A COMPREHENSIVE ASSESSMENT OF SHOULDER MOTION

by

Robert Garry Quinton

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biomechanics and Movement Science

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ABSTRACT

Introduction

Despite the prolonged existence of EMG, current literature still lacks a comprehensive set of muscle activations of commonplace shoulder motions. A complete and detailed understanding of shoulder muscle activation strategies is crucial for clinicians and therapists when making treatment decisions for either typically developed individuals with shoulder injuries or for patients with shoulder dysfunction as a result of conditions such as cerebral palsy or brachial plexus palsy. This descriptive laboratory study is the first of its kind to utilize synchronized EMG and motion capture data to evaluate the timing and amplitude of twenty muscular segments influencing scapulothoracic (ST) and glenohumeral (GH) motion in a group of typically developed individuals performing five ordinary shoulder motions. The data set was evaluated for conserved muscle activation patterns among subjects, synergistic muscular relationships and made available for validation of musculoskeletal shoulder models. This first of five articles discusses the results of the abduction trial.

Materials & Methods

Five typically developed adult subjects underwent simultaneous EMG and motion capture recording of twenty muscular segments of the shoulder during the five modified-Mallet motions of the shoulder (abduction in the coronal plane, full external rotation at 0° abduction, hand-to-mouth, hand-to-nape of neck, hand-to-

base of spine). Dynamic EMG signals were collected for three motion trials, processed, then averaged and normalized to dynamic maximal voluntary contraction trials for each muscle in order to make comparisons between subjects. Normalized EMG signals were visually analyzed in terms of their activation patterns, timing of pattern changes and magnitude of activation. This analysis combined with the resultant observed effects on humerothoracic (HT), GH and ST angular displacement for each motion trial allowed for categorization of muscle segments based on their functional role throughout the motion. Based on muscle activation patterns and their corresponding functional roles in a given motion, strategies of neuromuscular control and synergistic relationships emerged providing a description of how a motion is accomplished.

Results

The muscle activation patterns that were well conserved across all subjects during abduction include upper trapezius, lower trapezius, levator scapulae, supraspinatus, rhomboid major, anterior deltoid and posterior deltoid. Muscles that appeared to be highly individualized during abduction consisted of middle trapezius, infraspinatus, rhomboid minor, subscapularis, serratus anterior, coracobrachialis and pectoralis minor. Muscles that appeared to play no significant role in abduction were teres major, teres minor, pectoralis major, latissimus dorsi, biceps brachii and triceps brachii.

The muscle activation patterns that were well conserved across all subjects during external rotation include middle trapezius, lower trapezius, levator scapulae, infraspinatus, rhomboid minor, rhomboid major, teres minor, and subscapularis. Muscles that appeared to be highly individualized during external rotation consisted of upper trapezius, supraspinatus, teres major, serratus anterior, coracobrachialis, and pectoralis minor. Muscles that appeared to play no significant role in external rotation were pectoralis major, anterior deltoid, posterior deltoid, latissimus dorsi, biceps brachii and triceps brachii.

Conclusions

Based on the consistent waveform patterns observed in conjunction with the motion capture data, muscles were able to be grouped based on their main function during abduction. Humeral primary movers consisted of supraspinatus and anterior deltoid. Scapular primary movers included upper, middle and lower trapezius and levator scapulae. Infraspinatus, teres minor and subscapularis served as the primary GH stabilizers. Rhomboid major, rhomboid minor and pectoralis minor functioned as the primary scapular stabilizers. There were also several muscles that demonstrated activity congruent with the direction of body segment motion that appeared to play a stabilizing role but may have also contributed to motion. The humeral mixed movers/stabilizers were coracobrachialis and posterior deltoid. The sole scapular mixed mover/stabilizer was serratus anterior. The muscles that were essentially inactive during abduction are teres major, pectoralis major, latissimus dorsi, biceps brachii and triceps brachii. Synergistic relationships were also observed between the following muscle groups; supraspinatus-anterior deltoid, upper-middle-lower trapezius, and supraspinatus-levator scapulae.

Based on the consistent waveform patterns observed in conjunction with the motion capture data, muscles were able to be grouped based on their main function during external rotation. Humeral primary movers consisted of infraspinatus and teres minor. Scapular primary movers included middle trapezius, lower trapezius and rhomboid major. Teres major, subscapularis, pectoralis minor, and coracobrachialis served as the primary GH stabilizers. There were also several muscles that demonstrated activity congruent with the direction of body segment motion that appeared to play a stabilizing role but may have also contributed to motion. The ST mixed movers/stabilizers were upper trapezius, levator scapulae, supraspinatus, rhomboid minor, and serratus anterior. The muscles that were essentially inactive during external rotation were pectoralis major, anterior deltoid, posterior deltoid, latissimus dorsi, biceps brachii and triceps brachii. A synergistic relationship was also observed between the humeral and scapular primary movers (middle trapezius, lower trapezius, infraspinatus, rhomboid major and teres minor).

Chapter 1

DISSERTATION INTRODUCTION

The aim of this study is two-fold; first, to further advance the knowledge of shoulder neuromuscular control, second, to create a complete data set that can be used to validate musculoskeletal models of the shoulder. These aims were accomplished by utilizing synchronized electromyography (EMG) and motion capture data recording to directly visualize glenohumeral (GH) and scapulothoracic (ST) motion in three dimensions along with the associated neuromuscular activation patterns that govern them. By synchronizing EMG and motion capture to evaluate twenty muscle segments of the shoulder during two conventional motions, this study is the first to comprehensively illustrate the relationship of timing and magnitude of neuromuscular activation with humeral and scapular motion during normal shoulder function. The study results also demonstrated both obvious and obscure synergistic relationships among muscular segments. This new knowledge can be utilized by clinicians to improve therapies and surgical decisions for patients with innumerable types of shoulder dysfunction. In addition, the motion capture and EMG data set may be applied to musculoskeletal models to verify model accuracy in predicting shoulder kinematic and kinetic data. Such models can also be used by surgeons to help predict results of planned procedures to optimize patient outcomes.

This dissertation is organized into two distinct sections. The first section describes the muscle activation patterns associated with pure abduction/adduction and the second section describes the muscle activation patterns for external/internal rotation. Each chapter is intended to serve as a separate manuscript for dissemination.

Chapter 2

ABDUCTION

2.1. Introduction

EMG has been used to study muscle physiology since the early 1800s. Yet, to date, there are no published articles describing a comprehensive set of muscle activations of commonplace shoulder motions performed by typically developed individuals. A complete and detailed understanding of shoulder muscle activation strategies is crucial for clinicians and therapists when making treatment decisions for either typically developed individuals with shoulder injuries or for patients with shoulder dysfunction as a result of conditions such as cerebral palsy or brachial plexus palsy. Most shoulder EMG studies focus only on a few particular muscles related to a certain exercise(1–47) forcing clinicians to piece together an overview of shoulder muscle activity from numerous studies conducted under different circumstances. A few studies have been more comprehensive but focused only on the throwing motion which does not apply to a vast majority of the population.(37) Wickham et al (48) inspected fifteen muscles of the shoulder during commonplace motions. However, only HT angular displacement was measured using an accelerometer. Numerous publications tracked their subjects' motions during EMG collection either by goniometer, video or, skin-mounted electromagnetic motion sensors.(5,11–19) These methods present significant limitations with respect to drawing conclusions regarding the timing of muscle activations in reference to scapular and humeral motion which is integral in EMG investigations. No publications currently exist that utilize simultaneously recorded EMG and motion capture to describe timing of shoulder muscle activations in context of the segmental motions they govern (i.e. scapula and humerus). This study aims to fill this knowledge gap in neuromuscular control of shoulder motion and provide a databank for shoulder musculoskeletal modeling.

This descriptive laboratory study is the first of its kind to utilize synchronized EMG and motion capture data to evaluate the timing and amplitude of all twenty muscle segments influencing ST and GH motion in a group of five typically developed individuals performing five everyday shoulder motions. Certain muscles were divided into segments due to their varying lines of action (i.e. deltoid) or varying innervations (i.e. trapezius (49)). The data set was evaluated for conserved muscle activation patterns among subjects and made available for validation of musculoskeletal shoulder models. This first of five articles discusses the results of the abduction trial.

2.2. Materials and Methods

Five adult subjects (≥18 years old, 3 females, 2 males) with no history of or current shoulder pathology were recruited for this study. Approved written informed consent was obtained from all subjects prior to data collection. All data was collected at the University of Delaware Kinesiology and Applied Physiology

Biomechanics Lab, Newark, DE. This study was approved by the University of Delaware Institutional Review Board.

All subjects underwent simultaneous 3D motion capture and EMG recording of the right shoulder. Data was collected as subjects performed the modified-Mallet motions solely relating to the shoulder (full abduction in the coronal plane, full external rotation at 0° abduction, hand-to-mouth, hand-to-nape of neck, hand-to-base of spine). Subjects were first placed in a comfortably seated position. A combination of twenty fine-wire EMG (fwEMG) and surface EMG (sEMG) leads were then placed by a trained physician in/on the muscles listed in Table 1. All fwEMG electrodes were placed under aseptic conditions with a sterile hypodermic needle into muscle locations specified by Leis and Schenk et al.(50) Accurate placement of intramuscular leads were confirmed using a muscle stimulation unit and signal inspection during muscle activation. The intramuscular electrodes used were bipolar, nylon-coated, stainless steel wires with 2mm of exposed sensor approximately 0.3-0.5mm apart. All fwEMG data was recorded on a Konigsberg model multi-channel EMG recorder (Konigsberg Instruments, Inc., Monrovia, CA) at 1920Hz. All sEMG data was recorded on a Delsys Trigno model multi-channel EMG recorder (Delsys Inc., Natick, MA) at 1920Hz. Delsys Trigno surface leads are 99.9% pure silver, 5x1mm bars with an interelectrode distance of 10mm. Signal detection is double differential, input impedance not measured, common mode rejection ratio of

>80db, baseline noise <4.5μV pk-pk. sEMG leads were applied over the center of the muscle bellies indicated in Table 1 after the skin was shaved and cleaned with isopropyl alcohol. Ground leads were placed over the sternum and left acromion.

Table 1 – Anatomical sites for markers and EMG leads

Marker Sites	Muscles Measured by fwEMG	Muscles Measured by sEMG
Manubrium	Upper Trapezius	Pectoralis Major
Acromion Process	Middle Trapezius	Anterior Deltoid
Trigonum Spinae	Lower Trapezius	Posterior Deltoid
Inferior Angle of Scapula	Supraspinatus	Latissimus Dorsi
T1 Spinous Process	Infraspinatus	Biceps Brachii
T8 Spinous Process	Rhomboid Major	Triceps Brachii
Medial Humeral Epicondyle	Rhomboid Minor	
Lateral Humeral Epicondyle	Teres Major	
Radial Styloid	Teres Minor	
Ulnar Styloid	Subscapularis	
Dorsum of 3rd Metacarpal Head	Serratus Anterior	
	Pectoralis Minor	
	Coracobrachialis	
	Levator Scapulae	

Once all EMG leads were in place, 6mm retroreflective skin markers were affixed over ipsilateral landmarks listed in Table 1. An acromion marker cluster (AMC) was used to track scapular motion. This method was chosen over electromagnetic sensors for its relative accuracy(51–53), its ease of use, its ease of synchronization with EMG, and the fact that it functions unaffected by the stainless steel EMG components sensors.

Since this was a dynamic EMG study, dynamic maximal voluntary contractions (dMVC) were collected for each lead in accordance with recommendations by Burden et al(54) and Ball et al.(55) For each dMVC trial, the subjects arm began at resting position by the subject's side (referred to as the neutral position). The subject then moved the shoulder through the full range of motion of each particular muscle in its anatomic line of action as directed by the investigator. Manual resistance was applied to the arm by the investigator to ensure maximal exertion throughout the entire range of motion while maintaining the ability to adjust resistance should the subject's muscle be weaker in certain regions of the range. This method of resistance was chosen over use of mechanical resistance because mechanical methods cannot detect reductions in motion and instantaneously adjust to allow for the range of motion to be completed. This ability to adjust resistance load is desirable when collecting dMVC signals. Immediately prior to collection of the dMVC trial, the subject was allowed to practice the dMVC motion to ensure the correct muscle was being used properly and to allow for the dMVC signals to be inspected and adjusted for proper amplification without clipping. Once the signal was satisfactory and the subject was comfortable with the motion, they were instructed to "perform the motion as quickly and forcefully as possible". The dMVC trial was collected during this motion.

A twelve-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) recorded the 3D measurements of the skin markers at 60Hz throughout the entire range of each motion. Due to the use of an AMC for scapular tracking, a double calibration was performed for each subject with the arm at rest and at maximal elevation to maximize AMC tracking accuracy.(52) Immediately preceding each motion trial, subjects received standardized instructions for each of the six individual motions. Each motion was performed three times and the signals averaged to account for within subject variability. Motion trial speed was controlled by metronome to account for the effect of muscle contraction acceleration changes on EMG collection.

Each recorded EMG signal had the direct current bias removed, was full-wave rectified, band-pass filtered at 10-760Hz using a zero phase-shift, fourth order Butterworth filter, enveloped at 4Hz, and was averaged over the three repetitions of each motion trial. A 60Hz bandstop filter using a fourth order Butterworth filter was also applied to all signals. The signals for each muscle were then normalized to their respective dMVCs in order to make correlations between muscle activity and function both within subjects and between subjects. Motion trial EMG signals were normalized to the peak value of the corresponding dMVC for each muscle. All EMG signal processing was performed using custom code created in LabView version 12.0.1 (National Instruments Corporation, Austin, TX). Motion capture marker data was tracked via Cortex Motion Analysis software version 2.5.3 (Motion Analysis Corporation, Santa Rosa, CA).

Normalized EMG signals were categorized in terms of their activation patterns, timing of pattern changes and signal amplitude. To facilitate categorization of normalized signals, amplitudes greater than 60% were considered very high activity; amplitudes ranging 40-60% were considered high activity; amplitudes ranging 20-40% were considered moderate activity; amplitudes ranging from 0-20% were considered low activity. These ranges are consistent with previous studies.(9,37) Visual analysis of these neuromuscular activations and the resultant observed effects on HT and ST angular displacement for each motion trial revealed each muscles functional role throughout the motion. Based on muscle activation patterns and their corresponding functional roles in a given motion, different events and phases of neuromuscular control emerged providing a sequential description of how the motion was accomplished.

2.3. Results

End range of HT abduction occurred between 136°-165° for all subjects. End range of ST upward rotation occurred between 26°-39°. As there was variation between subjects' range of motion, all waveform aspects are described as either degrees of displacement from rest or degrees of displacement from the end range of motion. The graphs were generated to align the end range of abduction for each subject which is designated by the black vertical line unless otherwise stipulated. The waveforms were not time-distorted in any way. The Y-axis for the graphs represents the amplitude of the EMG signal during motion as a percentage of MVC for that muscle. X-axis for the graphs represents HT motion. However, slight variation in motion length, range and acceleration between subjects precludes the use of exact values for the x-axis. Figure 1 demonstrates these slight variations between subjects. Some subjects exhibited aberrant spikes of electrical activity which will be further discussed in the Limitations section.

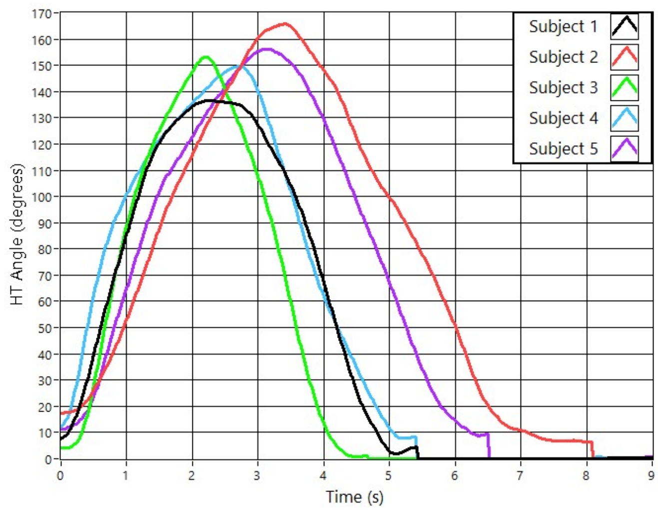

Figure 1 - HT Angle versus Time for each subject during abduction

Upper Trapezius (Table 2, Figure 2)

Across all five subjects upper trapezius demonstrated consistent activity onset, modal pattern, peak timing, and amplitude with minimal variation. This supports upper trapezius' role as the main elevator of the shoulder girdle and upward rotator of the scapula during abduction.

Table 2 - Peak activation of upper trapezius as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction.

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	2.5° Prior to end range	69.67%
2	End range	End range	40.25%
3	20° Prior to end range	4° Prior to end range	79.45%
4	5° Prior to end range	1° Prior to end range	81.37%
5	20° Prior to end range	4° Prior to end range	80.50%
AVG	10° Prior to end range	2.3° Prior to end range	70.25%

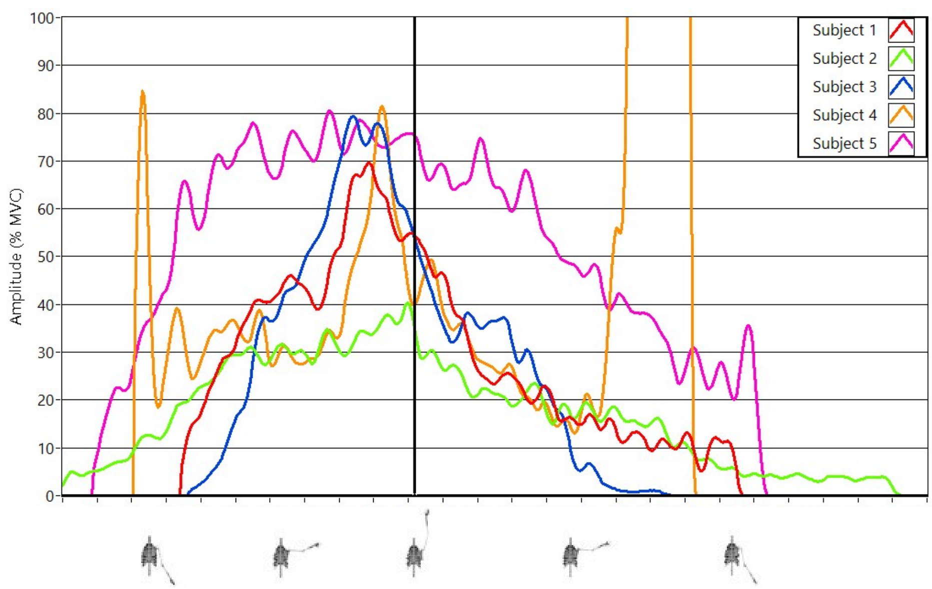

Figure 2 - Normalized upper trapezius EMG signal during abduction for all subjects

Middle Trapezius (Table 3, Figure 3)

Middle trapezius demonstrated two distinct activation patterns. Three subjects exhibited a unimodal peak pattern that peaked close to end range. Two subjects demonstrated broad lower level activity that plateaued earlier in abduction. This suggests middle trapezius utilized two or possibly more separate strategies for assisting scapular upward rotation during abduction.

