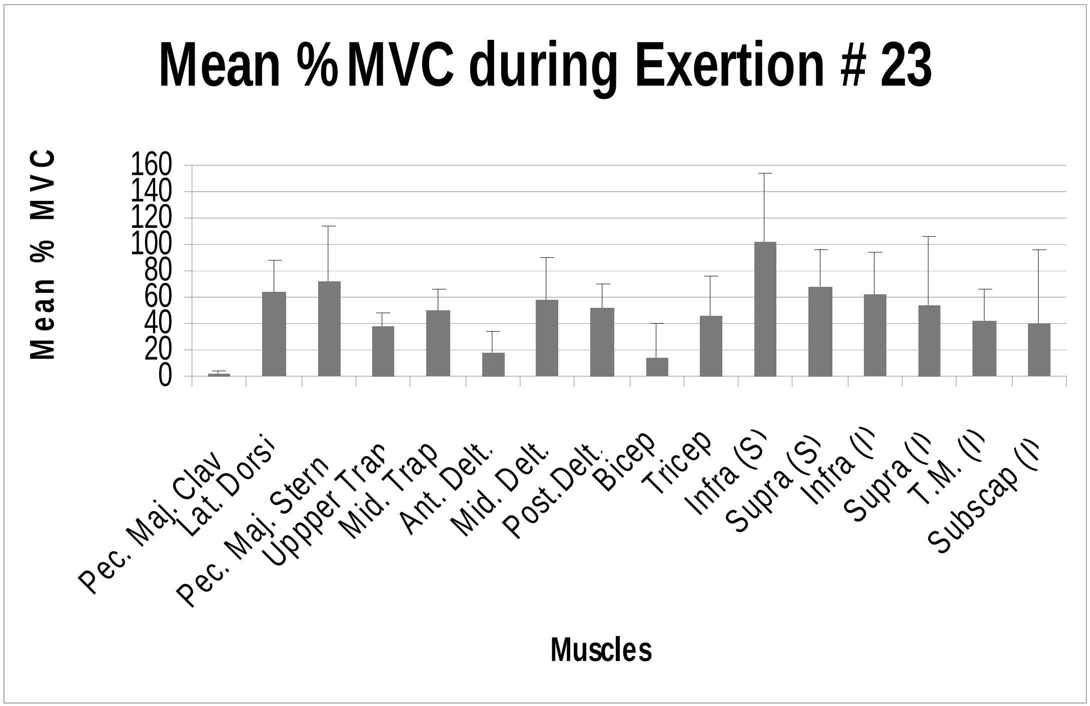

Mean % MVC during Exertion # 18
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

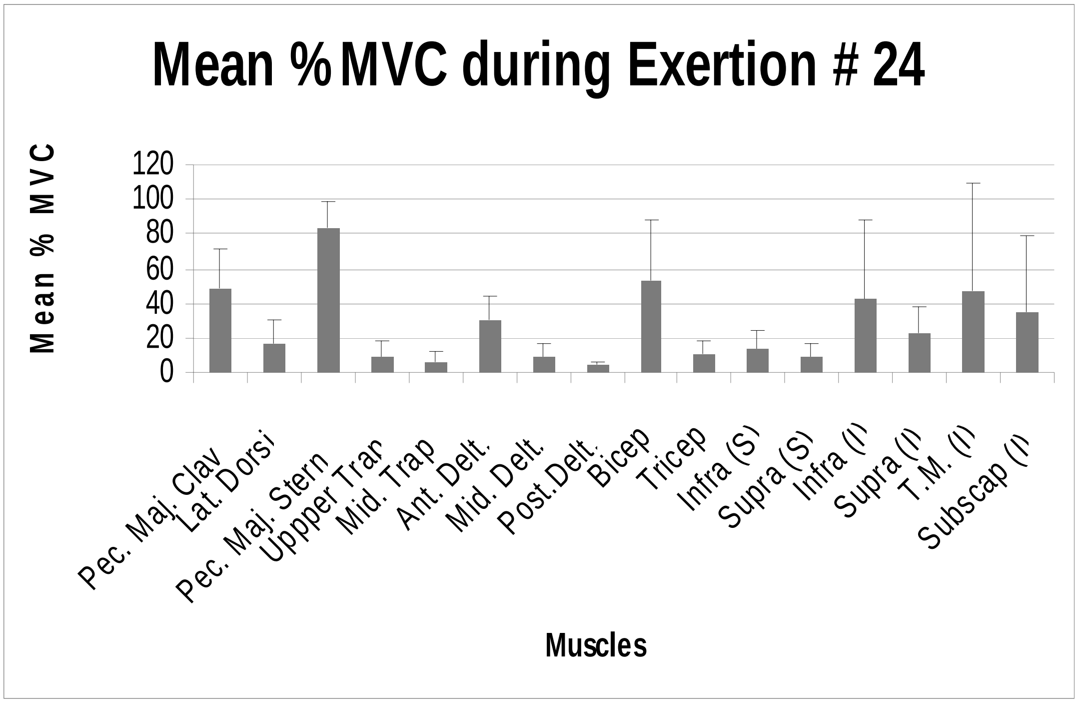

Mean % MVC during Exertion # 19
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

