SUBACROMIAL SHOULDER PAIN: A LOOK AT ACUTE MUSCLE PAIN, ACUTE RELIEF OF CHRONIC PAIN, AND AN ELECTROMYOGRAPHY NORMALIZATION TECHNIQUE

by

JENNIFER LEE COOPER

A DISSERTATION

Presented to the Department of Human Physiology
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

March 2021

DISSERTATION APPROVAL PAGE

Student: Jennifer Lee Cooper

Title: Subacromial Shoulder Pain: A Look at Acute Muscle Pain, Acute Relief of Chronic Pain, and an Electromyography Normalization Technique

This dissertation has been accepted and approved in partial fulfillment of the requirements for the Doctor of Philosophy degree in the Department of Human Physiology by:

Andrew Karduna	Chairperson
Michael Hahn	Core Member
Anita Christie	Core Member
Elliot Berkman	Institutional Representative

and

Kate Mondloch	Interim Vice Provost and Dean of the Graduate School

Original approval signatures are on file with the University of Oregon Graduate School.

Degree awarded March 2021

©2021 Jennifer Lee Cooper

DISSERTATION ABSTRACT

Jennifer Lee Cooper

Doctor of Philosophy

Department of Human Physiology

March 2021

Title: Subacromial Shoulder Pain: A Look at Acute Muscle Pain, Acute Relief of Chronic Pain, and an Electromyography Normalization Technique

Shoulder pain is a common orthopedic concern. The pain has a wide range of possible causes and may progress in a number of different manners. One large gap in knowledge is the specific pathway of a chronic condition resulting from an acute injury. The purpose of this dissertation was to begin to close that gap from both ends, investigating muscular changes after acute pain is introduced and after chronic pain is acutely relieved. Additionally, an electromyography normalization technique was investigated as a means to facilitate research in a patient population. The results indicate decreases in rotator cuff muscle activity both with acute pain and the acute relief of chronic pain. This suggests acute reactions and chronic adaptations to pain differ and require further investigation.

CURRICULUM VITAE

NAME OF AUTHOR: Jennifer Lee Cooper

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene OR
George Washington University, Washington DC
Massachusetts Institute of Technology, Cambridge MA

DEGREES AWARDED:

Doctor of Philosophy, Human Physiology, 2021, University of Oregon
Master of Science, Human Physiology, 2018, University of Oregon
Master of Science, Exercise Science, 2015, George Washington University
Bachelor of Science, Course 2, 2002, Massachusetts Institute of Technology

GRANTS, AWARDS, AND HONORS:

Eugene & Clarissa Evonuk Memorial Graduate Fellowship in Physiology, University of Oregon, 2020

Logistics Management Institute Student Veterans Scholarship, 2016

AT&T Veterans Scholarship, 2016

ACKNOWLEDGMENTS

First off, I’d like to thank the Eugene & Clarissa Evonuk Memorial Graduate Fellowship committee. We all seem to think that what we are doing is important (else why do it?), but there’s something special about someone agreeing and supporting the work.

Second, my lab mates. Primarily Kate and Holly, and of course Marlene. Your humor, our shared frustrations, honesty (is such a lonely word . . .) and above all sarcasm, were integral to my survival in the scholastic environment.

Thanks to my family for supporting that crazy decision to move across the country and go back to school. Thanks also for following me here so we can keep moving forward together. You’re welcome for Oregon.

Lastly, thanks to my Bossman. I know I have been an epic pain in so many ways over the past few years. Thanks for your patience, for letting me spout in circles before realizing you were right, for grammar arguments and smirky eye rolls. While I know I have provided a fair amount of frustration for you, I hope I’ve brought some humor along with it.

Well, one more. Thanks to the angels, those people who have supported me personally behind my back. I am forever grateful and will do my best to pay it forward.