Table 3 - Peak activation of middle trapezius as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction.

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	2.5° Prior to end range	82.90%
2	33° Prior to end range 45° After end range	End range	25.65%
3	20° Prior to end range	4° Prior to end range	72.45%
4	End range	End range	70.67%
5	30° Prior to end range 13° After end range	5° Prior to end range	34.43%
AVG	11° Prior to end range	2.3° Prior to end range	57.22%

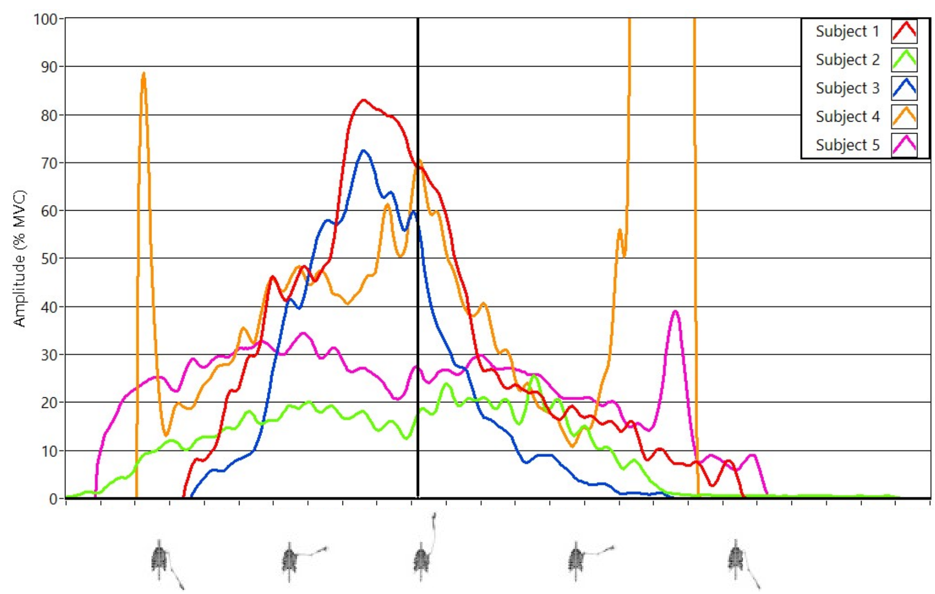

Figure 3 - Normalized middle trapezius EMG signal during abduction for all subjects

Lower Trapezius (Table 4, Figure 4)

Lower trapezius muscle activity demonstrated a highly conserved unimodal peak pattern among four subjects during abduction with the fifth subject demonstrating a broad, low level activation pattern. Both patterns were similar to those demonstrated by middle trapezius suggesting two strategies of coordination between middle and lower trapezius to assist with upward rotation of the scapula during abduction.

Table 4 - Peak activation of lower trapezius as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	2.5° Prior to end range	71.57%
2	5° Prior to end range	End range	55.69%
3	20° Prior to end range	End range	74.60%
4	20° Prior to end range	End range	72.90%
5	66° Prior to end range	5° Prior to end range	26.93%
AVG	23° Prior to end range	1.5° Prior to end range	60.34%

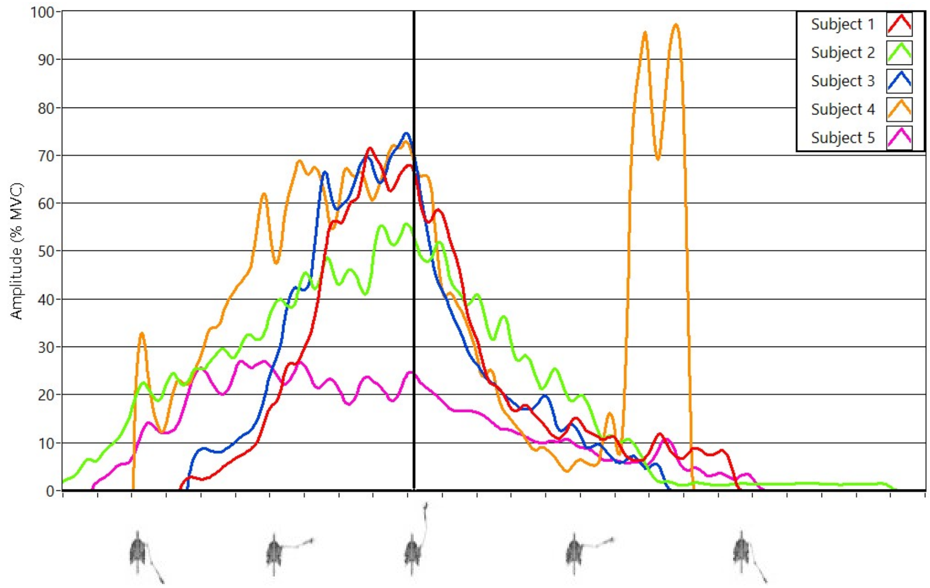

Figure 4 - Normalized lower trapezius EMG signal during abduction for all subjects

Levator Scapulae (Table 5, Figure 5)

The levator scapulae demonstrated moderate variability in activation patterns with four of five subjects reaching peak activity in a 25° window of HT abduction and 13° window of ST upward rotation whereas the fifth subject achieved peak activity at end range. Overall, levator scapulae activity onset, slope, timing of peak activation and peak activity level were well-conserved across most subjects while assisting with shoulder girdle elevation during abduction.

Table 5 - Peak activation of levator scapulae as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	End range (136°)	End range	83.30%
2	90°	13° Prior to end range	36.43%
3	113°	8° Prior to end range	73.96%
4	105°	9° Prior to end range	79.73%
5	110°	9° Prior to end range	75.10%
AVG	110°	7.8° Prior to end range	69.70%

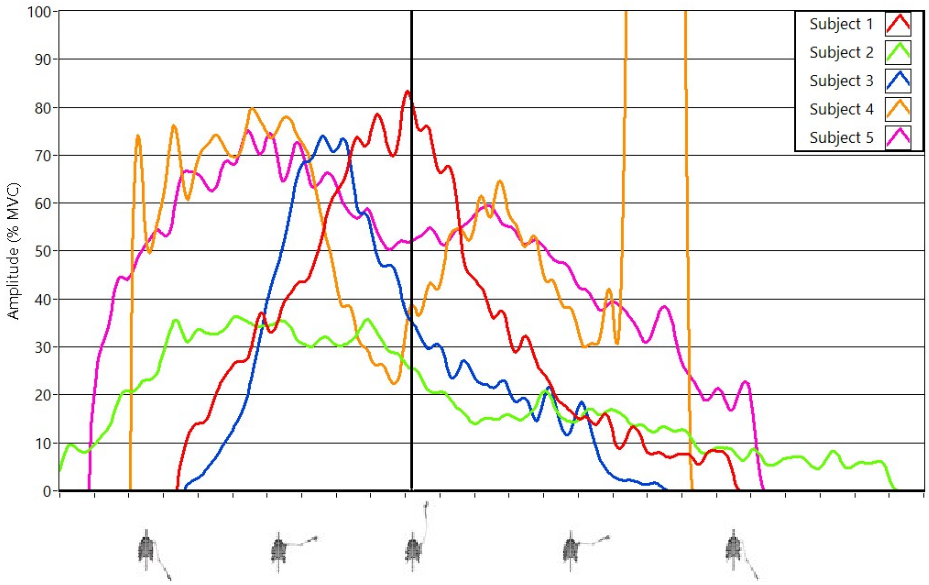

Figure 5 - Normalized levator scapulae EMG signal during abduction for all subjects

Supraspinatus (Table 6, Figure 6)

Supraspinatus activity in three of five subjects showed aberrant electrical interference spikes during recording. Aside from these aberrancies, a consistent pattern for supraspinatus activity still emerged with all five subjects demonstrating a bimodal peak pattern in narrow windows of GH and ST positioning as demonstrated in Table 6. All subjects also demonstrated a secondary lower intensity peak around 85°-105° of HT abduction on the arm's return to rest. Overall, supraspinatus muscle activity is well-conserved among all subjects in activation onset, waveform and timing but moderately variable in activation magnitude during abduction.

Table 6 - Peak activation of supraspinatus as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	End range (136°)	End range	75.00%
2	90°	13° Prior to end range	29.17%
3	113°	8° Prior to end range	88.40%
4	105°	9° Prior to end range	57.89%
5	110°	8° Prior to end range	53.97%
AVG	110°	7.6° Prior to end range	60.89%

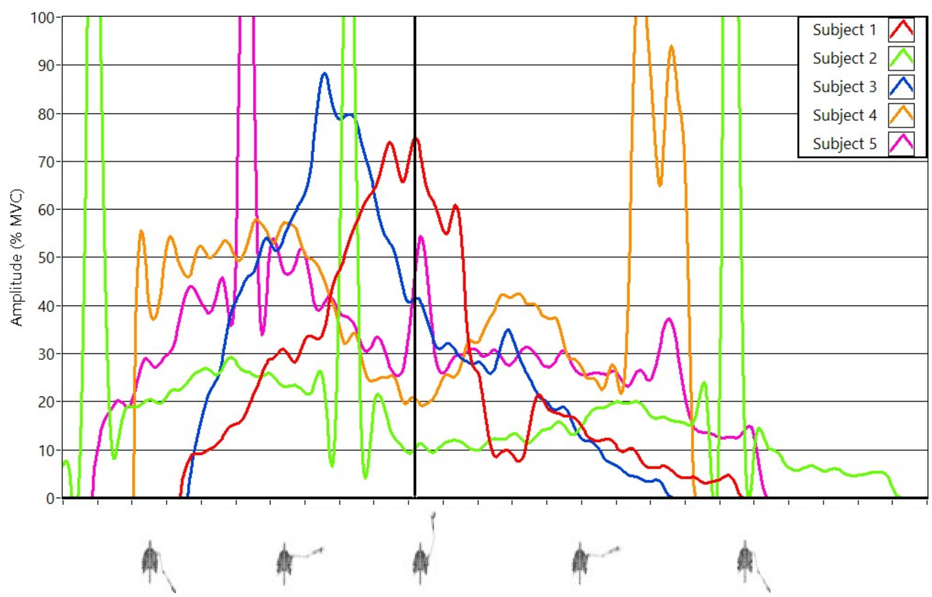

Figure 6 - Normalized supraspinatus EMG signal during abduction for all subjects

Infraspinatus (Figure 7)

Infraspinatus demonstrated five different patterns with varying timings and amplitudes among all five subjects. Overall, infraspinatus muscle activity is poorly conserved and its contribution to GH stability during abduction is highly individualized among subjects.

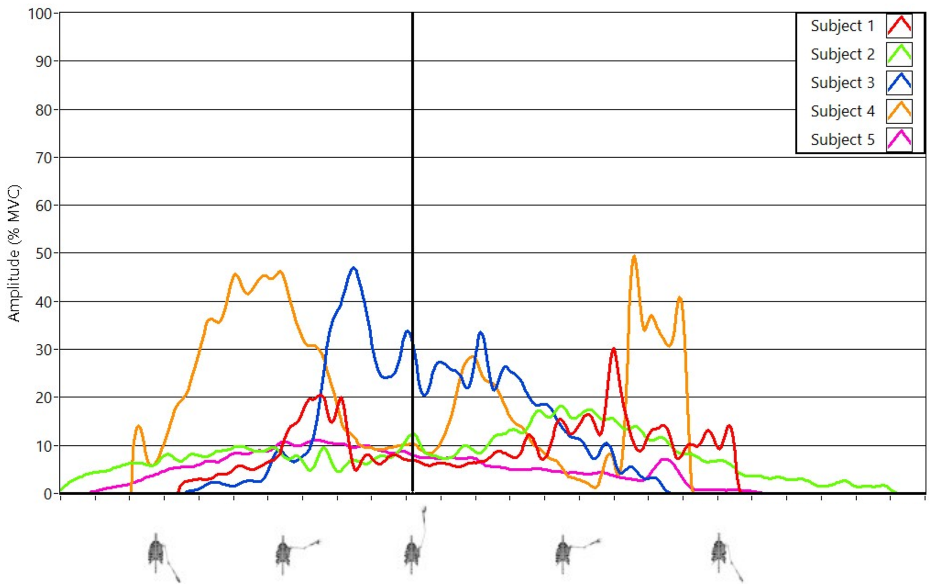

Figure 7 - Normalized infraspinatus EMG signal during abduction for all subjects

Rhomboid Minor (Figure 8)

Rhomboid minor demonstrated four different patterns of activity with varying timings across all five subjects. There are no aspects of pattern, timing, or amplitude that are conserved suggesting that the contribution of rhomboid minor activity to shoulder abduction is highly individualized.

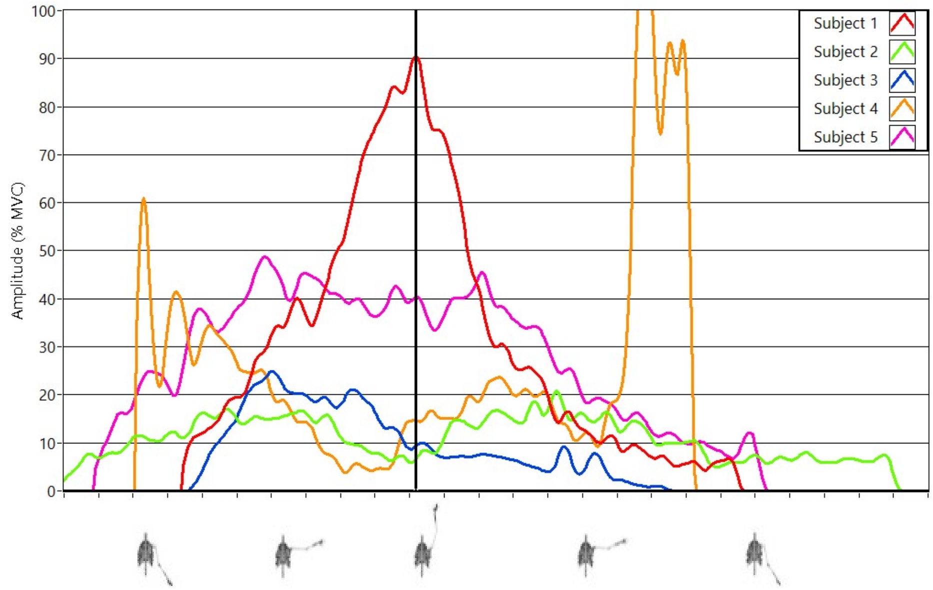

Figure 8 - Normalized rhomboid minor EMG signal during abduction for all subjects

Rhomboid Major (Table 7, Figure 9)

Rhomboid major activity demonstrated the same unimodal pattern for all five subjects peaking between 25° to end range of HT abduction and between 4° to end range of ST upward rotation. Four out of five subjects demonstrated narrow peaks with very high intensity, one subject demonstrated a broader peak maximizing at a low activity level. Overall, rhomboid major activity is highly conserved among all subjects during abduction.

Table 7 - Peak activation of rhomboid major as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	End range	End range	84.97%
2	25° Prior to end range	End range	19.27%
3	20° Prior to end range	4° Prior to end range	77.16%
4	5° Prior to end range	End range	78.36%
5	End range	End range	72.55%
AVG	10° Prior to end range	0.8° Prior to end range	66.46%

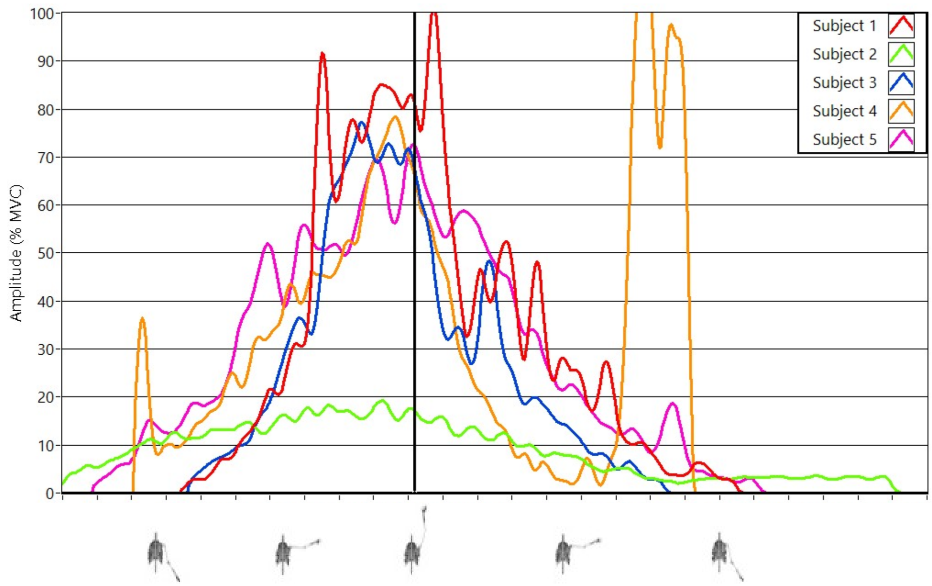

Figure 9 - Normalized rhomboid major EMG signal during abduction for all subjects

Teres Minor (Figure 10)

Teres minor activity showed no discernable consistent pattern among the subjects. Teres minor demonstrated essentially low activity with a couple spikes to moderate activity. Overall, teres minor plays an insignificant role in abduction.