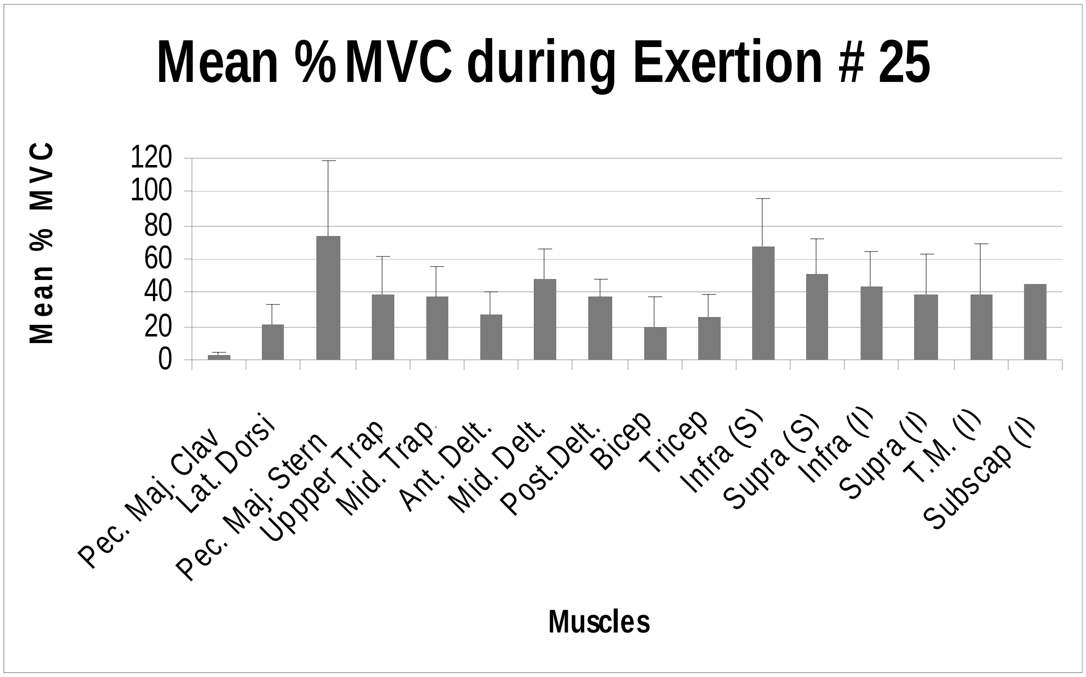

Mean % MVC during Exertion # 20
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

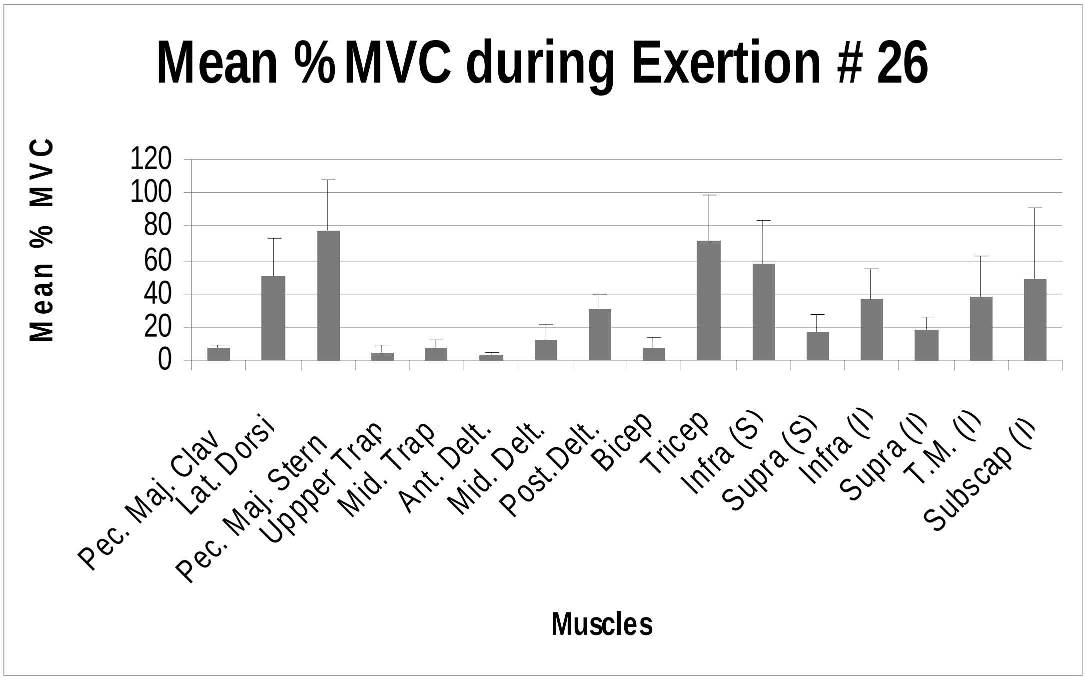

Mean % MVC during Exertion # 21
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S
Supra (S
Infra (I
Supra (I
T.M. (I
Subscap (I
Muscles