TABLE OF CONTENTS

Chapter Page

Chapter Page

Chapter Page

Chapter Page

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

Table Page

CHAPTER I

INTRODUCTION

1.1. Significance

Shoulder pain is one of the leading complaints of people seeking orthopedic assistance (Castelein, Cools, Parlevliet, & Cagnie, 2016; de Witte et al., 2011; Luime et al., 2004; Michener, McClure, & Karduna, 2003; Seitz, McClure, Finucane, Boardman, & Michener, 2011). The pain may be a result of an acute injury, it could be a chronic condition that worsened over time, or it may be a combination of an acute injury on top of a chronic condition. The pain adaptation model proposed by Lund et al. (1991) predicts that one main result of pain is a reduction in movement amplitude and velocity, presumably as a protective mechanism to lessen the potential for further injury to damaged structures (Hodges, 2015; Lund et al., 1991; Struyf et al., 2014). This is accomplished by reduced activity of agonists and synergists, with increased activity of antagonists (Hodges, 2015; Lund et al., 1991). A different model, proposed by Johansson & Sojka (1991), describes increases in muscle activity associated with rises in tension and stiffness and has been termed the “vicious cycle” model (Johansson & Sojka, 1991). This proposition has received less focus and support than has the pain adaptation model. There has been some evidence supporting Lund’s model (Diederichsen, Winther, Dyhre-Poulsen, Krogsgaard, & Nørregaard, 2009; Falla, Farina, & Graven-Nielsen, 2007; Graven-Nielsen, Svensson, & Arendt-Nielsen, 1997; Graven-Nielsen, Lund, Arendt-Nielsen, Danneskiold-Samsoe, & Bliddal, 2002). Other studies have displayed no change in painful muscles (Castelein et al., 2016; Diederichsen, Winther, et al., 2009; Schulte et al., 2004) or increased agonist activity (Bandholm, Rasmussen, Aagaard, Diederichsen, &

Jensen, 2008; Schulte et al., 2004), neither of which is in accordance with Lund's pain adaptation model (Lund et al., 1991).

Regardless of the model, there are situations in which an absolute task needs to be accomplished despite the pain involved. Here, a reduction in movement amplitude may not be feasible if the kinematic and kinetic parameters are not flexible. A dental assistant may need to hold his or her arms a specific way. An athlete may swing a bat or racquet in a particular manner. A parent may need to lift a child. In such situations, an absolute reduction in activity of agonists and synergists may lead to muscle forces insufficient to accomplish the task. This problem may be addressed in a number of ways: the kinetics or kinematics may be altered, there could be an increase in descending drive, or the person may deem the task undoable. Each of these courses of action has potentially negative consequences, as detailed below.

First, the alteration of kinetics or kinematics may subject other musculature to increased loads that could lead to further damage (Hodges, 2015; Madeleine, Mathiassen, & Arendt-Nielsen, 2008; Mista, Christensen, & Graven-Nielsen, 2015; Muceli, Falla, & Farina, 2014; Struyf et al., 2014). While some variability in movement patterns may be beneficial in a healthy state (Madeleine et al., 2008; Samani, Holtermann, Søgaard, & Madeleine, 2009; Sandlund, Srinivasan, Heiden, & Mathiassen, 2017; Struyf et al., 2014; Wassinger, Sole, & Osborne, 2013), repeatedly shifting to suboptimal positioning may result in undue stress on other structures (Hodges, 2015; Madeleine, Lundager, Voigt, & Arendt-Nielsen, 1999; Madeleine et al., 2008; Mista et al., 2015). Second, an increase in descending drive without alterations in kinematics could override protective mechanisms (Hodges, 2015). Muscle pain has been shown to cause a decrease in motor unit firing rate

(Farina, Arendt-Nielsen, Merletti, & Graven-Nielsen, 2004; Hodges, 2015). An increase in drive could counteract that reduction or increase motor unit recruitment, either or both of which would increase the effort required for the task (Hodges, 2015). The third course of action, avoidance of the task, is potentially the most detrimental to a person. The inability to function could cause a need for assistance and a loss of independence, eventually leading to a reduction in both morale and quality of life (Struyf et al., 2014).

One commonality amongst all three of these potential courses of action is the reduced use of structures that hurt. If the painful area includes a muscle, with time that reduced use leads to atrophy (Kelly et al., 2005). Shoulder pain may be deep in the structure and lead to reduced use of the rotator cuff musculature. Weak rotator cuff musculature, be it an initial cause or a result of pain, is a factor in a positive-feedback cycle potentially leading to catastrophic injury (Mackenzie, Herrington, Horlsey, & Cools, 2015).