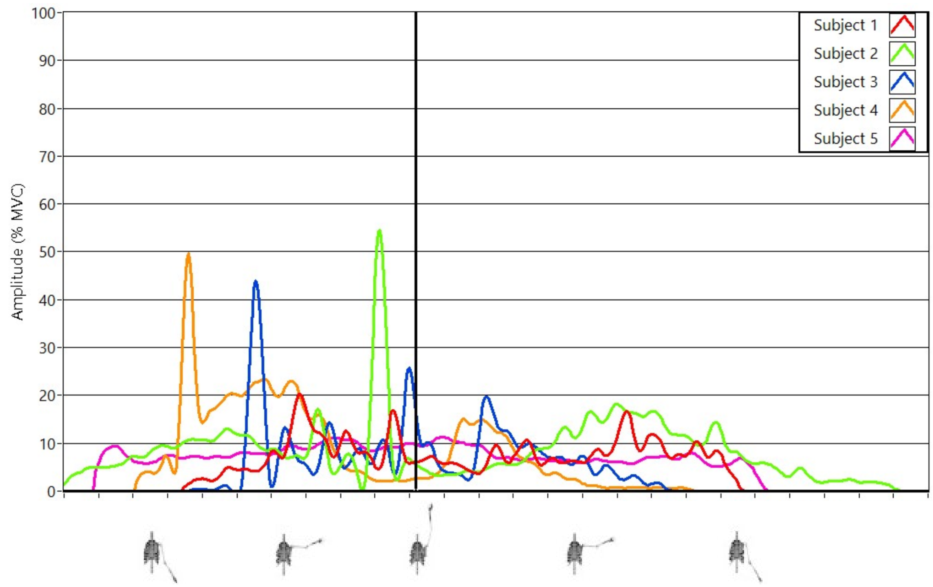

Figure 10 - Normalized teres minor EMG signal during abduction for all subjects

Teres Major (Figure 11)

Teres major activity showed no discernable consistent pattern among the subjects. Teres major demonstrated low activity across all subjects with one subject demonstrating a single spike within 15° of end range to moderate amplitude. Overall, teres major plays an insignificant role in abduction.

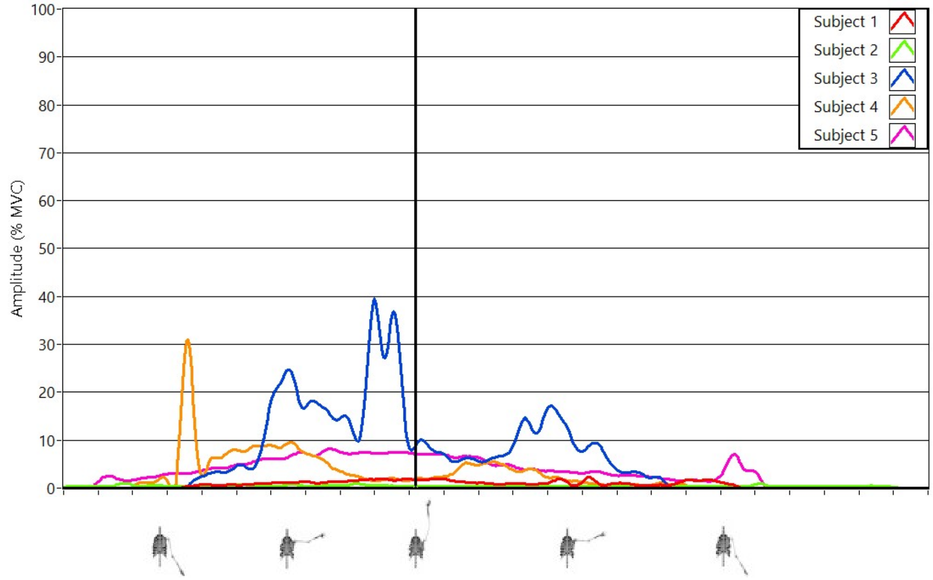

Figure 11 - Normalized teres major EMG signal during abduction for all subjects

Subscapularis (Figure 12)

Subscapularis activity showed no discernable consistent pattern in timing among the subjects. However, subscapularis activity levels were low for two subjects, moderate for two subjects and borderline low-moderate for one subject. This data suggests that the role of subscapularis in stabilization of the anterior GH joint during abduction is highly individualized.

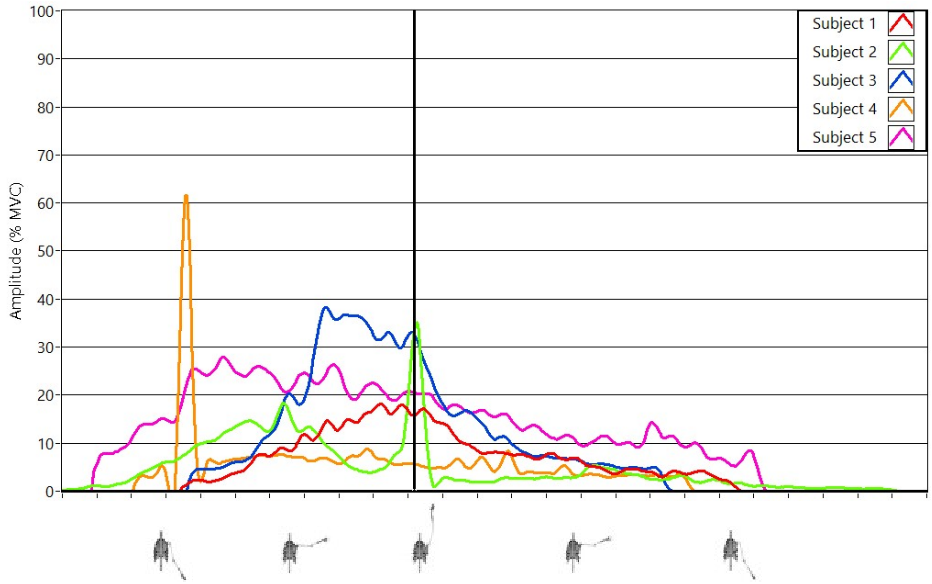

Figure 12 - Normalized subscapularis EMG signal during abduction for all subjects

Serratus Anterior (Table 8, Figure 13)

Serratus anterior demonstrated a unimodal pattern across all subjects for abduction. However, activity amplitude varied with three subjects in the moderate range, one subject in the high range and one subject in the very high range. Overall, serratus anterior activity onset, slope, pattern and timing was highly conserved across all subjects but activity amplitude was somewhat individualized during abduction.

Table 8 - Peak activation of serratus anterior as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	1° Prior to end range	83.30%
2	End range	End range	21.42%
3	20° Prior to end range	4° Prior to end range	54.92%
4	5° Prior to end range	1° Prior to end range	32.21%
5	5° Prior to end range	1° Prior to end range	35.65%
AVG	7° Prior to end range	1.4° Prior to end range	45.50%

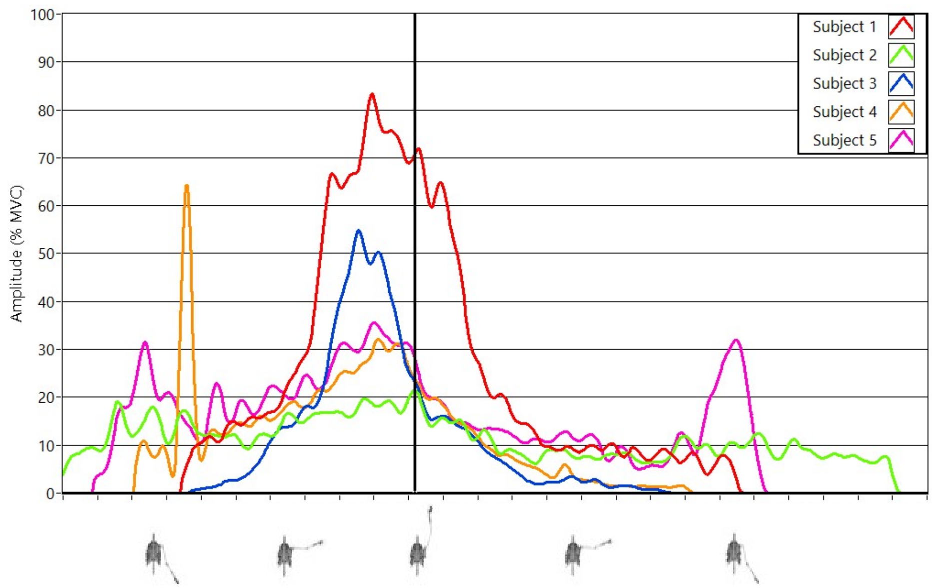

Figure 13 - Normalized serratus anterior EMG signal during abduction for all subjects

Coracobrachialis (Figure 14)

Coracobrachialis demonstrated no consistent discernable pattern of timing among the subjects. However, activation amplitude varied from moderate to very high across all subjects indicating that it does play a highly individualized role in either humeral stabilization to the coronal plane or stabilization of humeral 3D orientation during abduction.

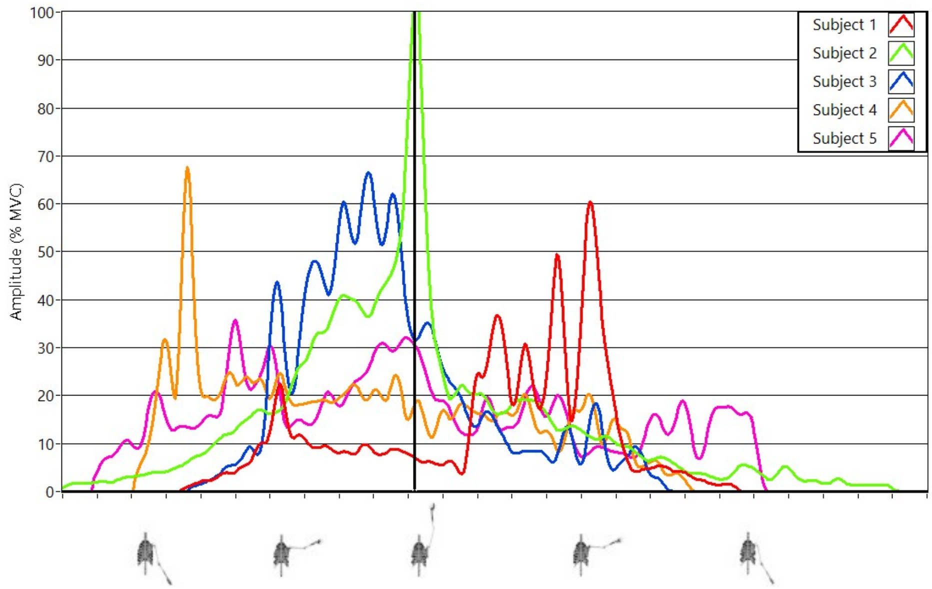

Figure 14 - Normalized coracobrachialis EMG signal during abduction for all subjects

Pectoralis Minor (Figure 15)

Pectoralis minor demonstrated no consistent discernable pattern of timing among the subjects. However, activation amplitude varied from low to very high across all subjects indicating that it does play a highly individualized role in scapular stabilization during abduction.

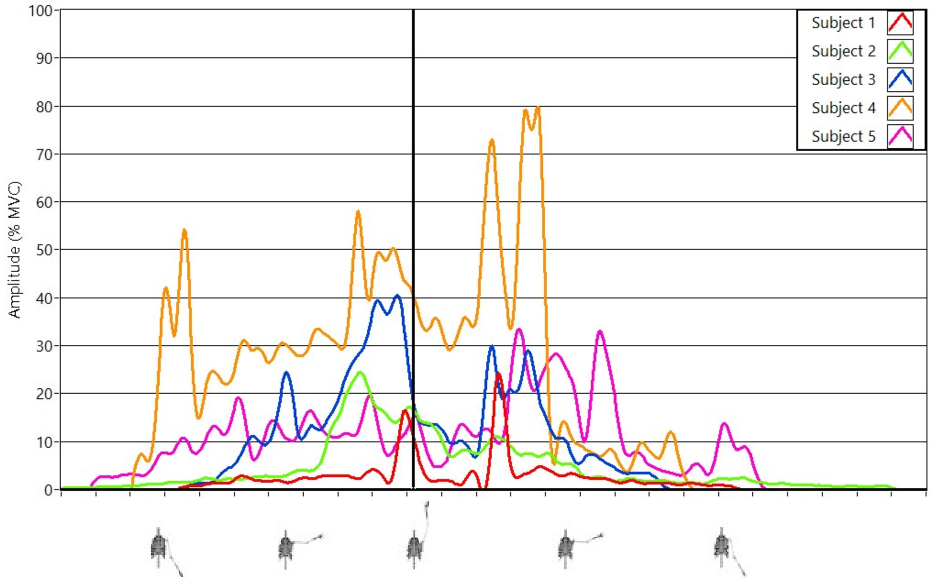

Figure 15 - Normalized pectoralis minor EMG signal during abduction for all subjects

Pectoralis Major (Figure 16)

Pectoralis major demonstrated almost no measurable activity during the entire range of abduction across all subjects. Therefore, it is concluded that pectoralis major is essentially inactive during abduction.

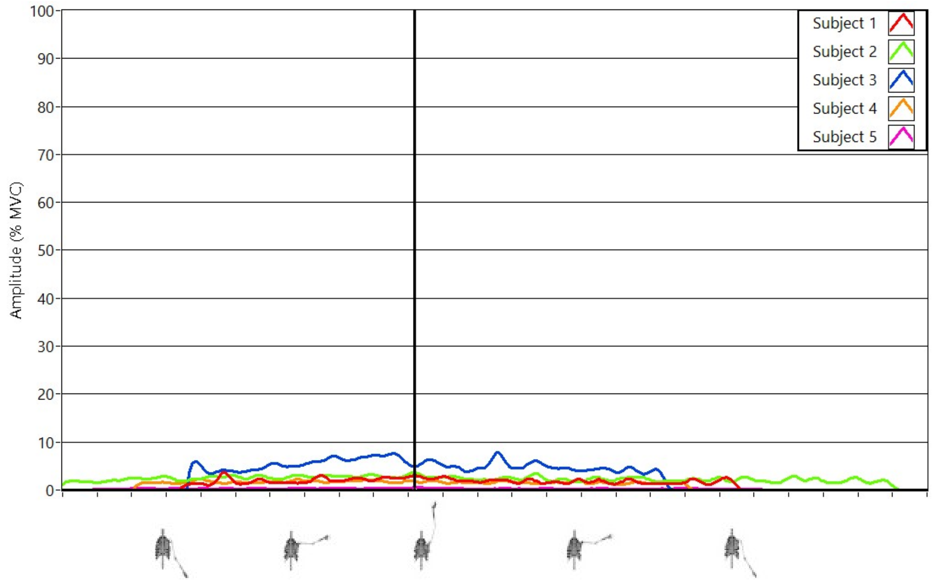

Figure 16 - Normalized pectoralis major EMG signal during abduction for all subjects

Anterior Deltoid (Table 9, Figure 17)

Anterior deltoid demonstrated a unimodal pattern across all five subjects. One subject demonstrated a low level spike of activity during the arm's return to rest but this was not observed in other subjects. Additionally, amplitude was consistently high to very high across all subjects. Overall, anterior deltoid's contribution to humeral elevation during abduction is highly conserved with respect to activity onset, pattern, timing and amplitude.

Table 9 - Peak activation of anterior deltoid as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	3° Prior to end range	49.10%
2	25° Prior to end range	1.5° Prior to end range	43.80%
3	20° Prior to end range	3° Prior to end range	72.41%
4	20° Prior to end range	3° Prior to end range	73.81%
5	End range	End range	54.24%
AVG	14° Prior to end range	2.1° Prior to end range	58.67%

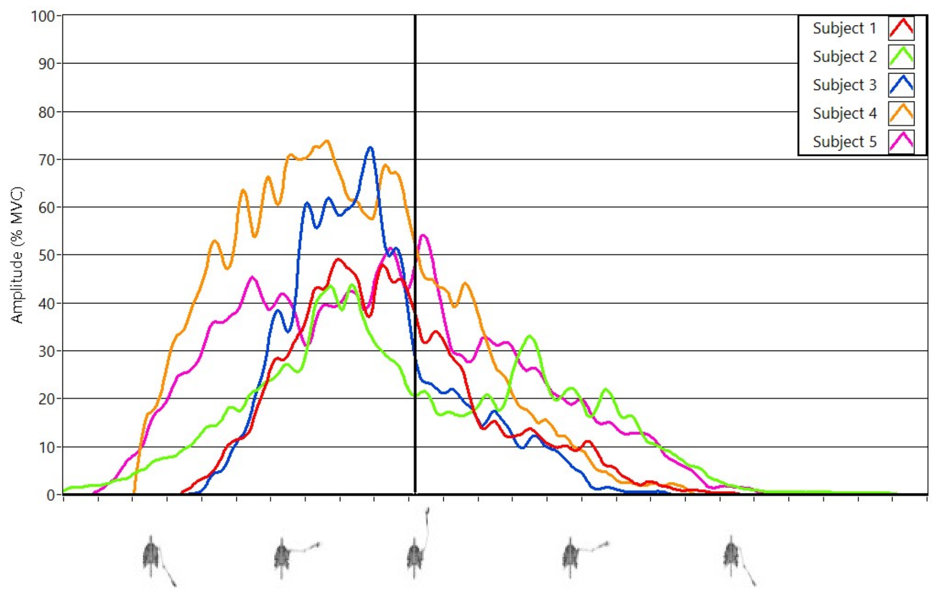

Figure 17 - Normalized anterior deltoid EMG signal during abduction for all subjects

Posterior Deltoid (Table 10, Figure 18)

Overall, posterior deltoid's contribution to humeral elevation during abduction is highly conserved with respect to activity onset, pattern, timing and amplitude albeit though to an overall lesser degree of amplitude than anterior deltoid.

Table 10 - Peak activation of posterior deltoid as a percentage of MVC and the timing of peak activation in reference to GH and ST position during abduction

Subject	GH position at peak	ST position at peak	Peak Activation
1	5° Prior to end range	2° Prior to end range	47.50%
2	5° Prior to end range	1.5° Prior to end range	26.02%
3	20° Prior to end range	2.5° Prior to end range	46.37%
4	5° Prior to end range	2.5° Prior to end range	32.46%
5	End range	End range	19.37%
AVG	7° Prior to end range	1.7° Prior to end range	34.34%

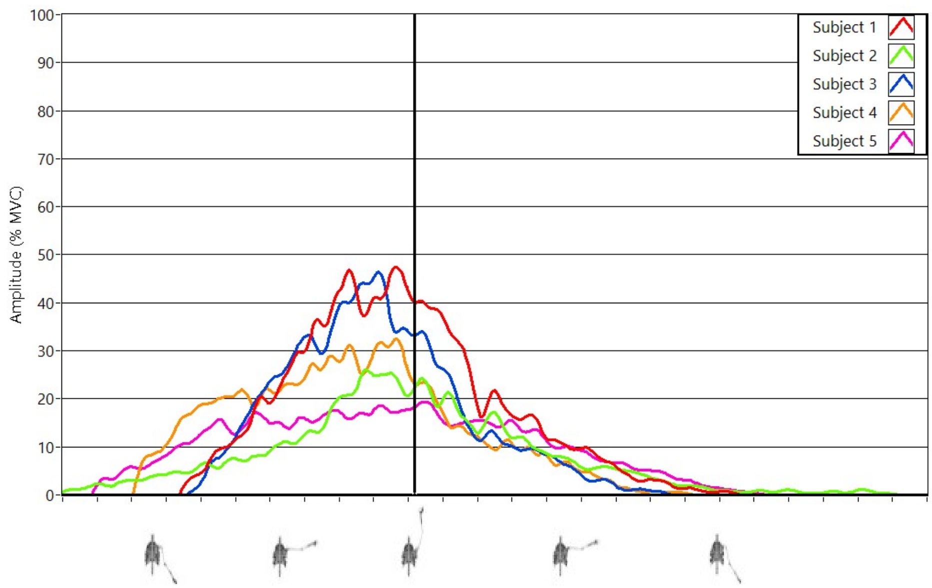

Figure 18 - Normalized posterior deltoid EMG signal during abduction for all subjects

Latissimus Dorsi (Figure 19), Biceps Brachii (Figure 20), Triceps Brachii (Figure 21)

Latissimus dorsi, biceps brachii and triceps brachii demonstrated a low to no activity in across all subjects indicating that these muscles play no significant role in abduction.