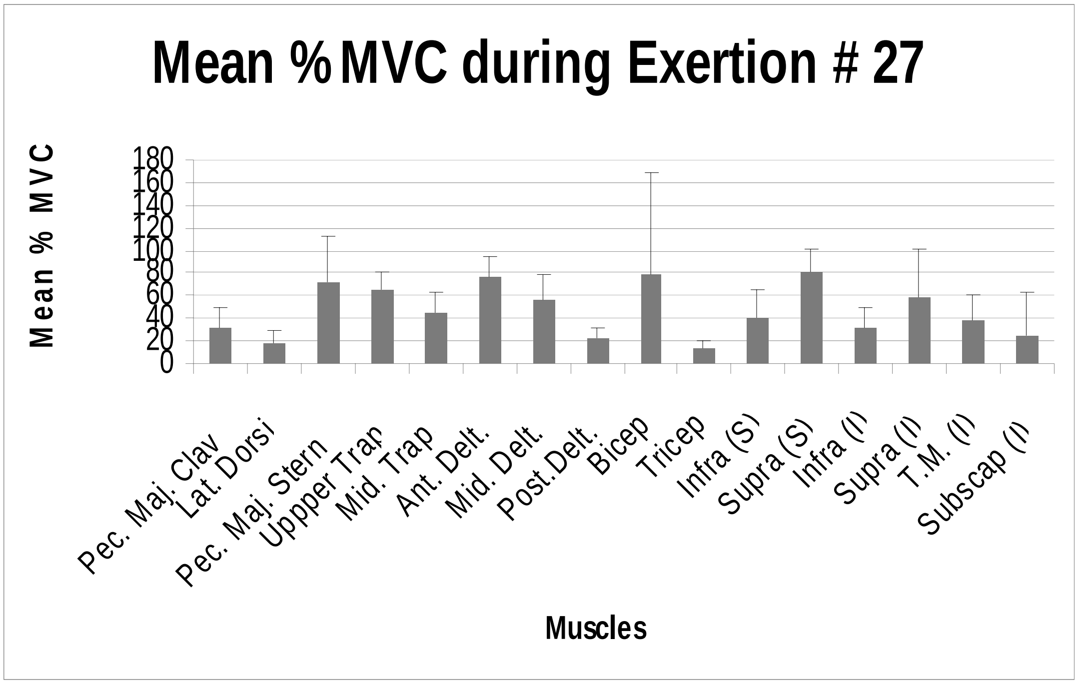

Mean % MVC during Exertion # 22
Mean % MVC
160
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I
Supra (I
T.M. (I
Subscap (I
Muscles

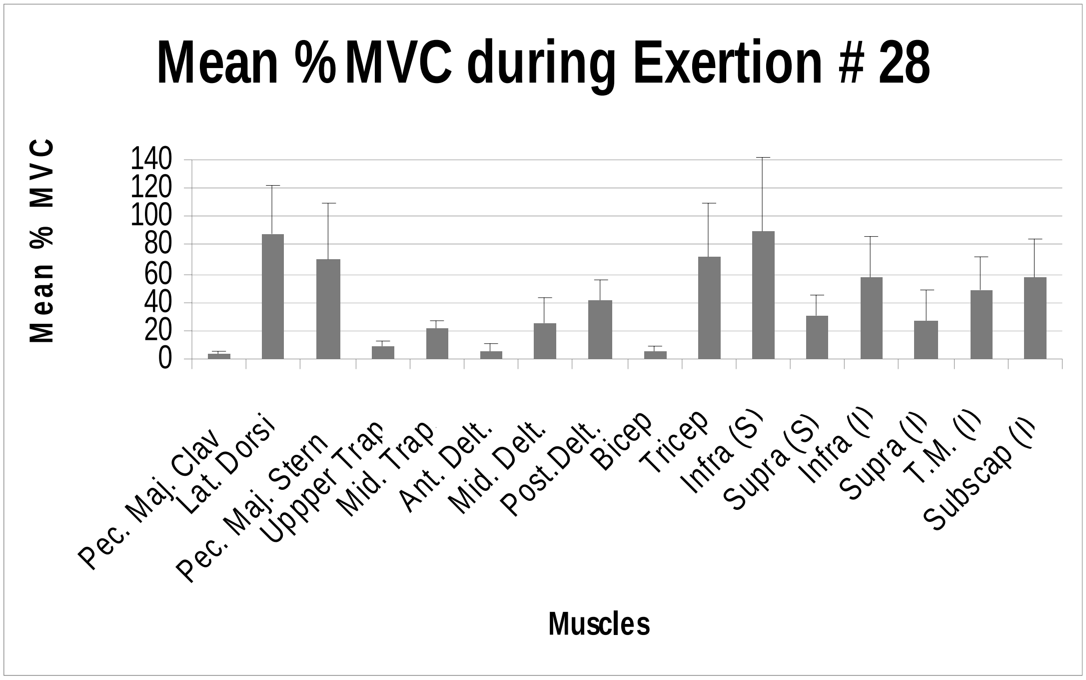

Mean %MVC during Exertion # 23
Mean % MVC
160
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