One such catastrophic injury is a rotator cuff tear. While this injury can result from acute trauma, it can also be caused by a tendon fraying over time (Mackenzie et al., 2015). Fraying could lead to a full-thickness tear, or it could weaken a tendon to the extent that a relatively minor insult results in a tear (Deutsch, Altchek, Schwartz, Otis, & Warren, 1996). A shoulder pathology consisting of insufficient room between the humeral head and the acromion process of the scapula, a volume known as the subacromial space, is a common cause of increased friction for the rotator cuff tendons (Dong et al., 2015; Graichen, Bonei, Stammberger, Haubner, & Englmeier, 1999; Mackenzie et al., 2015). This condition is called impingement syndrome and is a frequent diagnosis for patients reporting shoulder pain (Castelein et al., 2016; de Witte et al., 2011; Lawrence, Braman, Laprade, & Ludewig, 2014; Michener et al., 2003; Seitz et al., 2011). The circumstances leading to impingement syndrome appear to be multifactorial, but consist primarily of three main mechanisms (de Witte et al., 2011; Mackenzie et al., 2015; Seitz et al., 2011). One mechanism is impaired scapular kinematics, which can lead to a cyclic reduction of the subacromial space (de Witte et al., 2011; Larsen, Juul-Kristensen, Olsen, Holtermann, & Sogaard, 2014; Mackenzie et al., 2015; Seitz et al., 2011; Worsley et al., 2013). A second mechanism is an encroachment on the space by the surrounding structures (de Witte et al., 2011; Mackenzie et al., 2015; Seitz et al., 2011). A third mechanism is the expansion of structures inside the subacromial space (de Witte et al., 2011; Mackenzie et al., 2015; Seitz et al., 2011). The consequence of any of these mechanisms is that the soft tissues in the subacromial space, primarily the supraspinatus muscle and distal tendon, do not have the necessary room to slide freely as in a healthy situation. Mechanical impingement may be causing an increase in pressure and friction, either of which could be leading not only to fraying but also to pain (Dong et al., 2015). This pain could be causing further changes which may be detrimental, though they could be beneficial, to shoulder health (Hodges, 2015; Wassinger et al., 2013).

Pain is a complex phenomenon. It can be acute or chronic, persistent or intermittent, burning, aching, stabbing, shooting, dull, or sharp (Graven-Nielsen & Arendt-Nielsen, 2010). The wide array of pain types and potential sources complicates the determination of its effects (Dean, Gwilym, & Carr, 2013). Those effects also likely differ between the types of pain. Differences in muscle activity have been demonstrated between patients with chronic pain and subjects with acute pain in the same location (Bandholm et al., 2008; Diederichsen, Winther, et al., 2009; Madeleine et al., 2008). This indicates that acute reactions and chronic adaptations to pain differ (Bandholm et al., 2008; Hodges, 2015; Madeleine et al., 2008). Lund's pain adaptation model (1991) generally predicts a decrease in agonist activity (Lund et al., 1991), while Johansson's vicious cycle model (1991) predicts an increase in activity of painful muscles (Graven-Nielsen & Arendt-Nielsen, 2008; Johansson & Sojka, 1991). Some results support and some run against each of the potentially conflicting hypotheses (Hodges, 2015); this could be partially explained by the differences between acute and chronic conditions.

The lack of a clear effect of pain, be it acute or chronic, is a significant gap in knowledge. The varied results may be due to differences in methods or differences in pain-adaptation strategies, either of which indicates the need for further investigation. The primary goal of this dissertation is to improve our understanding of the effect of pain and pain relief on rotator cuff muscle activity.

1.2. Aims, Hypotheses, and Approach

Three inter-related studies, each with one aim, were conducted independent of each other while using consistent techniques regarding electromyography (EMG) and muscular contractions in order to allow for comparison. The first study focused on an EMG amplitude normalization technique which provides a method that may be more appropriate for use in a patient population than are current normalization methods. The second study focused on the effect of acute pain on muscle activity. The third study focused on the effect of the acute relief of chronic pain on muscle activity.

Aim 1, accomplished by the first study and detailed in Chapter II, was to assess an EMG amplitude normalization method using individualized sub-maximal isometric contractions. The expected result was that normalization of EMG amplitude to a sub-maximal force would be highly reliable and repeatable, regardless of the level of the force.

Aim 2, accomplished by the second study and detailed in Chapter III, was to investigate the effects of experimentally-induced acute shoulder pain on the rotator cuff muscle activity in healthy individuals. It was hypothesized that rotator cuff muscle activity would decrease with experimentally-induced acute pain. Additionally, it was hypothesized that the reductions in muscle activity would remain after the pain had subsided.

Aim 3, accomplished by the third study and detailed in Chapter IV, was to investigate the effects of the acute relief of chronic shoulder pain on the rotator cuff muscle activity in patients diagnosed with impingement syndrome. It was hypothesized that rotator cuff muscle activity would increase with the acute relief of chronic pain.

The overall approach, across all three aims and facilitating the comparison of results, involved consistent techniques regarding EMG, maximal voluntary isometric contractions (MVCs), sub-maximal isometric contractions, and kinematics. The EMG data were collected in the same muscles and in the same manner for all three studies. The

MVCs were performed in the same positions and for the same length of time in all three studies. Sub-maximal isometric contractions were performed in the same positions in all three studies. The initial results from the first study informed the level of submaximal contraction (30%) to be used consistently in later studies. The same kinematic protocol, three smooth repetitions of humeral elevation in the scapular plane, was also used in all three studies.

1.3. Acknowledgement of Co-Authored Material

This dissertation includes unpublished co-authored material. Dr. Andrew Karduna served as a co-author throughout due to his contributions regarding concepts, experimental design and execution, editing, and pervasive guidance. Chapter IV was also co-authored by Dr. Matthew Shapiro who was instrumental in recruiting patients with subacromial pain. Additionally, he performed the vast majority of subacromial injections.