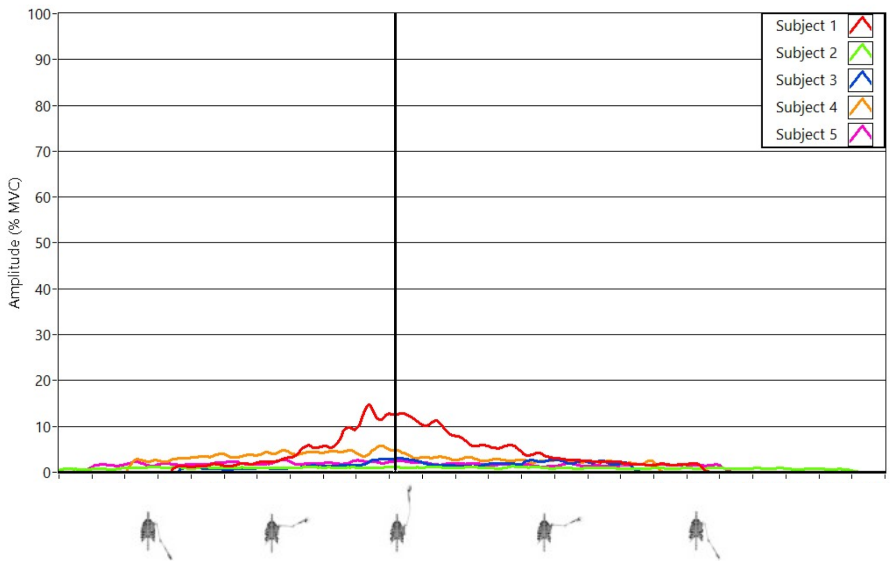

Figure 19 - Normalized latissimus dorsi EMG signal during abduction for all subjects

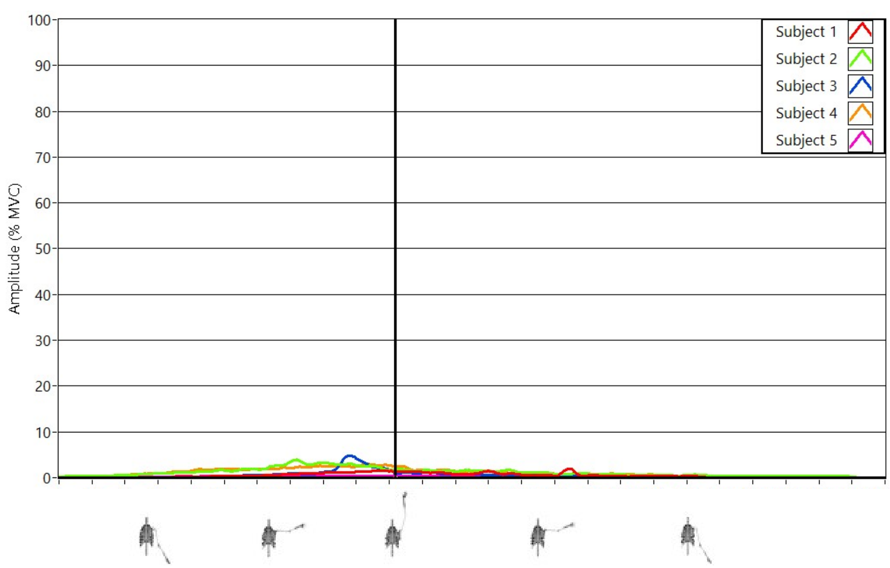

Figure 20 - Normalized biceps brachii EMG signal during abduction for all subjects

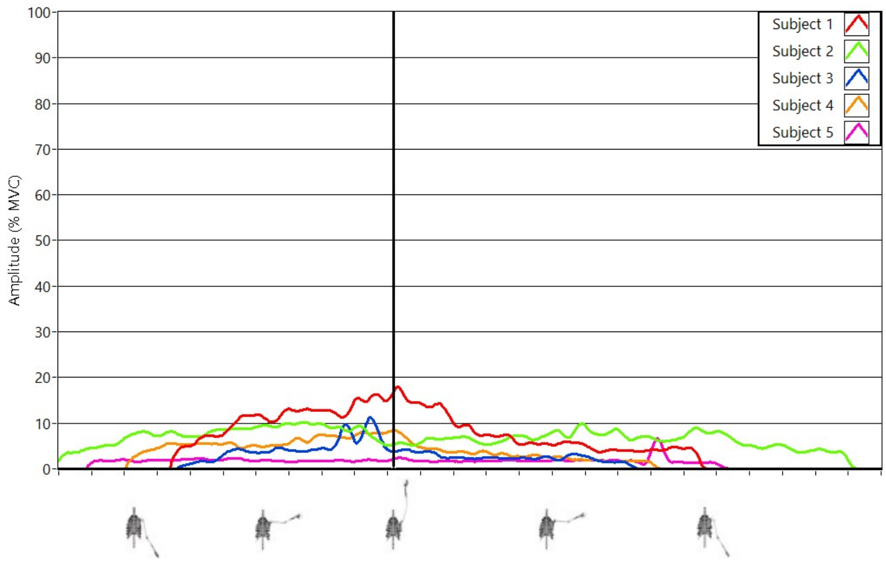

Figure 21 - Normalized triceps brachii EMG signal during abduction for all subjects

2.4. Discussion

This study focused on describing normal shoulder muscle activation patterns during abduction. From this data, muscular roles in achieving abduction can be inferred (i.e. primary movers versus stabilizers versus inactive muscles). In addition, certain synergistic relationships were observed providing some insight into muscular control and coordination during abduction.

2.4.1. Muscle Roles and Conservation

Combining activation onset, waveform amplitude and timing, observed segment motion, and known anatomical attachments and lines of action made it possible to infer the roles of muscles in accomplishing abduction. Muscles were categorized as either primary movers of body segments or joint/segment stabilizers during the motion. Muscles were further categorized as to the body segment or joint upon which their forces were applied.

The observed primary movers of abduction were upper trapezius, middle trapezius, lower trapezius, levator scapulae, supraspinatus, and anterior deltoid. These muscles can be organized into humeral and scapular primary movers. Humeral primary movers consist solely of supraspinatus and anterior deltoid (Fig. 22).   Both were highly conserved with respect to activation onset, pattern, timing and amplitude in four of five subjects. Supraspinatus activity in Subject One peaked slightly later than the other four subjects (Fig. 6).

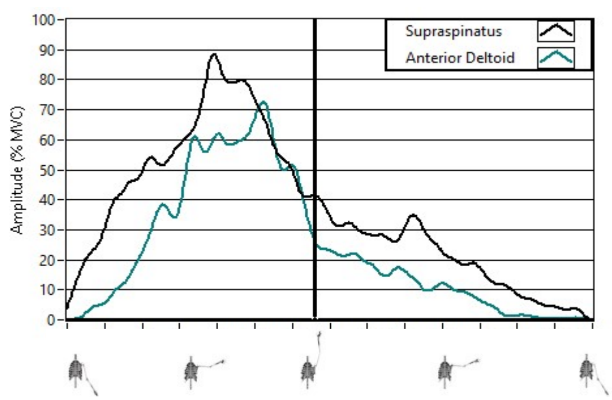

Figure 22 - Normalized EMG signal of the humeral primary movers of a representative subject during abduction

Scapular primary movers include upper, middle and lower trapezius and levator scapulae (Fig. 23). Upper, middle, and lower trapezius activity were also highly conserved in their role of shoulder girdle elevation and scapular upward rotation with respect to activation onset, timing and amplitude in four of five subjects. Middle and lower trapezius amplitudes in Subject Five were generally lower than that of the other four subjects (Figs. 3 and 4). Levator scapulae activity was highly conserved in its role assisting with elevation and upward rotation of the scapula with respect to activation onset, pattern, timing and amplitude except in subject one where activity peaked slightly later than the other four subjects (Fig. 5).

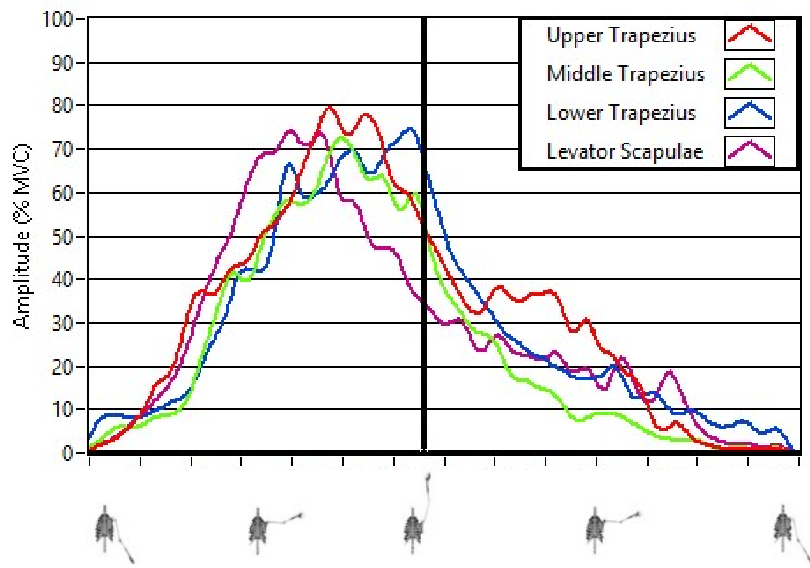

Figure 23 - Normalized EMG signal of the scapular primary movers of a representative subject during abduction

The observed primary stabilizers of abduction were infraspinatus, rhomboid minor, rhomboid major, subscapularis, teres minor and pectoralis minor. Infraspinatus, teres minor and subscapularis serve as the primary GH stabilizers (Fig. 24). All three muscles were poorly conserved with respect to activation onset, pattern and timing. However, they demonstrated some activity from low to moderate levels in all subjects which indicates that they do, in fact, play a role in stabilization but this role is highly individualized.

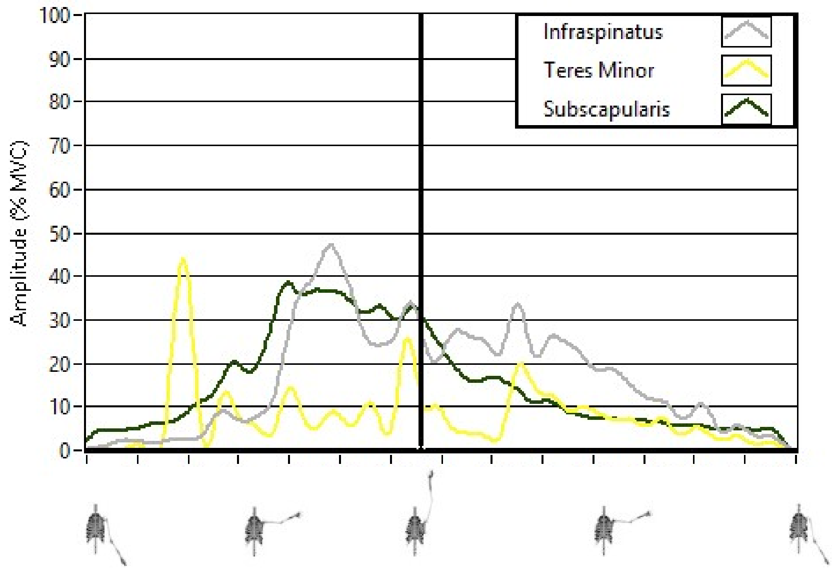

Figure 24 - Normalized EMG signal of the primary GH stabilizers of a representative subject during abduction

Rhomboid major, rhomboid minor and pectoralis minor functioned as the primary ST stabilizers during abduction (Fig. 25). Rhomboid major is highly conserved in its role of stabilizing the scapula to the thorax during scapular elevation and upward rotation. Rhomboid minor and pectoralis minor were much more individualized.

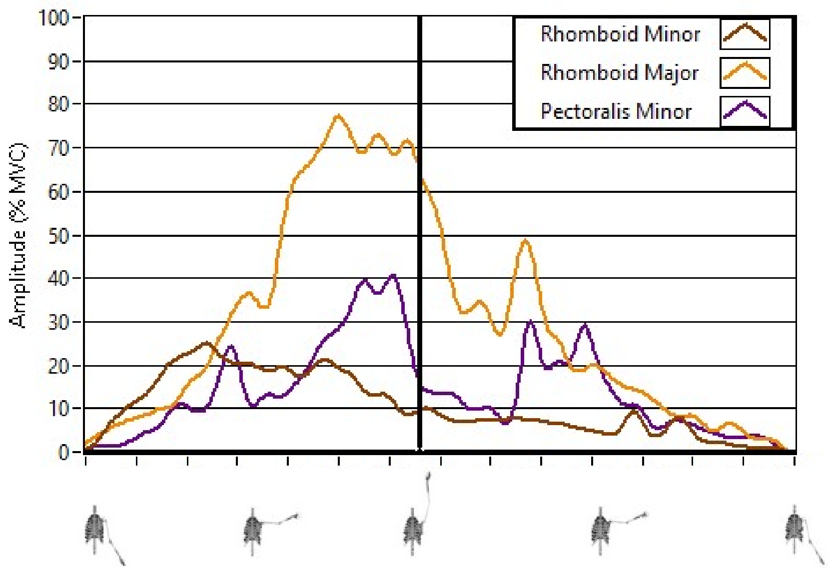

Figure 25 - Normalized EMG signal of the primary ST stabilizers of a representative subject during abduction

There were also several muscles that demonstrated activity congruent with the direction of body segment motion that appeared to play a stabilizing role but may have also contributed to motion. These mixed movers/stabilizers were serratus anterior, coracobrachialis, and posterior deltoid. The humeral mixed movers/stabilizers were coracobrachialis and posterior deltoid (Fig. 26). Coracobrachialis was highly individualized while stabilizing humeral orientation and/or assisting with the end range of humeral elevation. On the other hand, posterior deltoid was highly conserved in activation onset, timing and amplitude in its role assisting with humeral elevation and stabilization of the humerus in the coronal plane.

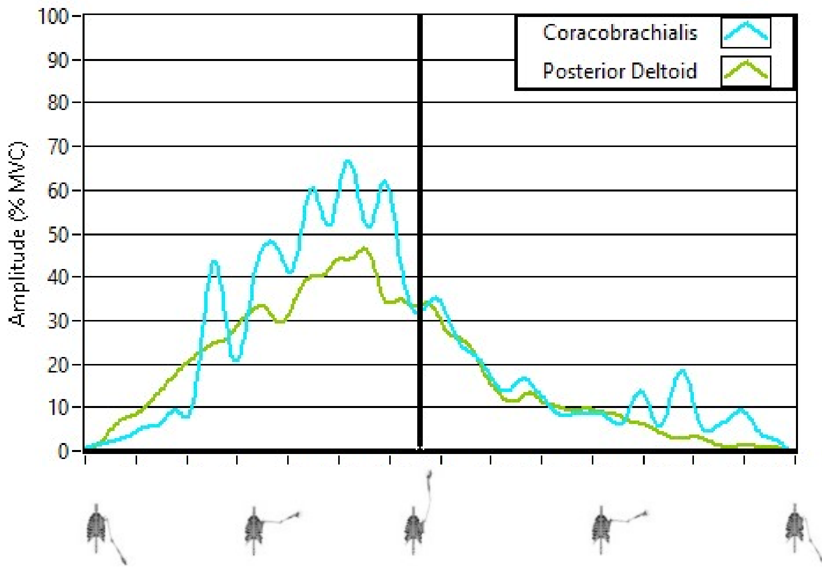

Figure 26 - Normalized EMG signal of the humeral mixed movers/stabilizers of a representative subject during abduction

The sole scapular mixed mover/stabilizer was serratus anterior (Fig. 27). Serratus anterior was well conserved in activation onset and timing but amplitude was more individualized as it contributed to scapular upward rotation and stabilization to the thorax.

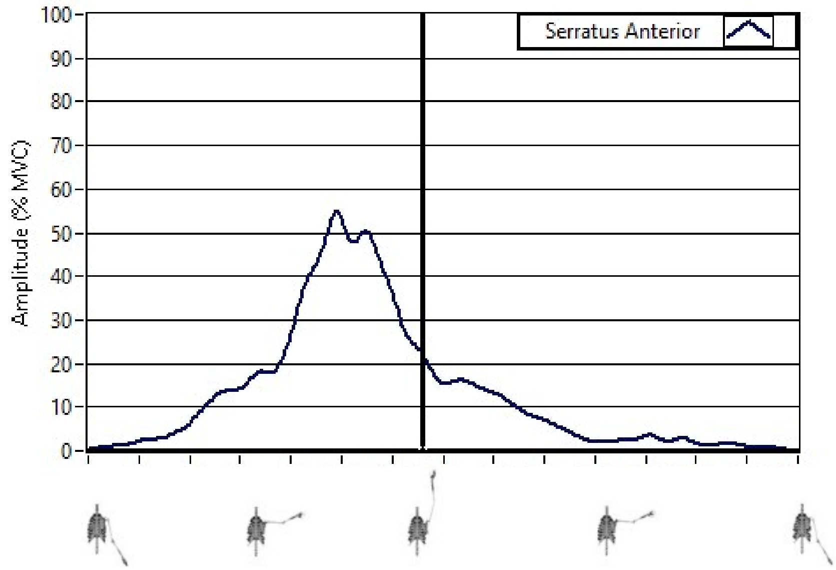

Figure 27 - Normalized EMG signal of the scapular mixed mover/stabilizer of a representative subject during abduction

The muscles that were inactive during abduction are teres major, pectoralis major, latissimus dorsi, biceps brachii and triceps brachii (Fig. 28).