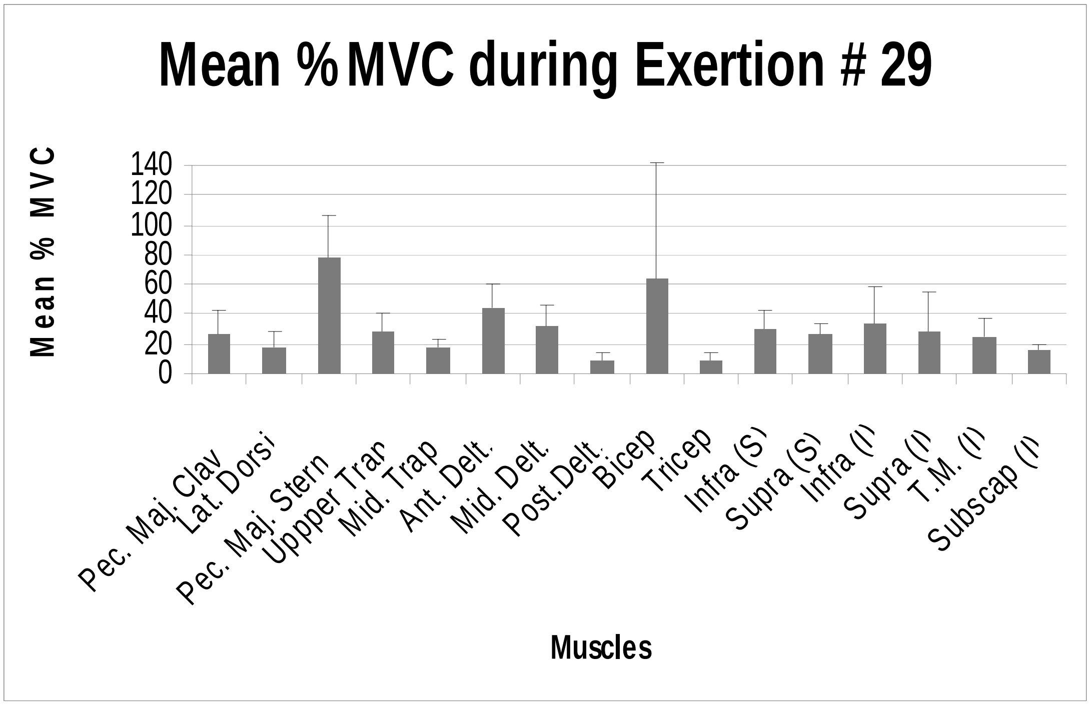

Mean %MVC during Exertion # 24
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles


Mean % MVC during Exertion # 25
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

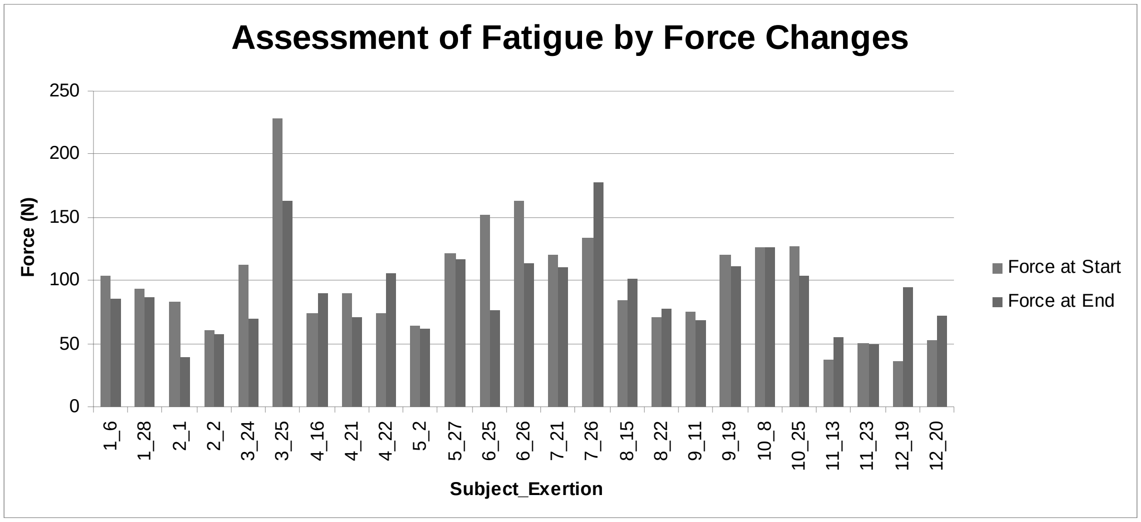

Mean % MVC during Exertion # 26
Mean % MVC
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles


Mean %MVC during Exertion # 27
Mean % MVC
180
160
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles


Mean %MVC during Exertion # 28
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles


Mean %MVC during Exertion # 29
Mean % MVC
140
120
100
80
60
40
20
0
Pec. Maj. Clav
Lat. Dorsi
Pec. Maj. Stern
Uppper Trap
Mid. Trap
Ant. Delt.
Mid. Delt.
Post.Delt.
Bicep
Tricep
Infra (S)
Supra (S)
Infra (I)
Supra (I)
T.M. (I)
Subscap (I)
Muscles

Appendix I Initial and final force outputs



Appendix J

Further details of one-way ANOVA tests performed on IR, IR2 and IR3

There were a total of 348 isolation ratios per rotator cuff muscle inputted into the ANOVA tests (12 subjects * 29 exertions). Some isolation ratios were omitted from the ANOVA analysis due to EMG artifact. Due to the small number of variables in the denominator of IR2 and IR3, the absence of variables due to artifact could significantly bias the ratio. For this reason isolation ratios (IR2 or IR3) were not produced unless there were two or more muscles in the denominator of IR2 and IR3 ratios for that trial. The table below indicates the number of missing observations, due to artifact, when ANOVA tests were performed on isolation ratios (IR, IR2, IR3) divided into the seven exertion groups:

Isolation Ratio	Observations	Missing	Total
IR infra	334	14	348
IR supra	249	99	348
IR teres	280	68	348
IR subscap	294	54	348
IR2 infra	295	53	348
IR2 supra	236	112	348
IR2 teres	260	88	348
IR2 subscap	281	67	348
IR3 infra	316	32	348
IR3 supra	236	112	348
IR3 teres	269	79	348
IR3 subscap	294	54	348