CHAPTER II

NORMALIZATION

2.1. Abstract

There are a number of ways to normalize electromyographical data, the most common of which is using a maximal contraction as a reference. This technique is not always practical. The purpose of this study was to assess the reliability of an electromyographical data normalization technique using predetermined submaximal percentages of an individual’s maximum. Twenty healthy subjects (ten male, ten female) were used for testing, which was performed using both surface and fine-wire electromyography over two sessions at 15, 30, 45, and 60 percent of the day 1 maximum force. Data were compared between days, and the resulting ICC and standard error of the measurement values indicate varying levels of reliability at each submaximal percent. Of the submaximal levels assessed, 30 and 45 displayed the overall highest levels of reliability between days. Both displayed reliability similar to that of normalization to MVC. For situations in which MVC is impractical or anticipated to change, EMG amplitude normalization to one of these submaximal percentages could be a viable technique.

2.2. Introduction

Electromyography (EMG) is a technique of using muscular electrical activity as an indicator of muscle force production. However, the raw levels of electrical activity are highly variable and are affected not only by muscle activity but by hydration level, adiposity, surface preparation, sensor location, and a number of other factors that may be out of experimental control (Allison, Godfrey, & Robinson, 1998; Halaki & Ginn, 2012; Kelly, Kadrmas, Kirkendall, & Speer, 1996). As such, EMG values are generally only useful when considered in a relative sense (Boettcher, Ginn, & Cathers, 2008; Halaki & Ginn, 2012). If the entire EMG data collection is being performed in one session, these factors remain relatively consistent across the session and the EMG can be compared throughout the session within each subject (Halaki & Ginn, 2012). These absolute values cannot, however, be compared between subjects (Halaki & Ginn, 2012). In order to make such a comparison, or to compare between sessions, EMG data are generally normalized for each subject (Burden, 2010; Halaki & Ginn, 2012). This normalization can be performed in a number of ways: peak magnitude displayed during a movement (Bolgla & Uhl, 2007; Yang & Winter, 1984), average magnitude across a movement (Bolgla & Uhl, 2007; Yang & Winter, 1984), magnitude while performing a reference contraction (Yang & Winter, 1984), or magnitude during an M-wave (Burden, 2010; Halaki & Ginn, 2012). One of the most common methods of normalization is comparison to a maximal voluntary contraction (MVC), so all other EMG values can be described as a percent of maximum for that subject (Boettcher et al., 2008; Burden, 2010; Halaki & Ginn, 2012; Kelly et al., 1996). Once normalization has been performed, values can be compared between subjects and between sessions (Halaki & Ginn, 2012).

Although normalization to maximum is widely used, it can be problematic (Allison et al., 1998; Halaki & Ginn, 2012). Research is often being performed using a patient population, and thus a maximal contraction might be challenging or dangerous to elicit since tissues may already be damaged. An MVC could be painful or lead to further damage, or could be unrepresentative of a true maximum due to the nature of the patient state (Allison et al., 1998; Halaki & Ginn, 2012; Hsu, Krishnamoorthy, & Scholz, 2006; Norcross, Blackburn, & Goerger, 2010). Additionally, experimentation often involves an intervention of some sort. Such an intervention may affect an individual's MVC, making it a suboptimal reference point (Park, Lee, & Lee, 2008). Normalization to a changing reference confounds the interpretation of any differences observed. Even without an intervention, maximal contractions have been shown to be more variable and less reliable than submaximal contractions (Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; Yang & Winter, 1983).

One method for avoiding this problem is normalization to a set task, such as lifting a two-kilogram weight. While this method provides consistency within subjects, any absolute task, as opposed to a relative task, does not provide the same challenge between subjects. What may be easy for one subject could be more difficult for another, necessitating a different level of muscle recruitment. This complicates comparison between subjects.

Considering these potential issues, an alternative method is to normalize to a value that is of the same relative intensity between subjects and can be repeated at the same absolute level within subjects. The aim of the present study is to investigate one such method, assessing the viability of normalization to an isometric contraction performed at a submaximal percentage of subjects' MVC force. The goal was to determine whether this method was consistent between two testing sessions on different days. The purpose of the present study was to assess the reliability of submaximal isometric contractions at multiple percentages when used for EMG normalization.

2.3. Methods

2.3.1. Subjects

Twenty subjects were recruited for the present study. Subject age range was 20-39 years (mean 25.0, SD 5.7 years). Ten of the subjects were female, ten male; sixteen subjects reported right hand dominance, four left hand. All subjects were healthy, with no current or previous shoulder injury. Exclusion criteria were any history of surgery or rotator cuff tear in either shoulder, needle-induced syncope, pain while performing any of the prescribed movements, any neurological disorder, or another condition the investigator deemed would make the candidate a poor fit for the study. The University of Oregon Institutional Review Board approved the project and all subjects signed an informed consent form before participating.