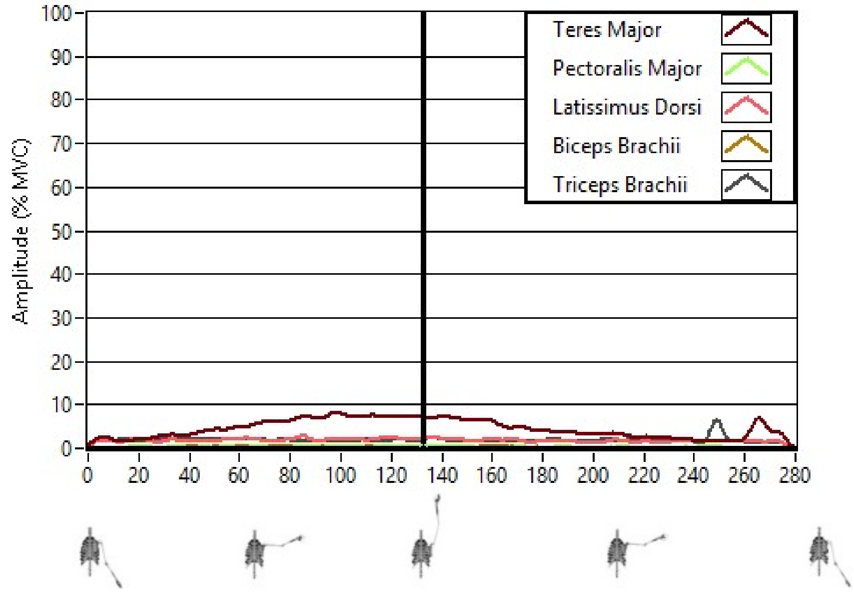

Figure 28 - Normalized EMG signal of the inactive muscles of a representative subject during abduction

2.4.2. Synergistic Relationships

During the course of data analysis, certain muscles were found to demonstrate unique relationships with respect to timing and/or waveform symmetry that begged special commentary. The first relationship that was observed was between supraspinatus and anterior deltoid (Fig. 29). It was observed that supraspinatus activity exhibited a steep upslope at the onset of action and peaked around 90°-115° of abduction. Alternatively, anterior deltoid activity exhibited a much more gradual onset of action that peaked after supraspinatus within 25° of end range of HT abduction. From this data, it can be concluded that supraspinatus is primarily responsible for GH abduction up to 90°-

115° at which point anterior deltoid's significant contribution is made to accomplish the remainder of GH abduction.

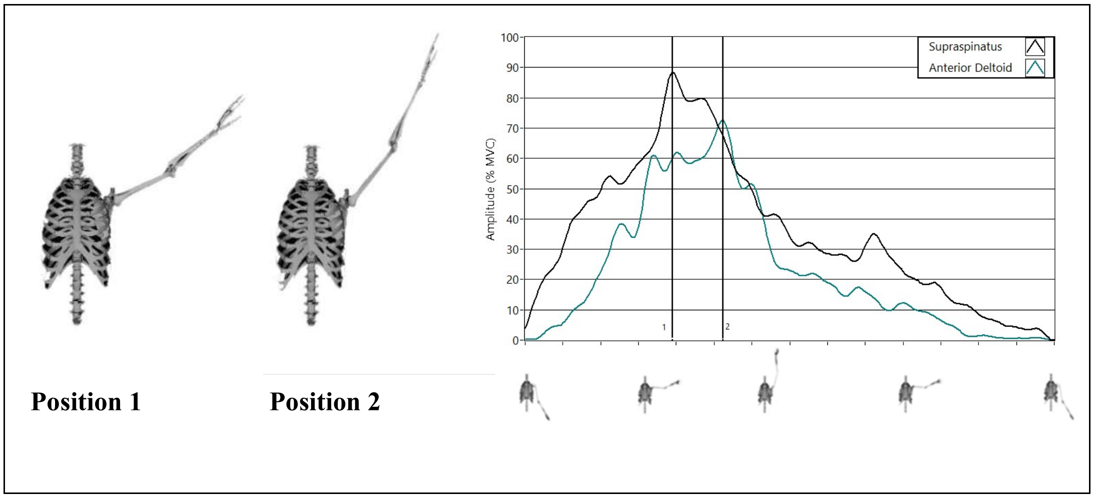

Figure 29 - This figure demonstrates the synergistic relationship between supraspinatus and anterior deltoid in a representative subject during abduction. The illustrations on the left represent the motion capture arm position data related to the EMG graph on the right. Position 1 corresponds to Vertical Marker 1 which is the peak of supraspinatus activity. Position 2 corresponds to Vertical Marker 2 which is the peak of anterior deltoid activity. Note anterior deltoid peaks later in abduction than supraspinatus.

Another synergistic relationship was observed between the upper, middle, and lower divisions of the trapezius muscle (Fig. 30). The three muscle divisions demonstrated different strategies of activation coordination. In certain subjects, all three segments of trapezius were activated with matching timing, waveform and amplitude. Other subjects demonstrated similar timing and waveform for middle and lower trapezius but lower amplitude. Pu et al(49) described variation in motor control of the trapezius by either the spinal accessory nerve alone or a combination of the spinal accessory nerve and branches C2-4 of the cervical plexus among the population. Consequently, the varying neurological control of the trapezius segments could account for the varying synergistic activation strategies demonstrated here.

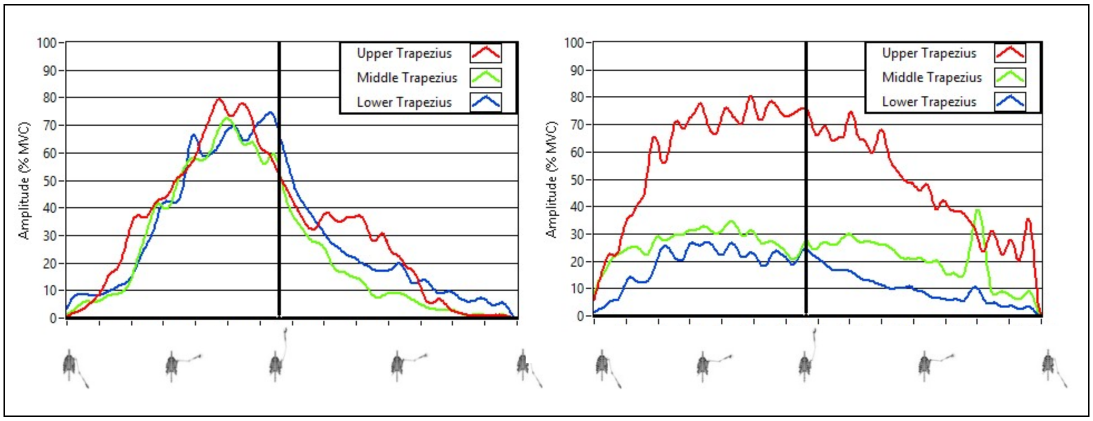

Figure 30 - This figure demonstrates the synergistic relationship between upper, middle and lower trapezius in two representative subjects during abduction. The graph on the left demonstrates a strategy where all three segments of trapezius were activated to the same timing, waveform and amplitude. The graph on the right demonstrates a differing strategy where middle and lower trapezius are activated with similar timing and waveform but to a much lower amplitude than that of upper trapezius.

Supraspinatus and levator scapulae also demonstrated an unexpected relationship. These muscles were observed to exhibit conserved activation onset, timing, pattern and amplitude within subjects and across all subjects (Fig. 31). This is an interesting observation as these two muscles do not share a common innervation and act on different bony segments. It is difficult to speculate the significance of this relationship but it is certainly one worth further investigation.

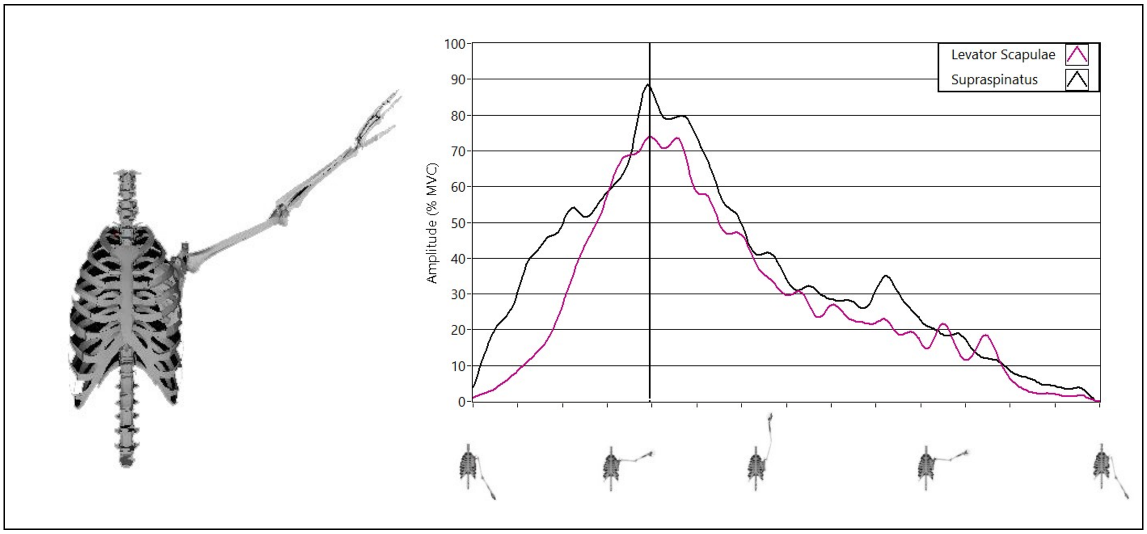

Figure 31 - This figure demonstrates a relationship between levator scapulae and supraspinatus in a representative subject during abduction with respect to activity onset, modal pattern, peak amplitude timing and pattern of signal offset. The humeral position (left) per the motion capture data corresponds to the peak of levator scapulae and supraspinatus activity as indicated by the cursor in the graph on the right.

2.4.3. Limitations

There were a few limitations to this study to consider. First, was the method for determining waveform symmetry with respect to overall pattern reproducibility. Several methods of mathematically analyzing waveform symmetry were investigated. These methods included signal integration, integration of subtracted signals, and waveform symmetry metrics via eigenvector analysis.(56) However, all of these methods failed to detect certain aspects of waveform symmetry or asymmetry with respect to the goals of analysis of this study. Therefore, visual analysis by the investigators was relied upon to determine waveform symmetry and subsequent conservation of muscle activation characteristics.

A second limitation of this study centered around signal abnormalities that did not become apparent until after collection and processing. First there were signal spikes noted mostly in the data collected from Subject Four's intramuscular leads. However, these signal spikes essentially occurred at the very beginning and end of motion so the overall waveform was not compromised and still suitable for analysis. Subjects Two and Five also demonstrated signal spikes but only in the supraspinatus. These spikes were strikingly similar to arterial pulse waveforms so it was suspected that these intramuscular leads were placed in close proximity to small arterioles in the muscle. Also of note, almost all activation waveforms from subject two were noticeably lower in amplitude compared to the other subjects. The reason for this phenomenon is unclear but the impact, if any, would be the understatement of amplitude conservation of those muscles.

Despite limitations, this study's data reveal novel aspects of shoulder muscle activation, function and coordination that will be useful for clinicians and researchers alike. It will also be useful for validating musculoskeletal models of the shoulder and will be made available for this purpose. Similar analysis of external rotation, hand-to-mouth, hand-to-nape, and hand-to-spine are to follow.

Chapter 3

EXTERNAL ROTATION

3.1. Introduction

See *Chapter 1, Introduction*

3.2. Materials and Methods

See *Chapter 1, Materials and Methods*

3.3. Results

End range of HT external rotation occurred between 67°-84° for all subjects. End range ST external rotation occurred between 12°-24°. As there was variation between subjects' range of motion, all waveform aspects are described as either degrees of displacement from rest or degrees of displacement from the end range of motion. The graphs were generated to align the end range of external rotation for each subject which is designated by the black vertical line unless otherwise stipulated. The waveforms were not time-distorted in any way. The Y-axis for the graphs represents the amplitude of the EMG signal during motion as a percentage of MVC for that muscle. X-axis for the graphs represents HT motion. However, slight variation in motion length, range and acceleration between subjects precludes the use of exact values for the x-axis. Figure 32 demonstrates these slight variations between subjects.

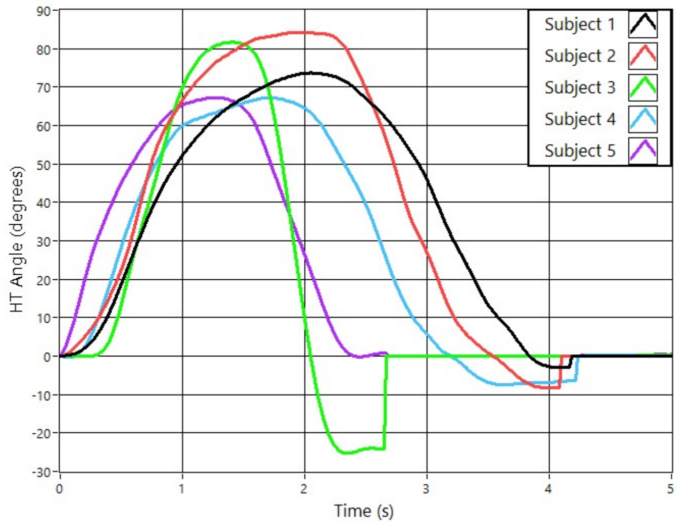

Figure 32 - HT Angle versus Time for each subject during external rotation

Upper Trapezius (Figure 33)

Upper trapezius activity demonstrated two different patterns of activity varying moderately in signal intensity. Three subjects demonstrated a low level plateau pattern throughout the entire range of motion. One subject demonstrated a low level early unimodal peak, while another subject demonstrated a high level unimodal peak at end range of external rotation. This data indicates that upper trapezius' role in scapular motion versus stabilization during external rotation is somewhat individualized.

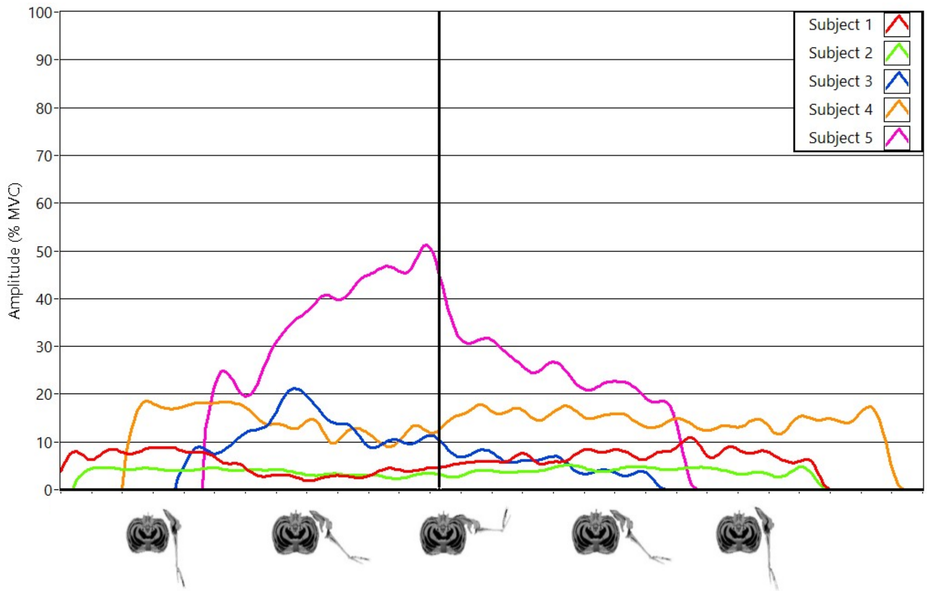

Figure 33 - Normalized upper trapezius EMG signal during external rotation for all subjects

Middle Trapezius (Table 11, Figure 34)

Middle trapezius is consistent in its unimodal activation pattern across all subjects and peak timing for all but one subject, Subject Five, which occurred earlier in external rotation. Activation magnitude varied significantly ranging from low to very high. Overall, middle trapezius is well conserved in activation pattern and timing in its role in retracting and externally rotating the scapula with variation in activation amplitude.

Table 11 - Peak activation of middle trapezius as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	2° Prior to end range	2° Prior to end range	44.63%
2	End range	End range	26.70%
3	3° Prior to end range	End range	73.94%
4	End range	End range	39.20%
5	19° Prior to end range	12° Prior to end range	17.45%
AVG	4.8° Prior to end range	2.8° Prior to end range	40.38%

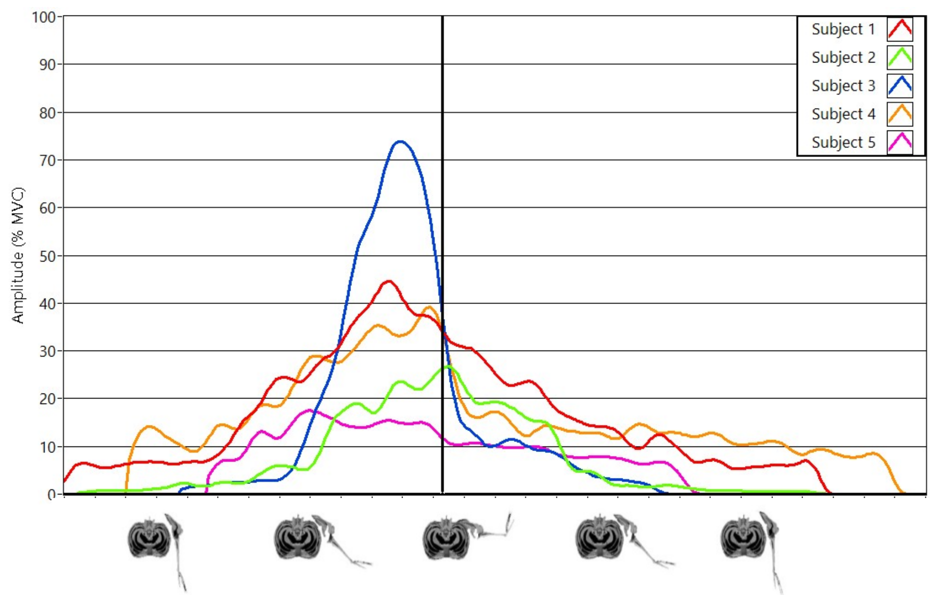

Figure 34 - Normalized middle trapezius EMG signal during abduction for all subjects

Lower Trapezius (Table 12, Figure 35)

Lower trapezius demonstrated a consistent unimodal pattern with peak activation occurring within a few degrees of end range GH and ST external rotation across all subjects. Lower trapezius varied widely in its activation amplitude from low to very high. Overall, lower trapezius is well-conserved with respect to activation pattern and timing but varied somewhat in amplitude while assisting with scapular retraction and external rotation.