Appendix K Photographs of pilot testing on a female subject

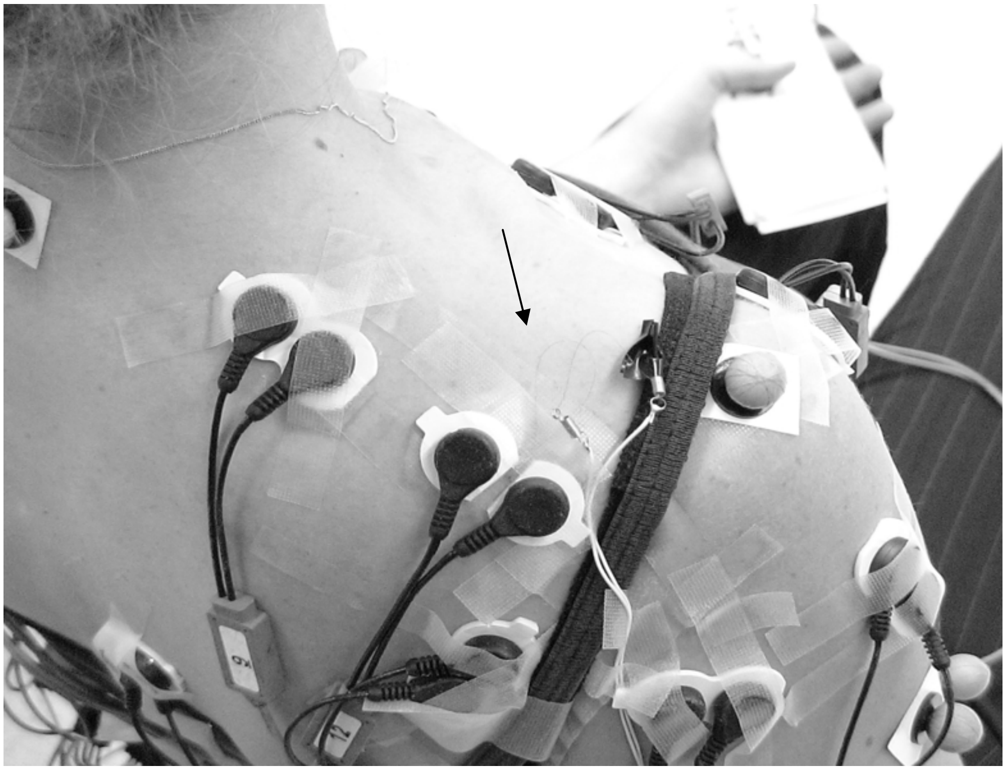


Figure 1: Supraspinatus Surface & Intramuscular Electrode Placement (see arrow)