2.3.2. Experimental Set-up

All instrumentation and data collection were conducted by a single investigator. The subject’s dominant side was instrumented with wireless Trigno EMG electrodes (Delsys Inc., Boston, MA) and wireless MTi inertia measurement unit (IMU) sensors (Xsens, The Netherlands) to collect muscle activity and kinematic data, respectively. The skin on the dominant shoulder and arm was abraded and cleaned with alcohol, then insertion points for fine-wire EMG collection were determined for the supraspinatus and infraspinatus muscles (Delagi, Iazzetti, Perotto, & Morrison, 2005; Geiringer, 1999). Wires were inserted into the bellies of these two muscles and then connected to spring sensors for fine-wire EMG data collection (Basmajian & De Luca, 1985; Kelly, Cooper, Kirkendall, & Speer, 1997). Surface EMG sensors were placed atop the anterior, middle, and posterior deltoid, upper trapezius, serratus anterior, and latissimus dorsi (Cram, Kasman, & Holtz, 1998).

One IMU was placed on the lateral aspect of the dominant arm, superior to the elbow. The other was placed on the contralateral torso at the level of the xiphoid process. Force was collected through a mounted load cell (Omega Engineering Inc., Norwalk, CT). All data were collected using custom Motion Monitor software at 2000 Hz (Innovative Sports Training, Inc., Chicago, IL). The EMG data were filtered at 20-450 Hz through the Delsys hardware. The Common Mode Rejection Ratio of the system was greater than 80 dB.

2.3.3. Maximal Voluntary Contractions

Two positions were used for isometric contractions: humeral elevation in the scapular plane and external rotation, both conducted while seated. Humeral elevation was performed at 90 degrees of elevation and approximately 30 degrees forward of the frontal plane, elbow extended. External rotation was performed at approximately 10 degrees of abduction, elbow flexed to 90 degrees. The order of contractions (humeral elevation, external rotation) was randomized for each subject. The order was maintained for the second day of testing, which was performed between 2 and 9 (average 5.3) days after the first day of testing. The MVCs were completed on both the dominant and non-dominant sides, with strong verbal encouragement being provided during each attempt. The subject performed each MVC for approximately three seconds and alternated between the dominant and non-dominant sides. Once all MVCs had been performed once, they were performed again for a second attempt in the same order.

2.3.4. Submaximal and Dynamic Contractions

The MVCs performed on the first day of testing were used to determine the submaximal target forces for each subject. The order of submaximal contractions (15, 30, 45, 60 percent) was randomized per subject. The order was maintained on the second day of testing. Using the custom Motion Monitor software, the subject was provided with a computer screen that displayed a visual range of +/- 2% around the target force, e.g. 13-17% for the 15% contraction, and a line indicating the force currently being exerted. The subject was instructed to press against the load cell hard enough to get between the lines and to hold that force for approximately three seconds. Each submaximal contraction was performed twice in each position, humeral elevation and external rotation, using the dominant side. The non-dominant side was not used for submaximal contractions.

Once the submaximal contractions were complete, the subject was given a description of the dynamic contraction, humeral elevation in the scapular plane. The subject performed this movement in a single three-repetition trial. This concluded testing for that day; the instrumentation was removed and the subject was excused.

2.3.5. Data Analysis

A custom LabVIEW program (National Instruments Corporation, Austin, TX, USA) was used to perform the data processing. A Root Mean Square (RMS) analysis was performed using a 200-millisecond window. For the maximal contractions, the peak force was determined and the 200-millisecond window around that peak was used. For the submaximal contractions, a range of plus/minus two percent of the target force (the same range given to the subjects for visual feedback) was calculated and the first 200 milliseconds inside that window were used to represent the EMG at that submaximal percentage.

All IMU data were processed using the ISB standard for humerothoracic kinematics (YXY Euler angle rotation sequence) (Wu et al., 2005), generating plane, elevation, and internal/external rotation of the humerus relative to the thorax. These data were used to determine the point at which the subject achieved ninety degrees of humerothoracic elevation. A time window of 200 milliseconds around that point was selected as the portion of the EMG data to be normalized using each technique.

The submaximal EMG values were linearly extrapolated to determine a projected 100% value for normalization purposes. For example, the value obtained at 30% was divided by 0.3 to calculate a projected value at 100%, assuming a linear relationship between force and EMG. This calculation was performed for comparison purposes between normalization techniques.