Table 12 - Peak activation of lower trapezius as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	3° Prior to end range	2° Prior to end range	39.13%
2	End range	End range	30.75%
3	3° Prior to end range	End range	85.97%
4	1° Prior to end range	End range	15.53%
5	1° Prior to end range	3° Prior to end range	43.93%
AVG	1.6° Prior to end range	1° Prior to end range	43.06%

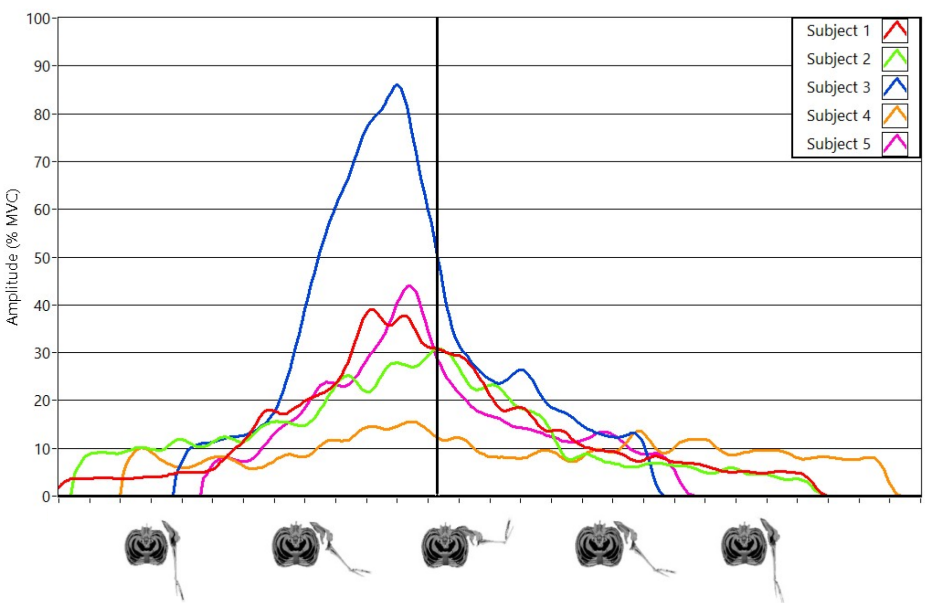

Figure 35 - Normalized lower trapezius EMG signal during abduction for all subjects

Levator Scapulae (Figure 36)

Levator scapulae demonstrated two separate patterns of activation. Four subjects demonstrated a sharp onset to plateau pattern without a clear peak of activity while Subject Three demonstrated a unimodal peak pattern. Activation amplitude varied moderately with three subjects achieving low activity levels and two subjects achieving high activity levels. Overall, levator scapulae was moderately conserved with respect to activation pattern and timing in four of five subjects and amplitude only varying between low to high levels.

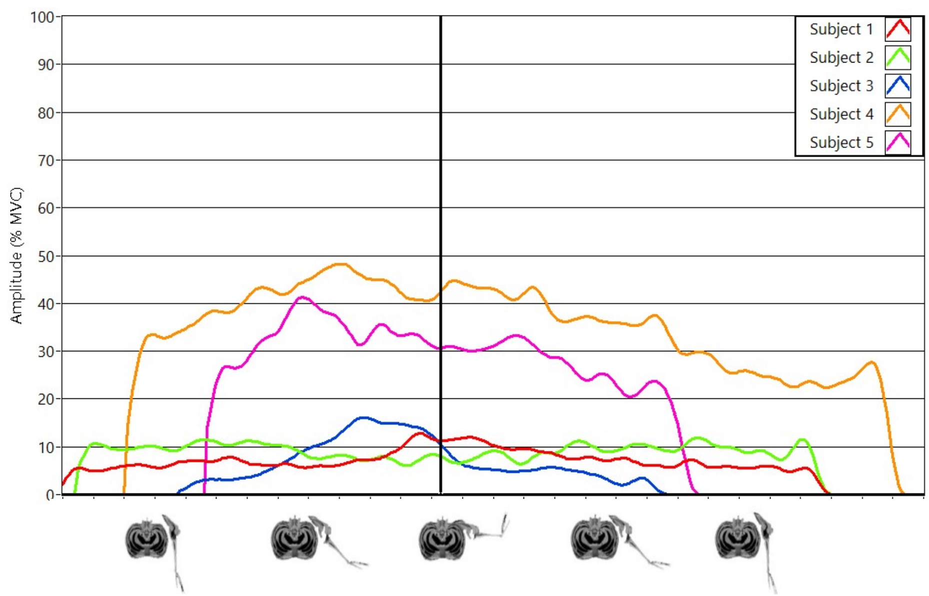

Figure 36 - Normalized levator scapulae EMG signal during abduction for all subjects

Supraspinatus (Figure 37)

Supraspinatus demonstrated varying activation patterns, onset slope and timing across all subjects. Activation amplitude was consistent ranging from low to moderate levels. Overall, supraspinatus' contribution to GH external rotation was somewhat individualized.

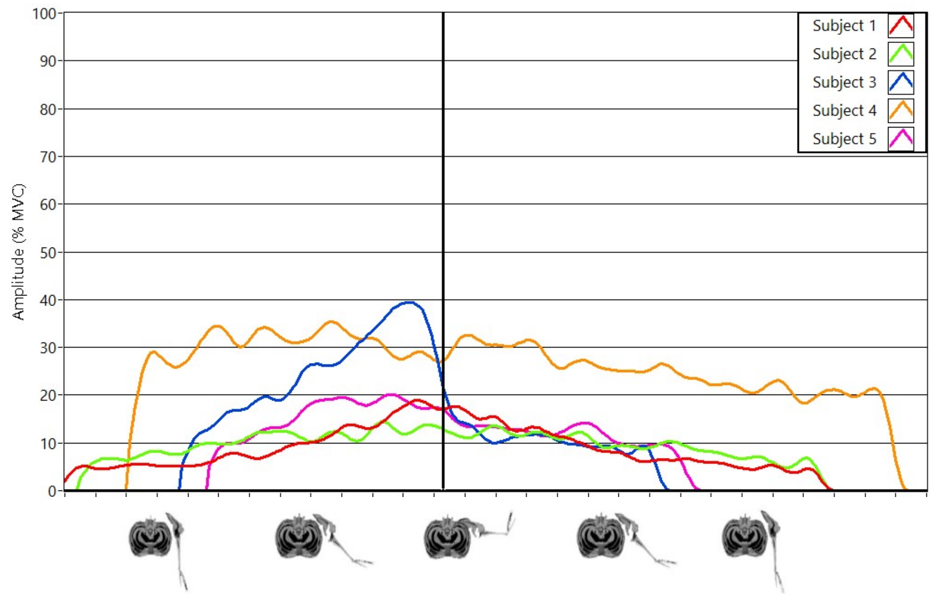

Figure 37 - Normalized supraspinatus EMG signal during abduction for all subjects

Infraspinatus (Table 13, Figure 38)

Infraspinatus demonstrated a unimodal peak pattern with peak activity occurring within a few degrees of end range GH and ST external rotation across all subjects. Activation amplitude was high to very high for four subjects while Subject 5 demonstrated moderate activity levels. Overall, infraspinatus is highly conserved with respect to activation pattern, timing and amplitude in its role in GH coupling and external rotation.

Table 13 - Peak activation of infraspinatus as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	1° Prior to end range	1.5° Prior to end range	61.33%
2	1° Prior to end range	4° Prior to end range	51.30%
3	3° Prior to end range	End range	89.87%
4	2° Prior to end range	1° Prior to end range	68.40%
5	2° Prior to end range	5° Prior to end range	20.47%
AVG	1.8° Prior to end range	2.3° Prior to end range	58.27%

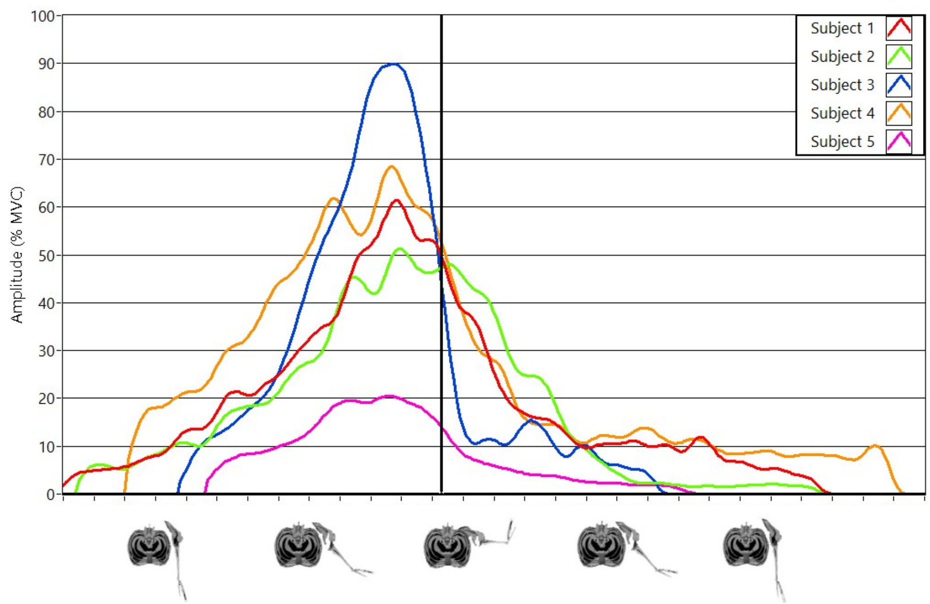

Figure 38 - Normalized infraspinatus EMG signal during abduction for all subjects

Rhomboid Minor (Table 14, Figure 39)

Rhomboid minor demonstrated a unimodal peak pattern across all subjects though timing of peak activation and slope of signal from onset to peak varied somewhat. Four of five subjects demonstrated peak activation within a few degrees of end range GH external rotation while Subject Three's peak activation occurred 40º prior to end range. Subjects One, Two and Four demonstrated gradual slopes from onset to peak activation while Subjects Three and Five demonstrated steep slopes. Activation amplitude varied moderately between low to high. Overall, rhomboid minor was well-conserved with respect to activation pattern across all subjects but varies somewhat in timing, activation slope and amplitude while assisting with scapular retraction during external rotation.

Table 14 - Peak activation of rhomboid minor as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	1° Prior to end range	1.5° Prior to end range	20.81%
2	End range	End range	34.84%
3	40° Prior to end range	16° Prior to end range	13.90%
4	End range	End range	33.74%
5	1° Prior to end range	3° Prior to end range	45.23%
AVG	8.4° Prior to end range	4.1° Prior to end range	29.70%

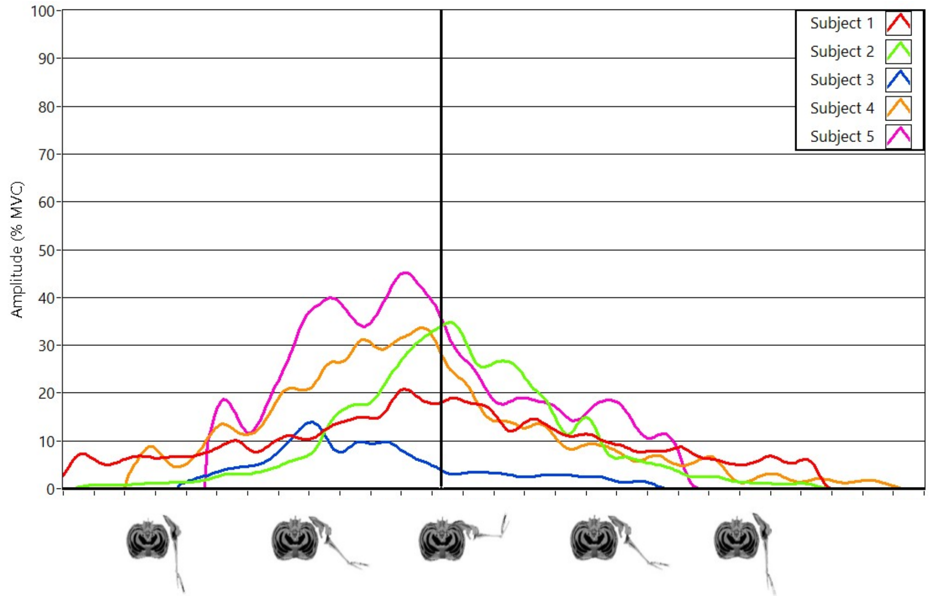

Figure 39 - Normalized rhomboid minor EMG signal during abduction for all subjects

Rhomboid Major (Table 15, Figure 40)

Rhomboid major demonstrated a unimodal peak pattern with peak activation occurring within a few degrees of end range GH and ST external rotation across all subjects. Activation amplitude varied somewhat with two subjects achieving very high activation levels, two achieving moderate levels and Subject Four only achieved a low activation level. Overall, rhomboid major is well-conserved with respect to activation pattern and timing with some variation in amplitude in its role retracting the scapula during external rotation.

Table 15 - Peak activation of rhomboid major as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	End range	1.5° Prior to end range	72.57%
2	1° Prior to end range	4° Prior to end range	30.57%
3	2° Prior to end range	End range	81.45%
4	1° Prior to end range	End range	7.07%
5	1° Prior to end range	3° Prior to end range	29.76%
AVG	1° Prior to end range	1.7° Prior to end range	44.28%

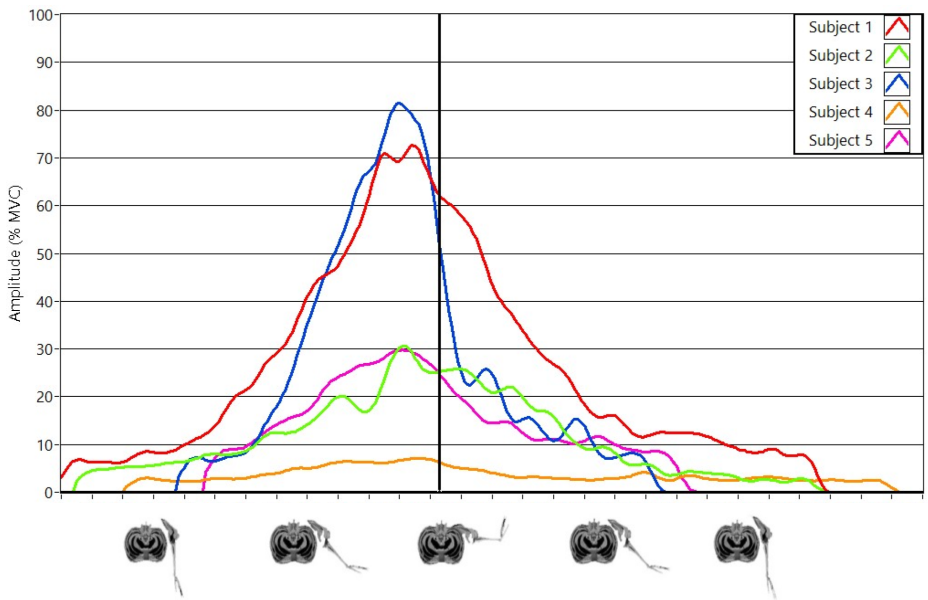

Figure 40 - Normalized rhomboid major EMG signal during abduction for all subjects

Teres Minor (Table 16, Figure 41)

Teres minor demonstrated a unimodal peak pattern with peak activation occurring within a few degrees of end range GH and ST external rotation across all subjects. Four of five subjects demonstrated peak activation amplitude of high to very high levels. Subject One demonstrated a low level of peak activation. Overall, teres minor was highly conserved with respect to activation pattern, timing and amplitude in its role assisting with GH coupling and external rotation.

Table 16 - Peak activation of teres minor as a percentage of MVC and the timing of peak activation in reference to GH and ST position during external rotation

Subject	GH position at peak	ST position at peak	Peak Activation
1	End range	1.5° Prior to end range	17.03%
2	1° Prior to end range	4° Prior to end range	50.90%
3	3° Prior to end range	3° Prior to end range	88.97%
4	4° Prior to end range	1° Prior to end range	42.14%
5	2° Prior to end range	5° Prior to end range	77.77%
AVG	2° Prior to end range	2.9° Prior to end range	55.36%

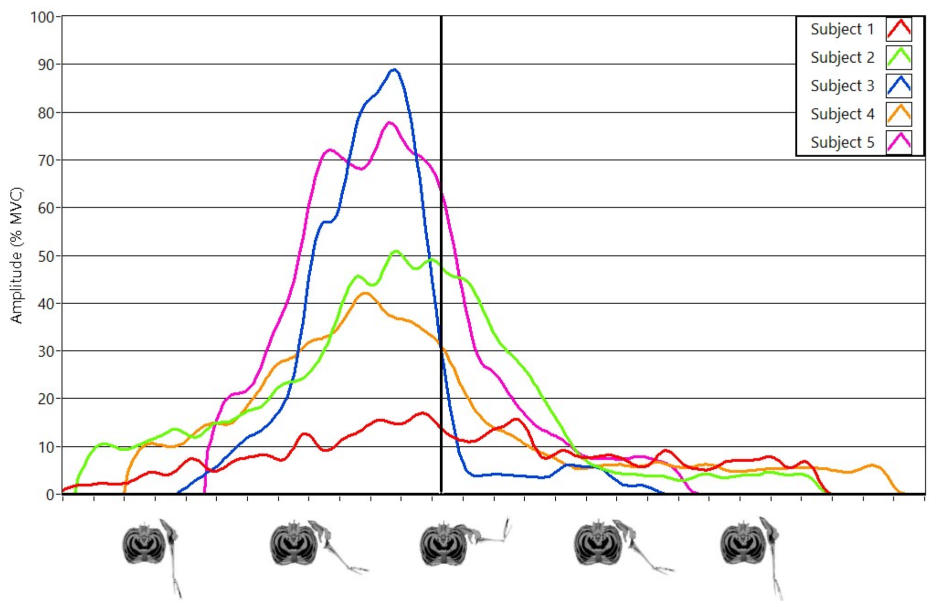

Figure 41 - Normalized teres minor EMG signal during abduction for all subjects

Teres Major (Figure 42)

Teres major demonstrates varying patterns of activation with variable timing across all subjects. Peak activation amplitude was low across all subjects. Overall, teres major appears to play a minor and highly individualized role in anterior GH joint stabilization during external rotation.