Figure 2: Supraspinatus Surface & Intramuscular Electrode Placement

Figure 3: Infraspinatus Surface & Intramuscular Electrode Placement

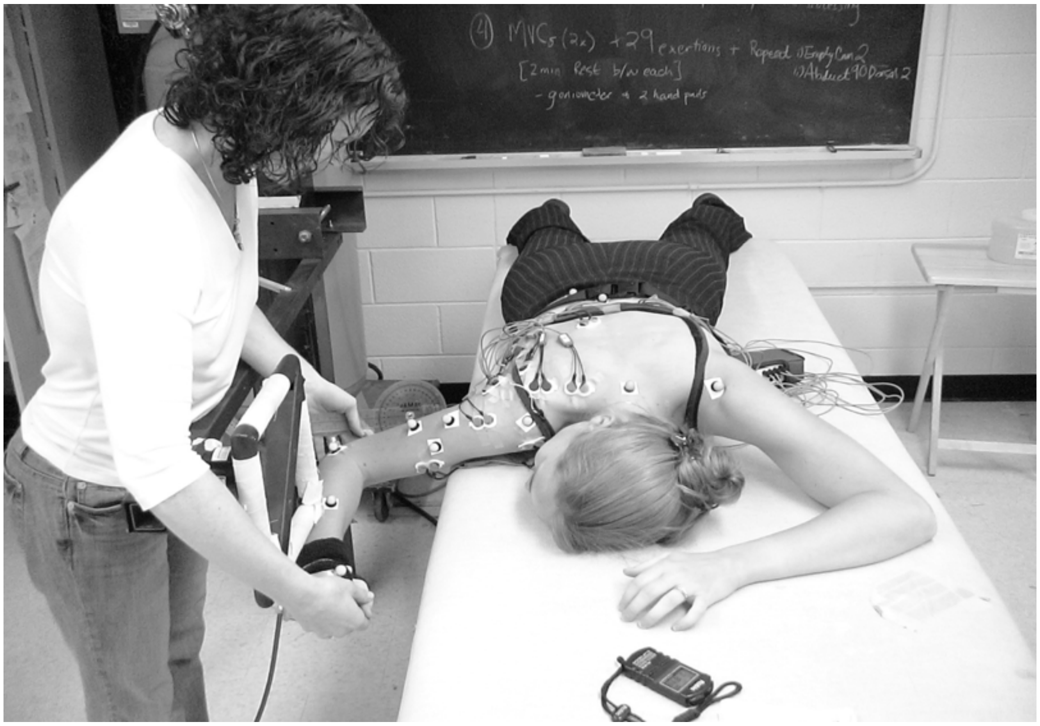


Figure 4: Exertion #13 Confirmed with Goniometry

Figure 5: Exertion # 14

Figure 6: Exertion #20

Appendix L Mean and median power frequency values pre and post testing

Mean power frequency values (Hz) pre experimental testing

Subject	Posture	Pec Maj (clav)	Lat Dorsi	Upper Trap	Mid Trap	Ant Delt	Mid Delt	Post Delt	Bicep	Tricep	Infra (S)	Supra (S)	Infra (W)	Supra (W)	T Minor (W)	Subscap (W)
1	28	73.9	81.9	55.5	67.4	84.7	73.4	76.9	106.8	124.1	64.6	71.2	127.0	37.1	65.4	50.7
1	6	73.1	80.0	88.5	83.6	66.7	68.1	62.0	70.0	85.7	60.5	77.7	110.9	58.2	114.3	11.1
2	1	51.1	49.5	79.5	75.2	70.8	90.8	72.2	59.5	65.9	85.4	88.2	98.8	17.5	61.2	17.5
2	2	78.2	67.7	58.6	83.0	56.1	80.1	85.3	77.0	78.4	78.2	90.2	109.1	57.5	88.1	
3	24	55.9	61.5	62.4	55.3	61.3	60.6	64.2	58.4	56.1	67.9	63.5	36.9	17.0	53.0	52.5
3	25	51.4	61.9	76.5	74.4	61.2	69.8	71.2	55.1	82.5	65.9	95.3	67.4	115.7	64.9	
4	16	65.8	103.9	84.4	127.7	90.0	92.3	94.1	89.3	96.6	78.6	93.7	213.5			231.1
4	21	66.1	65.8	73.3	85.1	121.4	97.2	89.5	63.0	82.2	103.9	71.7	167.7			230.8
4	22	86.6	62.4	80.1	81.8	99.3	74.5	54.1	73.1	61.2	93.0	76.5	57.9	31.2	140.4	
5	2	61.9	71.0	54.1	82.4	53.2	107.6	65.8	76.6	81.6	56.4	66.7	24.6			
5	27	85.8	62.4	79.2	74.7	94.4	111.1	70.4	78.0	154.7	92.2	90.1	63.9		15.3	57.2
6	25	56.1	81.7	80.2	101.1	84.8	74.5	75.0	64.0	91.2	80.9	117.9	94.2		143.9	
6	26	51.1	70.8	63.4	68.5	70.8	70.4	59.8	55.2	73.0	62.8	63.5	81.0			16.3
7	21	52.1	39.1	97.9	72.4	79.5	72.0	71.0	99.7	75.0	105.8	78.4	107.2	205.2		
7	26	40.1	60.0	52.0	63.6	55.8	54.5	58.8	101.2	79.7	42.9	56.6	228.7	3.1	3.4	14.7
8	15	63.8	61.1	71.4	69.3	80.2	82.8	77.9	65.6	81.8	82.8	79.0	99.2			
8	22	87.8	49.8	73.8	65.9	56.3	65.9	50.5	58.1	64.2	71.6	85.8	46.3	13.0		14.2
9	11	56.9	95.1	74.2	62.8	60.9	76.1	65.4	62.9	88.2	102.6	74.1	40.6	112.6	7.9	170.1
9	19	30.9	81.2	75.8	61.5	31.8	63.8	71.0	73.0	92.6	54.3	79.0	12.5	46.9	11.2	58.1
10	25	80.7	56.6	86.4	72.5	109.8	95.1	82.8	89.0	116.7	86.3	69.6	79.3	114.2		
10	8	89.4	77.3	80.7	57.5	84.6	105.4	67.5	80.0	60.0	113.3	62.1	87.0	125.4	182.2	99.2
11	13	100.3	53.8	68.7	64.9	73.4	74.6	73.8	65.5	66.7	57.9	69.7	113.0		56.7	36.1
11	23	88.7	95.7	58.6	64.2	76.9	72.4	67.8	78.0	91.4	53.2	78.8	114.7			43.8
12	19	36.7	62.6	57.0	40.3	55.7	75.2	58.4	46.2	75.6	85.5	56.9	185.3	6.6	132.8	234.5
12	20	56.6	51.2	82.9	58.9	73.6	71.3	56.9	55.6	81.7	119.3	66.7	176.1	99.1	81.2	15.9