2.3.6. Statistical Analysis

An intraclass correlation coefficient (ICC) was determined for each method of normalization (four submaximal percentages and MVC). The ICC model used was a two-way mixed effects where people effects are random and measures effects are fixed (ICC

3,1). SPSS (IBM Corporation, Release 26.0.0.0) was used to perform these analyses. The standard error of the measurement was also calculated for each method of normalization:

$$SEM = S_{pooled}\sqrt{1 - ICC}$$

Equation 2. 1

where S_{pooled} is the pooled standard deviation:

$$S_{pooled} = \sqrt{\frac{(SD_1^2 + SD_2^2)}{2}}$$

Equation 2. 2

where $SD_1$is the standard deviation on day 1 and SD_2 is the standard deviation on day 2.

Additionally, a paired *t*-test was used to compare the forces produced by the dominant and non-dominant arms during MVCs.

2.4. Results

None of the data collected initially were excluded from analysis. The analysis was performed in two manners: retaining and excluding outliers, as determined by the value exceeding three standard deviations from the mean. For the normalization to 15%, three values were outlying: one anterior deltoid, one upper trapezius, and one latissimus dorsi. For the normalization to 30%, two values were outlying: one infraspinatus and one posterior deltoid. For the normalization to 45%, one value was outlying: a supraspinatus. For the normalization to 60%, six values were outlying: one anterior deltoid, two posterior deltoids, one latissimus dorsi, one serratus anterior, and one supraspinatus. For the normalization to MVC, seven values were outlying: two anterior deltoid, two posterior deltoid, two supraspinatus, and one infraspinatus.

Results are displayed below. They are presented first with the outliers excluded (Figure 2.1, Table 2.1), then with the outliers retained (Figure 2.2, Table 2.2).

Considering the potential uses of this normalization technique, it seemed prudent to determine whether the maximum force value on the non-dominant side could be used as a proxy for the dominant side and vice versa. In order to inform that potential use, a comparison of the force elicited during MVCs on the dominant and non-dominant side was performed. Those results displayed no significant difference between sides for either the humeral elevation or the external rotation MVC performed, so one side could indeed be used as a proxy for the other ($p = 0.85$ and 0.83, respectively, Figure 2.3).

2.5. Discussion

The purpose of the present study was to assess the reliability of submaximal percentages used for EMG normalization. Normalization to a submaximal contraction could be a useful technique for a number of reasons (Halaki & Ginn, 2012). Regarding safety and comfort, maximal contractions, which are widely used for normalization (Halaki & Ginn, 2012; Kelly et al., 1996), could cause further damage or pain in a patient population (Allison et al., 1998; Halaki & Ginn, 2012; Hsu et al., 2006).