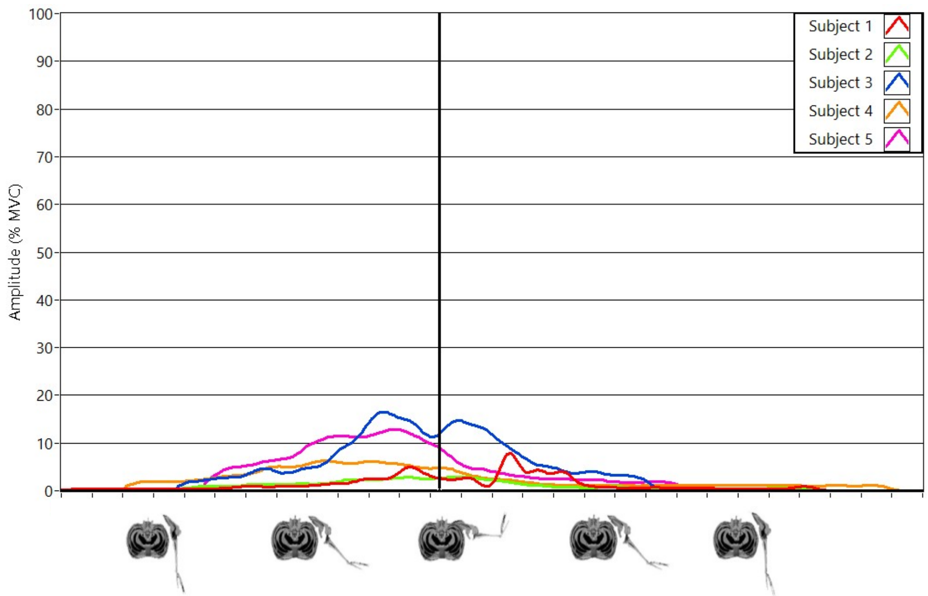

Figure 42 - Normalized teres major EMG signal during abduction for all subjects

Subscapularis (Figure 43)

Subscapularis demonstrated a unimodal peak pattern with peak activation occurring within a few degrees of end range GH and ST external rotation across all subjects. Peak activation amplitude varied somewhat between minimal to high activity levels. Overall, subscapularis was well-conserved with respect to activation pattern and timing with some variation in amplitude in its role in anterior GH stabilization during external rotation.

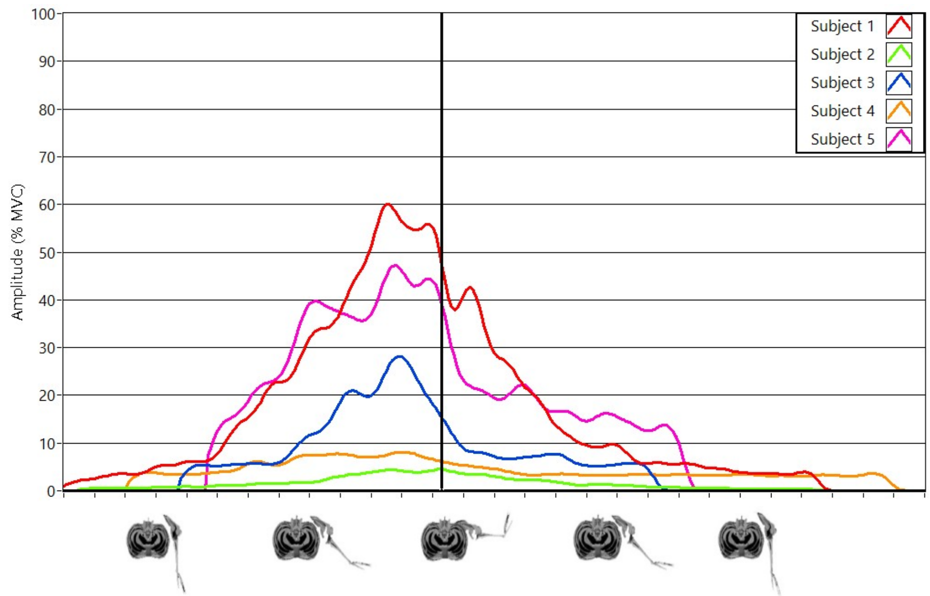

Figure 43 - Normalized subscapularis EMG signal during abduction for all subjects

Serratus Anterior (Figure 44)

Serrated anterior demonstrated varying activation patterns and timing across all subjects. Activation amplitude ranged from low to moderate levels. Overall, serrated anterior was highly individualized in its role in scapular stabilization during external rotation.

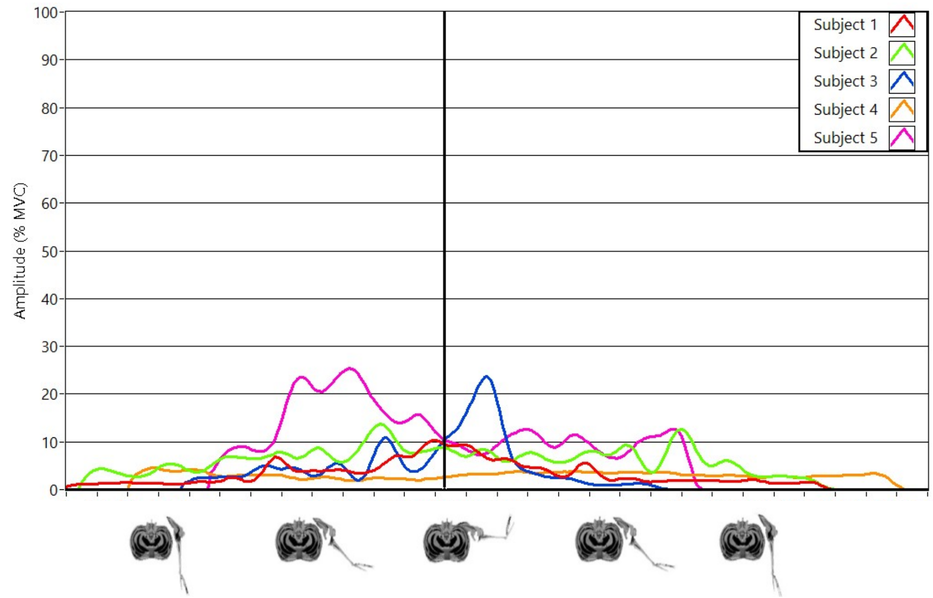

Figure 44 - Normalized serratus anterior EMG signal during abduction for all subjects

Coracobrachialis (Figure 45)

Coracobrachialis demonstrated varying activation patterns and timing across all subjects. Activation amplitude ranged from low to high levels. Overall, coracobrachialis was highly individualized in its role in anterior GH stabilization during external rotation.

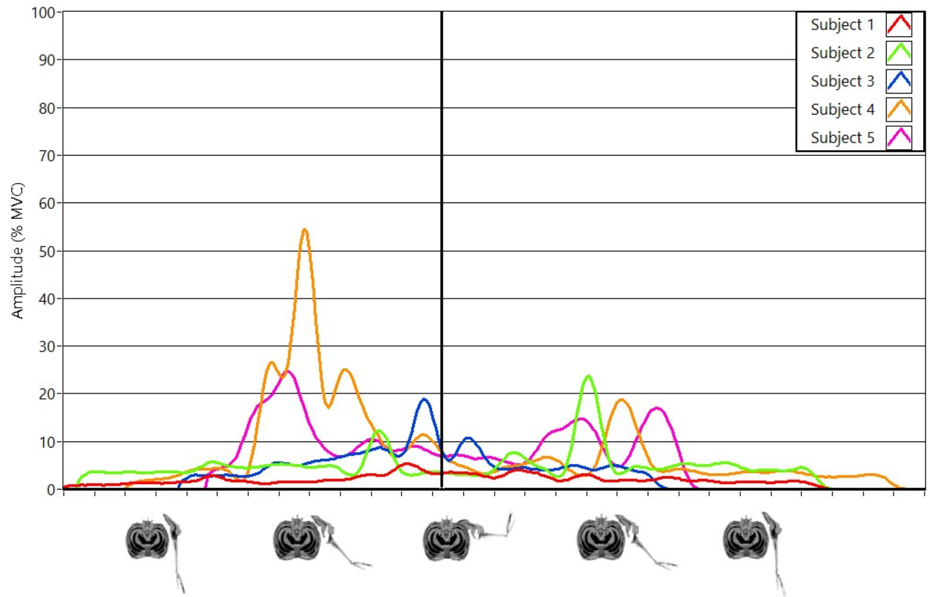

Figure 45 - Normalized coracobrachialis EMG signal during abduction for all subjects

Pectoralis Minor (Figure 46)

Pectoralis minor demonstrated varying activation patterns and timing across all subjects. Activation amplitude ranged from low to moderate levels. Overall, pectoralis minor was highly individualized in its role in anterior scapular stabilization during external rotation.

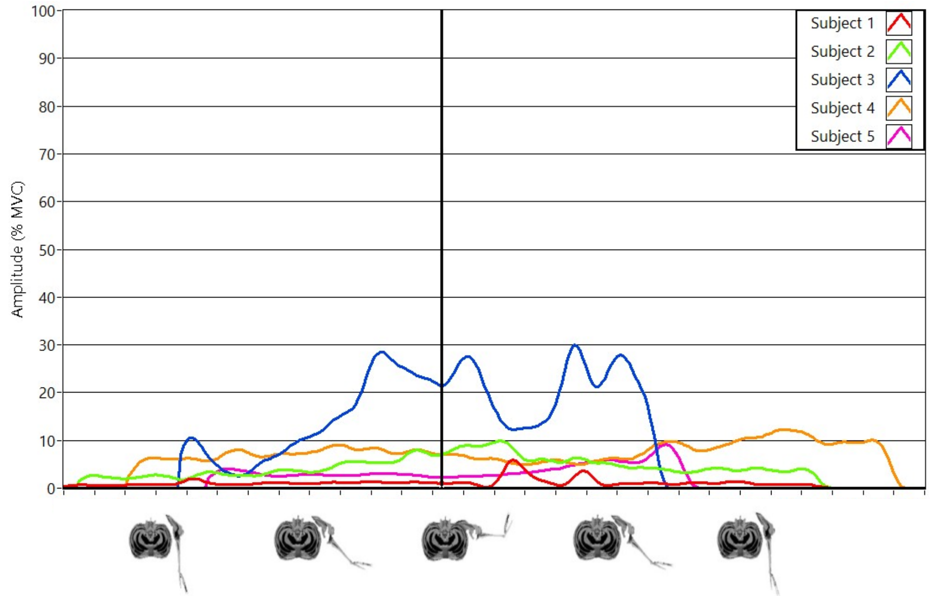

Figure 46 - Normalized pectoralis minor EMG signal during abduction for all subjects

Pectoralis Major (Figure 47), Anterior Deltoid (Figure 48), Posterior Deltoid (Figure 49), Latissimus Dorsi (Figure 50), Biceps Brachii (Figure 51), Triceps Brachii (Figure 52)

Pectoralis major, anterior deltoid, posterior deltoid, latissimus dorsi, biceps brachii, and triceps brachii all demonstrated minimal to low activity across all subjects suggesting it plays no significant role in external rotation.

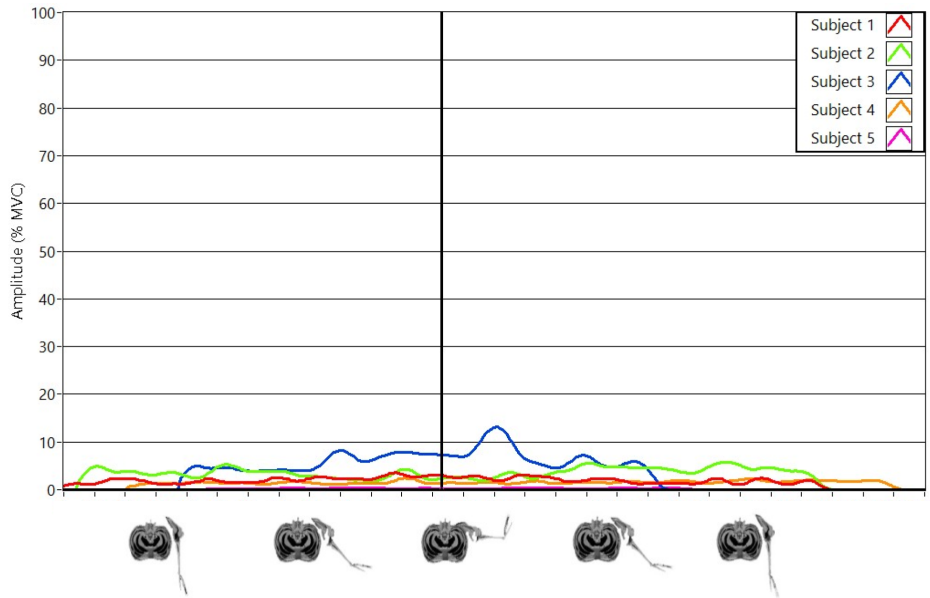

Figure 47 - Normalized pectoralis major EMG signal during abduction for all subjects

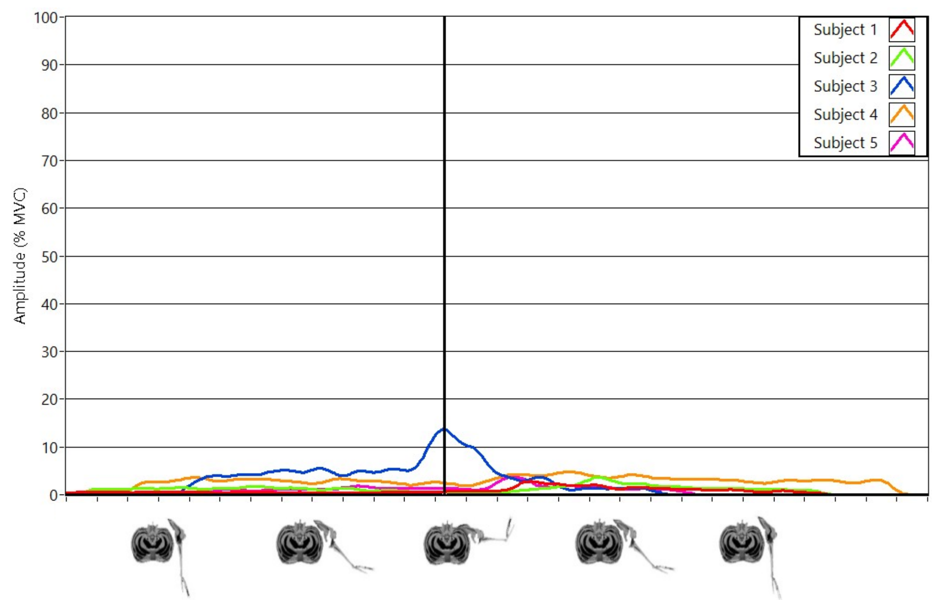

Figure 48 - Normalized anterior deltoid EMG signal during abduction for all subjects

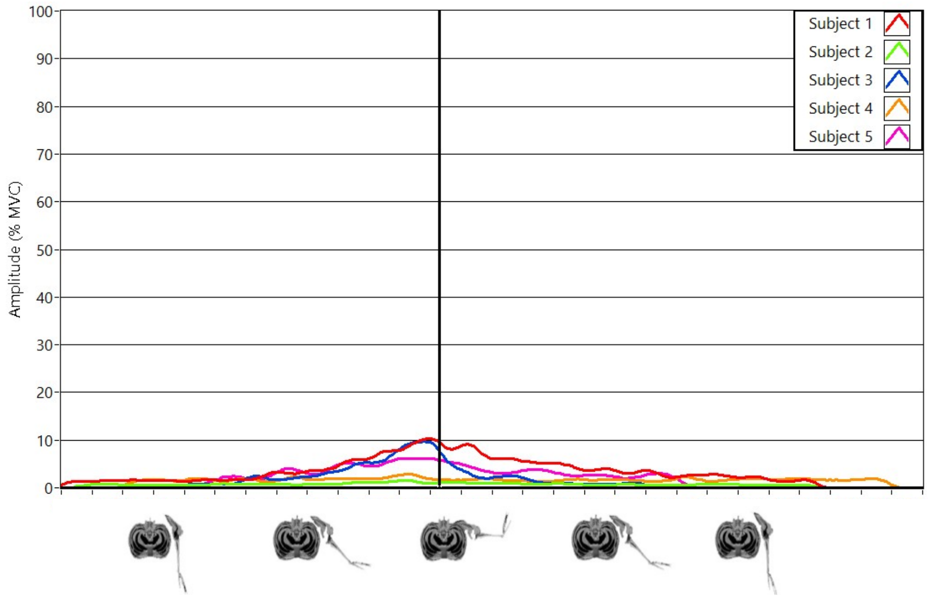

Figure 49 - Normalized posterior deltoid EMG signal during abduction for all subjects

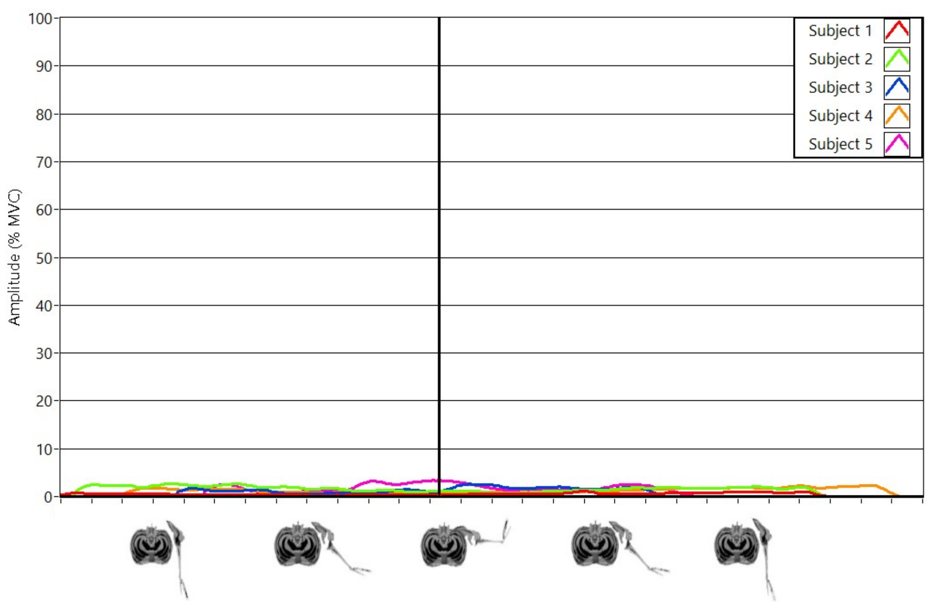

Figure 50 - Normalized latissimus dorsi EMG signal during abduction for all subjects

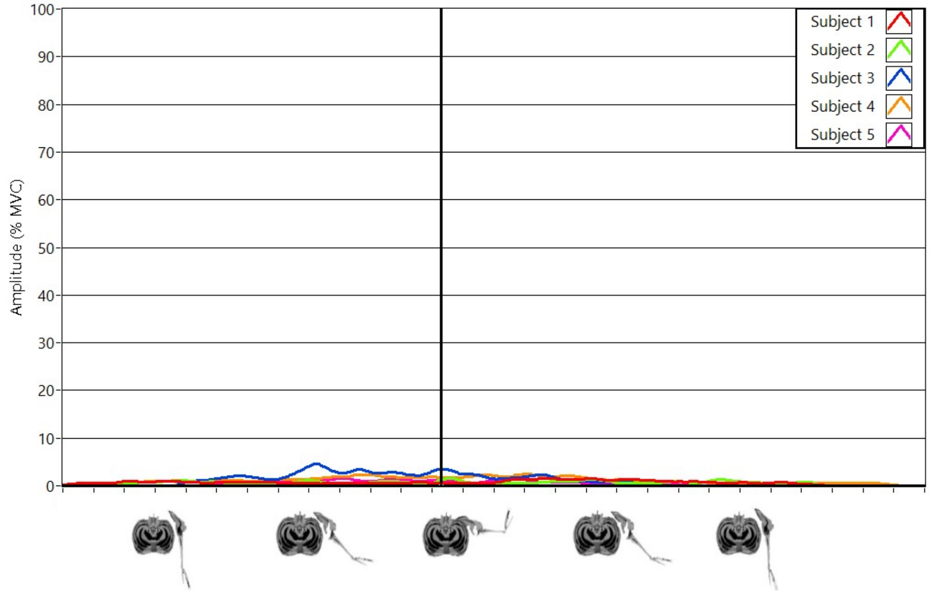

Figure 51 - Normalized biceps brachii EMG signal during abduction for all subjects