Mean power frequency values (Hz) post experimental testing

Subject	Posture	Pec Maj (clav)	Lat Dorsi	Upper Trap	Mid Trap	Ant Delt	Mid Delt	Post Delt	Bicep	Tricep	Infra (S)	Supra (S)	Infra (W)	Supra (W)	T Minor (W)	Subscap (W)
1	28	41.7	82.8	56.4	48.3	90.3	78.6	77.6	101.3	115.8	59.4	68.5	122.3	40.1	76.6	
1	6	60.5	66.8	82.0	86.6	59.0	61.3	63.0	60.4	100.7	58.9	77.8	104.1	64.1	100.7	
2	1	62.8	47.1	79.8	77.5	68.1	88.4	62.9	54.5	85.0	72.4	94.9	90.2	18.8	52.3	
2	2	76.7	61.6	49.2	78.0	51.5	80.9	79.6	59.8	74.0	72.3	87.7	120.4	40.3	92.8	95.4
3	24	57.6	67.5	63.7	64.2	64.7	67.4	64.7	54.0	63.7	75.5	77.4	40.9	31.4	8.5	50.7
3	25	52.4	64.1	67.3	60.9	62.1	81.2	71.6	66.2	80.1	63.5	84.0	61.4	121.1	18.0	
4	16	67.1	127.6	84.1	123.0	104.0	100.6	101.4	55.5	99.7	80.3	95.2	168.5	99.3	176.9	129.1
4	21	68.1	101.9	76.7	93.4	127.9	111.3	88.2	65.3	78.2	92.0	77.1	157.6	50.1	222.7	
4	22	82.6	66.1	74.6	73.0	101.3	70.1	51.3	68.1	52.5	99.1	68.7	53.6	15.1	138.7	46.1
5	2	68.6	74.7	50.8	63.5	49.0	104.5	58.5	71.8	103.2	59.3	58.9		14.9		
5	27	80.7	68.4	81.6	79.6	98.2	114.1	69.3	66.3	161.8	106.6	93.5		41.5	16.8	53.9
6	25	44.8	71.3	75.1	99.6	72.7	71.1	72.2	61.8	103.6	64.2	108.7	37.1	35.2	110.6	
6	26	50.0	66.4	70.3	67.3	78.6	68.9	50.8	57.1	80.0	64.0	94.0	95.3		88.2	37.0
7	21	53.0	36.7	95.9	68.6	68.5	65.4	63.7	79.9	69.8	116.8	72.9	111.0		7.0	17.4
7	26	33.3	62.2	52.9	56.8	59.8	56.1	62.2	63.2	82.9	43.6	61.2	229.8			12.5
8	15	52.4	53.5	71.3	68.0	74.1	85.2	71.4	59.1	84.9	79.4	78.8	87.0			
8	22	87.8	49.8	73.8	65.9	56.3	65.9	50.5	58.1	64.2	71.6	85.8	46.3	13.0		14.2
9	11	54.9	66.1	80.5	63.2	60.0	73.2	75.3	105.1	96.0	81.6	82.0	52.3		11.9	36.1
9	19	31.7	85.8	62.5	67.6	33.9	77.9	70.4	65.5	92.9	60.7	80.6	11.3	73.5		58.3
10	25	88.7	63.2	84.0	70.7	122.6	97.8	74.3	82.0	82.6	86.9	66.3	55.5		57.1	31.8
10	8	90.8	65.8	77.6	57.5	89.9	102.1	67.6	84.8	68.6	99.6	63.3			188.7	
11	13	97.1	71.9	74.2	71.2	73.4	76.5	75.2	66.2	61.9	57.2	71.0	102.4			
11	23	99.2	79.0	56.0	68.2	79.1	75.2	72.4	84.4	97.1	55.1	77.1	126.9	67.7	107.9	31.7
12	19	48.1	61.9	63.3	41.3	48.0	55.1	58.9	45.2	85.8	87.9	60.3	122.9		152.3	
12	20	54.2	49.3	77.8	57.2	70.4	71.6	56.5	50.8	77.9	105.9	63.2	108.8	110.7	122.4	

Median power frequency values (Hz) pre experimental testing

Subject	Posture	Pec Maj (clav)	Lat Dorsi	Upper Trap	Mid Trap	Ant Delt	Mid Delt	Post Delt	Bicep	Tricep	Infra (S)	Supra (S)	Infra (W)	Supra (W)	T Minor (W)	Subscap (W)
1	28	55.2	72.1	46.0	60.2	69.5	59.7	71.7	85.8	111.7	55.1	56.8	96.0	15.0	56.3	38.9
1	6	58.9	41.4	83.7	70.9	58.7	47.8	54.8	61.3	68.9	49.1	62.4	74.4	45.5	79.1	7.0
2	1	45.4	45.5	74.3	64.4	62.8	76.9	64.3	50.8	58.6	66.4	75.4	79.2	7.3	49.1	14.5
2	2	57.7	60.3	53.5	65.8	48.2	68.4	72.6	61.5	68.5	67.7	75.4	87.9	39.2	74.5	
3	24	49.0	44.3	55.5	46.8	53.8	53.7	54.8	53.8	46.8	58.6	50.1	21.2	7.0	45.3	45.5
3	25	42.1	55.1	73.0	70.4	54.4	54.7	62.0	42.8	73.0	54.1	84.4	54.0	95.7	50.0	
4	16	50.7	79.4	74.2	111.2	74.6	74.6	78.0	67.1	84.8	63.5	78.9	201.4			200.0
4	21	67.0	48.3	65.3	73.7	108.6	82.9	77.7	55.9	65.1	73.8	65.6	129.5			200.0
4	22	76.4	49.7	70.8	71.8	76.8	64.6	48.1	65.2	49.1	65.1	66.9	37.2	3.9	79.7	
5	2	51.8	58.8	44.7	62.8	42.8	94.7	46.8	70.6	56.6	45.1	47.9	0.5			
5	27	76.8	44.2	69.5	67.5	84.6	101.6	59.9	67.8	138.5	70.4	74.7	45.6		12.6	42.9
6	25	46.4	71.6	74.0	86.5	79.5	64.5	64.5	57.7	72.0	62.1	95.1	58.1		136.3	
6	26	44.1	58.3	48.7	57.6	61.4	59.0	48.1	48.7	64.9	51.5	50.8	50.7			7.1
7	21	46.7	27.1	78.3	64.3	61.1	66.7	62.5	90.1	62.7	80.3	69.3	89.2	200.0		
7	26	40.1	54.0	41.3	48.9	46.7	46.4	46.5	78.6	68.8	41.0	43.1	233.1	0.1	2.3	10.6
8	15	60.2	56.7	62.9	62.3	63.0	63.3	63.2	62.3	63.1	63.3	63.1	69.9			
8	22	71.3	40.7	64.2	52.2	44.6	48.6	41.6	49.6	48.5	51.1	70.0	39.2	10.9		5.3
9	11	50.7	70.2	56.6	57.8	56.8	59.4	57.7	49.6	78.2	83.6	61.3	32.5	78.3	5.0	109.3
9	19	24.7	59.3	63.3	50.8	21.7	51.1	59.8	55.7	80.8	44.1	59.4	11.2	14.2	11.1	36.5
10	25	69.2	43.8	75.5	66.8	96.1	75.9	68.7	82.7	90.1	72.7	59.8	65.6	86.8		
10	8	78.6	51.8	67.9	46.4	71.4	92.9	57.4	72.1	42.2	91.7	56.2	62.5	114.3	167.3	28.9
11	13	81.6	39.5	55.5	57.7	62.2	61.1	63.1	53.2	58.0	53.0	56.8	77.5		59.9	59.4
11	23	74.6	67.4	50.1	54.6	70.6	62.2	60.8	66.6	79.6	49.7	67.9	72.6			41.5
12	19	33.1	51.2	46.9	35.7	48.3	70.5	48.1	43.8	60.8	51.9	40.4	129.7	0.1	107.8	232.1
12	20	57.5	32.7	69.8	55.8	63.3	62.3	51.5	52.8	61.6	91.6	60.7	143.5	59.9	22.2	10.2