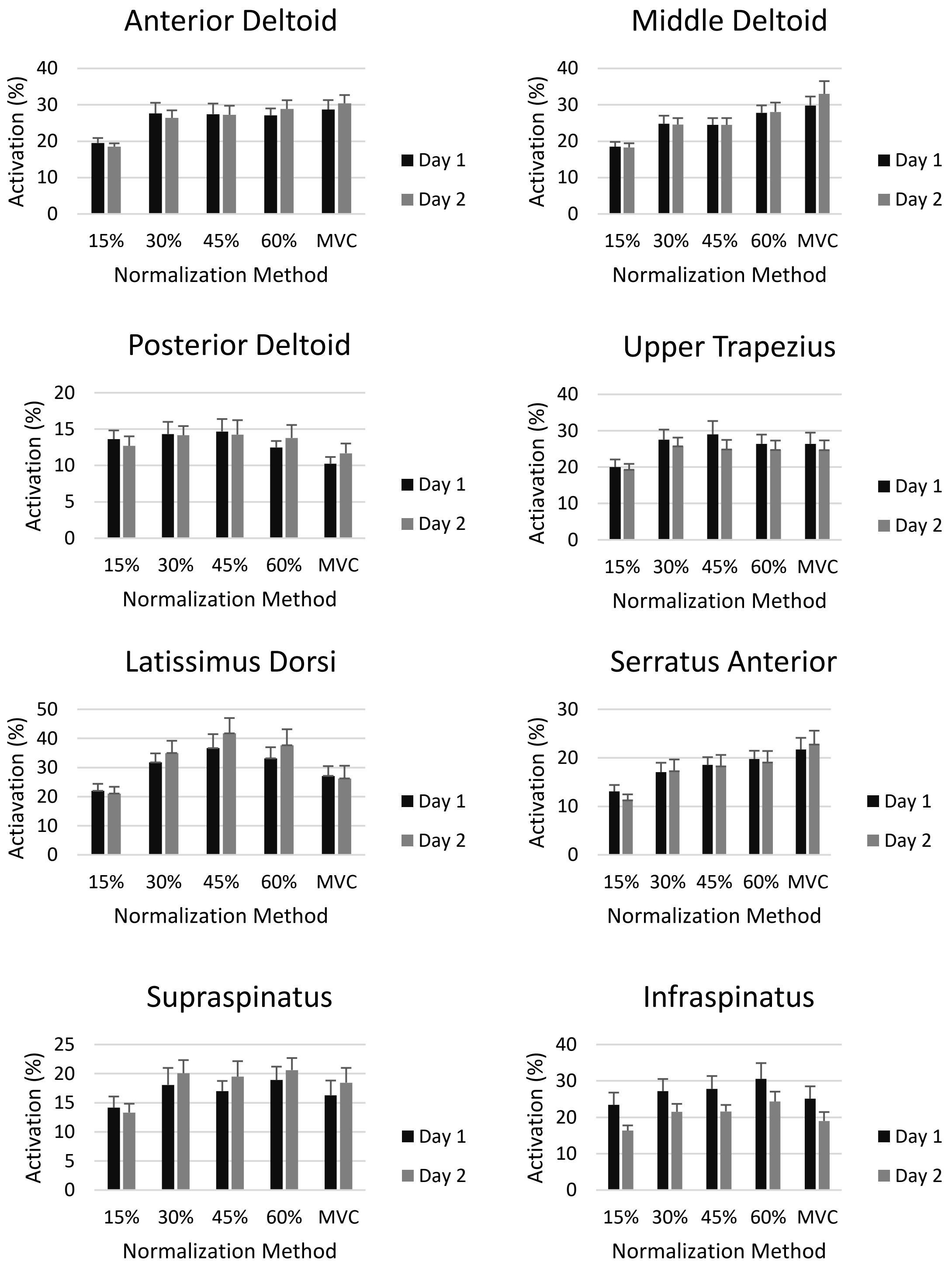

Figure 2.1**.** Graphs of EMG Amplitude Normalization with Outliers Excluded. EMG amplitude at ninety degrees of humeral elevation normalized to four submaximal (15, 30, 45, 60 percent) values and to MVC. Day 1 (black) and day 2 (grey) mean values and associated standard errors of the mean are displayed for each of the eight muscles tested. These values exclude any data points exceeding 3 standard deviations from the mean.

Table 2.1. EMG Amplitude Normalization ICCs and SEMs with Outliers Excluded

Summary of Intraclass Correlation Coefficients and Standard Errors of the Measurement for between-day normalization, outliers removed

	Normalization technique									
	15%		*30%*		*45%*		*60%*		*MVC*	
Muscle	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*
Anterior Deltoid	0.56	3.3	0.77	5.4	0.85	4.7	0.74	4.8	0.88	3.7
Middle Deltoid	0.51	3.8	0.71	4.9	0.81	3.6	0.70	5.7	0.68	7.7
Posterior Deltoid	0.57	3.7	0.79	2.9	0.85	3.2	0.61	3.8	0.52	4.2
Upper Trapezius	0.66	4.8	0.74	6.0	0.63	8.7	0.63	7.0	0.82	5.4
Latissimus Dorsi	0.21	9.2	0.51	11.5	0.45	16.7	0.35	16.7	0.77	8.3
Serratus Anterior	0.61	3.6	0.83	4.1	0.80	4.0	0.63	5.5	0.73	6.2
Supraspinatus	0.41	5.9	0.65	6.9	0.42	7.5	0.44	7.1	0.10	10.2
Infraspinatus	0.13	10.7	0.51	8.6	0.23	11.1	-0.05	16.7	0.61	8.1

Note. The listed *SEM* follows the ICC of the associated normalization technique. The ICC model used was two-way mixed effects where people effects are random and measures effects are fixed (3,1).