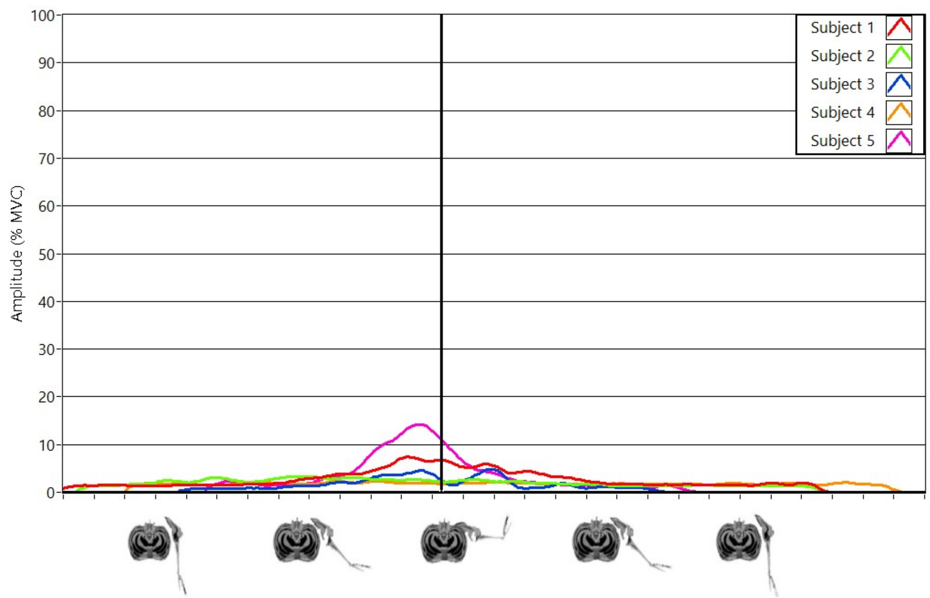

Figure 52 - Normalized triceps brachii EMG signal during abduction for all subjects

3.4. Discussion

This study focused on describing normal shoulder muscle activation patterns during external rotation. From this data, muscular roles in achieving external rotation can be inferred (i.e. primary movers versus stabilizers versus inactive muscles). In addition, certain synergistic relationships were observed providing some insight into muscular control and coordination during external rotation.

3.4.1. Muscle Roles and Conservation

Combining activation onset, waveform amplitude and timing, observed segment motion, and known anatomical attachments and lines of action made it possible to infer the roles of muscles in accomplishing external rotation. Muscles were categorized as to whether they were serving as primary movers of body segments versus joint or segment stabilizers during the motion. Muscles were further categorized as to the body segment or joint upon which their forces were applied.

The primary movers of external rotation were middle trapezius, lower trapezius, infraspinatus, teres minor and rhomboid major (Fig. 53). The primary humeral movers are infraspinatus and teres minor. Both were highly conserved with respect to activation pattern, timing, and amplitude in externally rotating the humeral head in the glenoid.

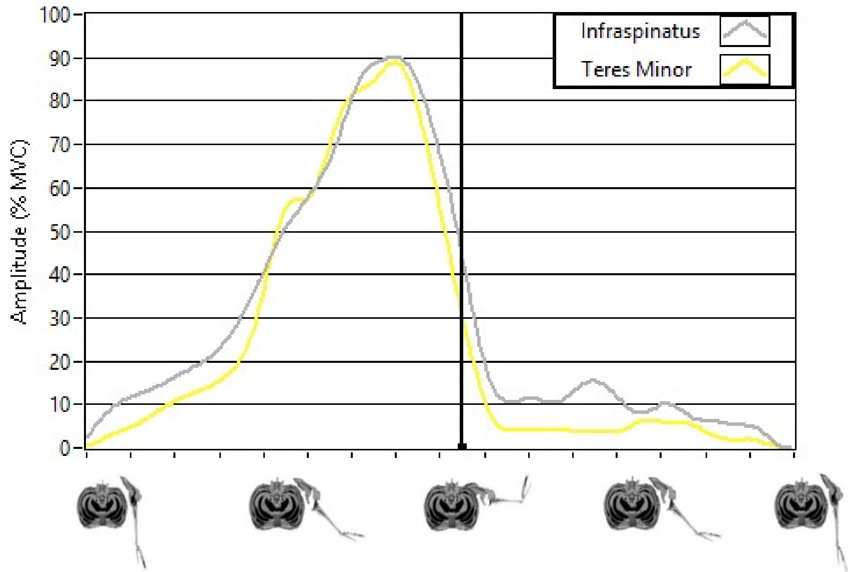

Figure 53 - Normalized EMG signal of the humeral primary movers of a representative subject during external rotation

The primary scapular movers were middle trapezius, lower trapezius, and rhomboid major (Fig. 54). All three muscles were well-conserved with respect to activation pattern and timing but varied somewhat in their peak activation amplitude. These three muscles appeared to work in conjunction at relatively similar magnitudes within subjects to retract and externally rotate the scapula to allow for maximal humeral external rotation.

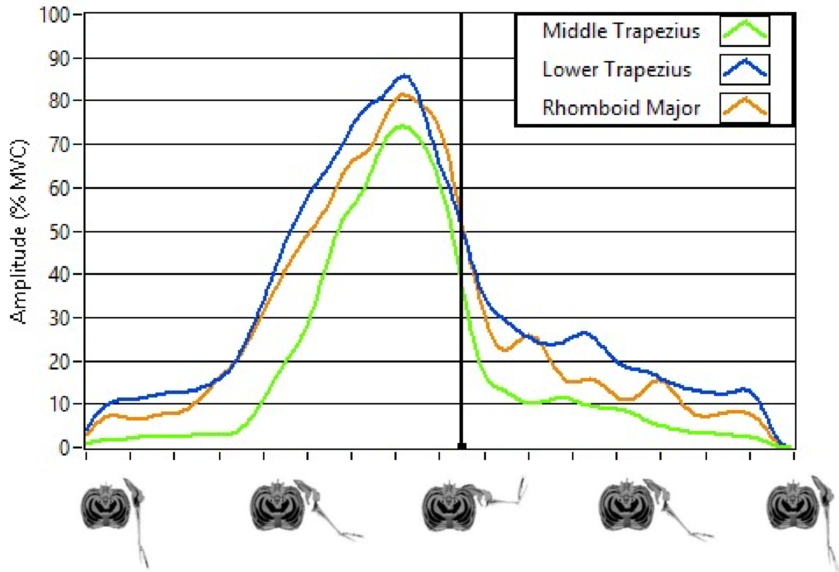

Figure 54 - Normalized EMG signal of the scapular primary movers of a representative subject during external rotation

The primary stabilizers of external rotation are teres major, subscapularis, pectoralis minor and coracobrachialis (Fig. 55). Teres major, subscapularis and pectoralis minor were somewhat variable in their functional characteristics with subscapularis being the most consistent during stabilization of the anterior GH joint to prevent anterior GH dislocation during external rotation. Coracobrachialis was active but highly individualized maintaining the elbow at 90º during external rotation.

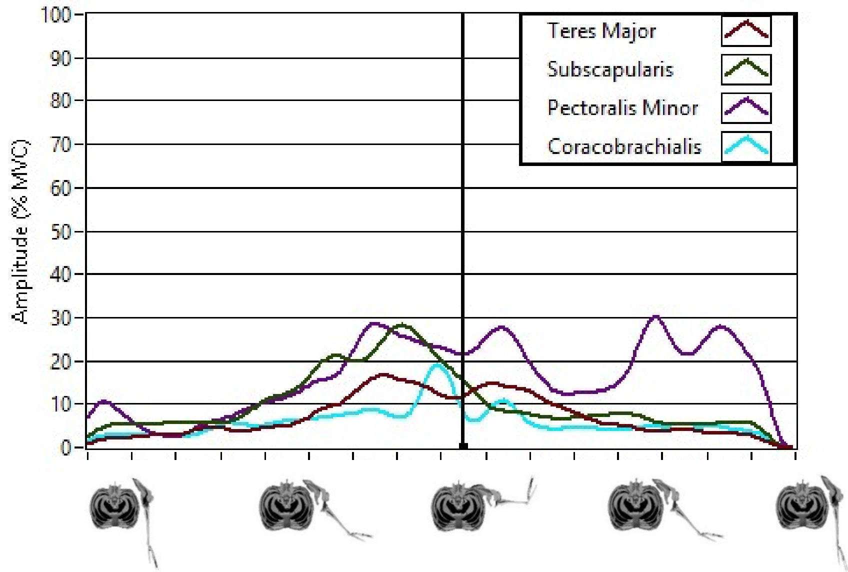

Figure 55 - Normalized EMG signal of the primary stabilizers of a representative subject during external rotation

The mixed movers/stabilizers of external rotation are upper trapezius, levator scapulae, supraspinatus, rhomboid minor, and serratus anterior (Fig. 56). All of these muscles work on either assisting with and/or stabilizing the ST joint during external rotation. Upper trapezius, levator scapulae and rhomboid minor were more conserved in there activity while supraspinatus and serratus anterior were more highly individualized.

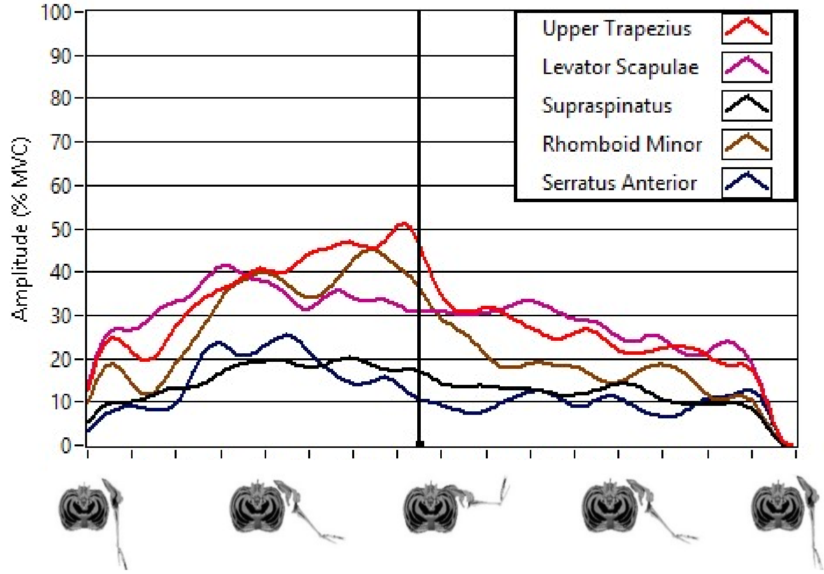

Figure 56 - Normalized EMG signal of the scapular mixed movers/stabilizers of a representative subject during external rotation

The inactive muscles of external rotation are pectoralis major, anterior deltoid, posterior deltoid, latissimus dorsi, biceps brachii, and triceps brachii (Fig. 57).

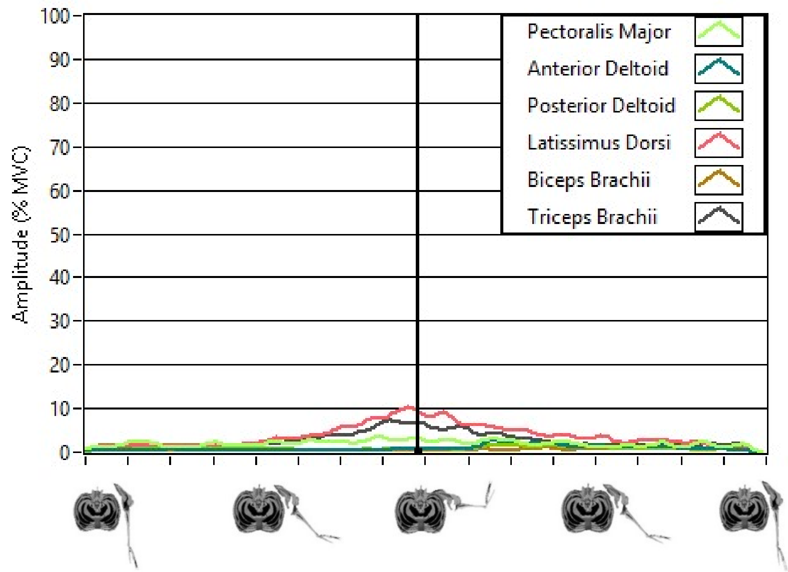

Figure 57 - Normalized EMG signal of the inactive muscles of a representative subject during external rotation

3.4.2. Synergistic Relationships

During the course of data analysis, certain muscles were found to demonstrate unique relationships with respect to timing and/or waveform symmetry that begged special commentary. The synergistic relationship observed during external rotation was the synchronized timing of the primary humeral and scapular movers. Figure 58 demonstrates how the activation patterns and timing of middle trapezius, lower trapezius, infraspinatus, rhomboid major and teres minor coincide despite acting on different body segments. This is strong evidence to suggest close neurologic coordination of scapular and humeral control, otherwise known as the scapular-humeral rhythm.

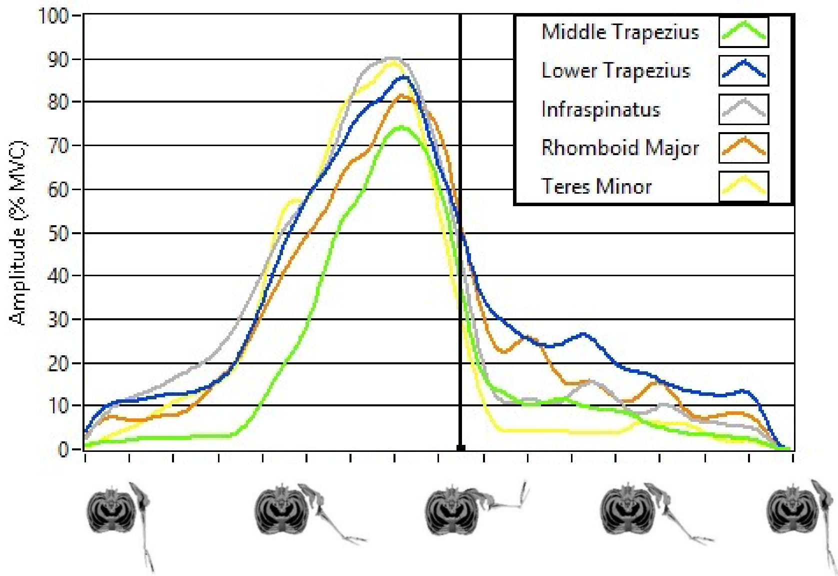

Figure 58 - Normalized EMG signal of the humeral and scapular primary movers of a representative subject during external rotation

3.4.3. Limitations

There were two main limitations to this study to consider. First would be the relatively limited number of subjects. Secondly, several methods of mathematically analyzing waveform symmetry were investigated including signal integration, integration of subtracted signals and waveform symmetry metrics via eigenvector analysis. However, all of these methods failed to detect certain aspects of waveform symmetry or asymmetry with respect to the goals of analysis of this study. Therefore, visual analysis by the investigators was relied upon to determine waveform symmetry and subsequent conservation of muscle activation characteristics.

Despite limitations, this study's data reveal novel aspects of shoulder muscle activation, function and coordination that will be useful for clinicians and researchers alike. It will also be useful for validating musculoskeletal models of the shoulder and will be made available for this purpose. Similar analysis of hand-to-mouth, hand-to-nape, and hand-to-spine are to follow.

Chapter 4

DISSERTATION SUMMARY

A summary of findings from the abduction and external rotation trials brought to light some novel aspects of shoulder function in addition to supporting some previously held understanding of shoulder function. During abduction, supporting evidence was demonstrated for supraspinatus and anterior deltoid as the primary humeral movers. A synergistic relationship between the two was observed with supraspinatus initiating GH abduction and anterior deltoid subsequently assuming and completing the motion. It was also found that upper trapezius, middle trapezius, lower trapezius and levator scapulae were the primary movers of the scapula during abduction. Levator scapulae activation, interestingly in concurrent timing with supraspinatus, initiated scapular movement with the three divisions of trapezius demonstrating varying activation strategies to complete scapular upward rotation. Infraspinatus, teres minor, subscapularis, serratus anterior, rhomboid minor, rhomboid major, pectoralis minor, coracobrachialis and posterior deltoid demonstrate more supportive roles while teres major, pectoralis major, latissimus dorsi, biceps brachii, and triceps brachii were largely inactive during abduction.

During external rotation, supporting evidence was demonstrated for infraspinatus and teres minor as the primary humeral external rotators with extraordinarily synchronized timing. Additionally, middle trapezius, lower trapezius and rhomboid major were demonstrated to be the primary scapular retractors during external rotation also with remarkably similar timing. Upper trapezius, levator scapulae, supraspinatus, rhomboid minor, serratus anterior, teres major, subscapularis, pectoralis minor and coracobrachialis demonstrated a mostly supportive role in external rotation. Pectoralis major, anterior deltoid, posterior deltoid, latissimus dorsi, biceps brachii and triceps brachii were essentially inactive during external rotation.

The knowledge gained from the abduction and external rotation trials demonstrates the aims of this study were undoubtedly met. The clearly defined roles and timing information resultant from these motion trials expands the knowledge base of shoulder function and may lead to improved medical and surgical therapeutic decisions for patients. Together with similar analysis and interpretation of hand-to-mouth, hand-to-nape, and hand-to-spine to follow, the motion capture and EMG data from all trials will be stored in a public databank for use for musculoskeletal modeling of the shoulder.

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Appendix

A. IRB/HUMAN SUBJECTS APPROVAL

UNIVERSITY OF DELAWARE

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	April 17, 2015
TO:	Robert Quinton, D.O.
FROM:	University of Delaware IRB
STUDY TITLE:	[724623-1] A Comprehensive Electromyographic Study of the Shoulder
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	April 17, 2015
EXPIRATION DATE:	March 17, 2016
REVIEW TYPE:	Full Committee Review

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Full Committee Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

- 1 - Generated on IRBNet

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.