Mean power frequency values (Hz) post experimental testing

Subject	Posture	Pec Maj (clav)	Lat Dorsi	Upper Trap	Mid Trap	Ant Delt	Mid Delt	Post Delt	Bicep	Tricep	Infra (S)	Supra (S)	Infra (W)	Supra (W)	T Minor (W)	Subscap (W)
1	28	23.7	74.9	44.4	40.0	76.5	71.1	70.9	79.7	97.9	51.2	53.8	91.9	18.7	67.4	
1	6	49.9	41.5	76.5	68.7	49.7	46.5	52.3	53.0	91.7	50.1	62.7	70.5	50.7	69.9	
2	1	48.9	41.8	73.4	69.4	61.0	74.9	58.3	50.0	67.4	55.5	73.8	69.6	10.1	42.0	
2	2	58.2	53.4	41.5	61.1	45.4	70.1	64.9	47.6	61.4	62.4	73.2	90.8	19.0	80.5	62.3
3	24	51.5	55.1	54.1	50.9	56.2	59.7	53.4	46.6	51.2	64.1	61.2	18.7	8.1	6.9	45.6
3	25	46.3	59.6	64.5	55.6	55.2	65.4	63.1	44.6	72.9	56.1	72.6	50.8	99.3	12.4	
4	16	57.1	125.4	73.8	100.5	83.9	90.2	84.5	44.1	85.6	64.6	82.5	137.6	14.2	130.5	109.9
4	21	63.0	63.2	71.0	82.9	116.3	99.6	78.8	59.0	60.6	60.6	71.8	113.5	4.7	257.5	
4	22	76.2	50.0	66.9	66.2	85.9	58.0	43.3	60.5	44.2	74.8	60.2	36.5	5.9	43.9	36.2
5	2	60.9	58.2	45.2	54.1	38.1	98.3	44.5	69.4	75.4	44.4	45.7		13.1		
5	27	72.9	44.6	73.2	72.7	88.8	103.4	59.0	60.2	145.4	87.5	83.1		5.4	13.0	43.6
6	25	33.8	61.4	67.7	82.9	62.2	60.2	60.0	55.4	83.8	50.0	83.5	8.9	3.0	69.6	
6	26	38.4	58.4	62.4	56.8	65.9	60.4	42.0	52.0	73.3	50.4	71.6	49.9		68.7	15.3
7	21	44.7	24.0	80.0	60.8	51.3	58.4	54.8	75.5	55.0	90.7	62.4	94.9		5.2	7.7
7	26	27.6	52.7	41.9	44.9	50.0	51.1	50.5	52.1	71.1	39.6	46.5	232.7			13.0
8	15	48.8	48.2	59.8	59.3	59.5	63.3	59.6	58.3	60.3	60.8	60.3	65.0			
8	22	71.3	40.7	64.2	52.2	44.6	48.6	41.6	49.6	48.5	51.1	70.0	39.2	10.9		5.3
9	11	46.3	45.9	70.0	57.3	56.0	59.5	62.0	70.6	82.1	65.4	64.7	40.9		5.4	6.5
9	19	17.8	69.5	49.2	56.5	17.1	60.4	55.2	50.1	81.6	45.5	62.2	11.1	14.7		36.7
10	25	78.5	55.7	73.5	66.2	106.6	82.3	65.9	75.4	67.7	73.3	56.4	40.5		6.6	10.2
10	8	78.4	43.5	66.6	48.5	79.1	92.4	59.5	76.1	52.2	79.1	56.4			177.4	
11	13	73.9	50.7	59.3	60.8	61.4	62.0	62.3	58.5	55.0	55.6	58.5	61.9			
11	23	81.9	55.8	49.5	61.2	73.6	68.9	66.2	71.8	79.6	52.4	68.6	115.4	59.9	64.2	7.8
12	19	39.2	53.1	51.4	35.4	38.9	42.8	50.1	41.5	71.4	63.2	43.4	74.6		140.7	
12	20	49.3	31.5	64.6	54.4	63.0	62.0	53.5	46.4	61.9	71.6	59.8	68.2	86.6	96.1	