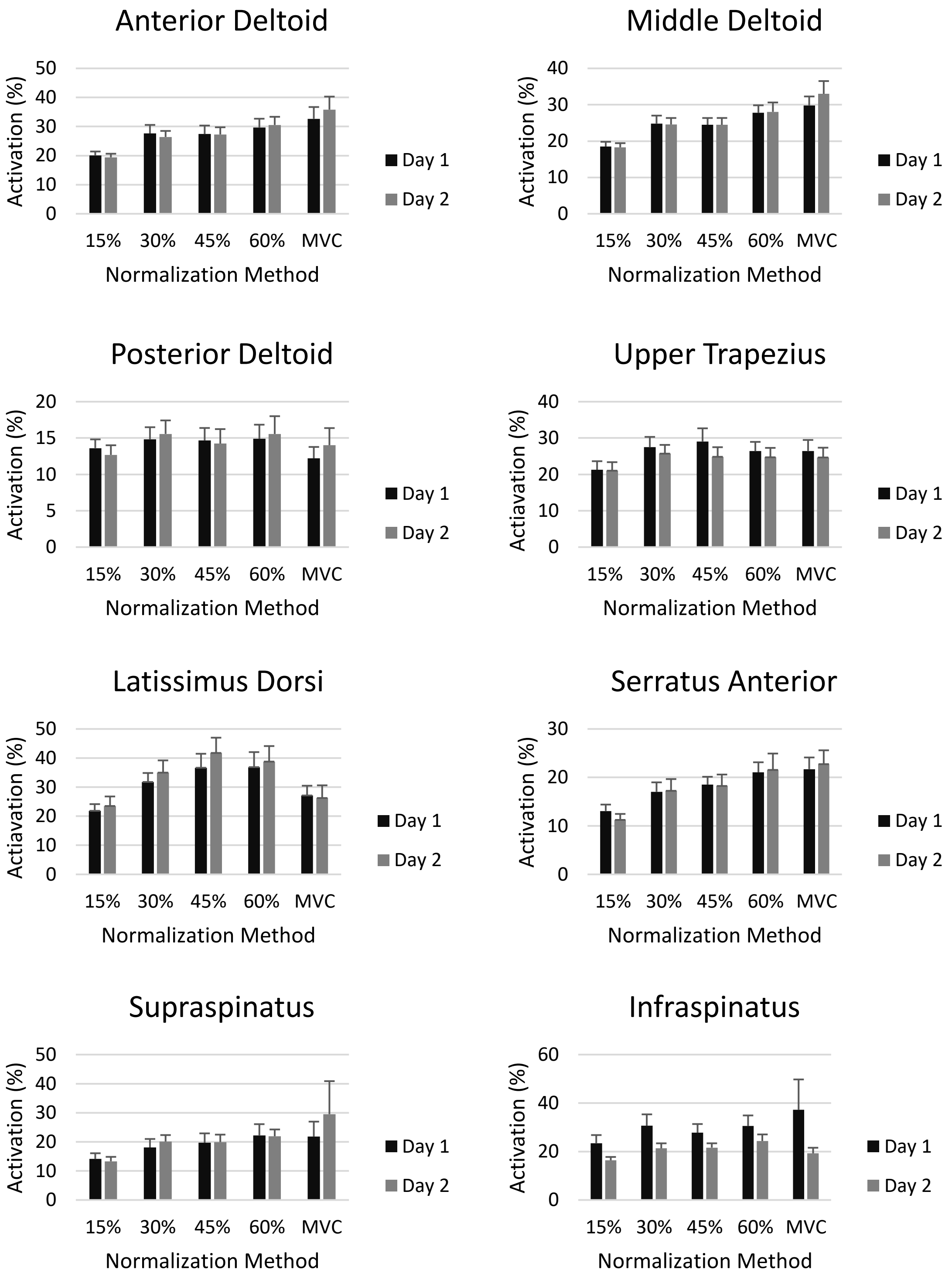

Figure 2.2. Graphs of EMG Amplitude Normalization with Outliers Retained. EMG amplitude at ninety degrees of humeral elevation normalized to four submaximal (15, 30, 45, 60 percent) values and to MVC. Day 1 (black) and day 2 (grey) mean values and associated standard errors of the mean are displayed for each of the eight muscles tested. These values include potential outliers.

Table 2.2. EMG Amplitude Normalization ICCs and SEMs with Outliers Retained

Summary of Intraclass Correlation Coefficients and Standard Errors of the Measurement for between-day normalization, with outliers retained

	Normalization technique									
	15%		*30%*		*45%*		*60%*		*MVC*	
Muscle	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*	*ICC*	*SEM (%)*
Anterior Deltoid	0.70	3.2	0.77	5.4	0.85	4.7	0.87	4.8	0.75	9.5
Middle Deltoid	0.51	3.8	0.71	4.9	0.81	3.6	0.70	5.7	0.68	7.7
Posterior Deltoid	0.57	3.7	0.79	3.7	0.85	3.2	0.58	6.4	0.70	5.0
Upper Trapezius	0.81	4.5	0.74	6.0	0.63	8.7	0.63	7.0	0.82	5.4
Latissimus Dorsi	0.06	12.3	0.51	11.5	0.45	16.7	0.47	17.2	0.77	8.3
Serratus Anterior	0.61	3.6	0.83	4.1	0.80	4.0	0.78	5.9	0.73	6.2
Supraspinatus	0.41	5.9	0.65	6.9	0.45	9.6	0.68	8.1	0.22	3.5
Infraspinatus	0.13	10.7	0.24	14.2	0.23	11.1	-0.05	16.7	0.15	3.7

Note. The listed *SEM* follows the ICC of the associated normalization technique. The ICC model used was two-way mixed effects where people effects are random and measures effects are fixed (3,1).

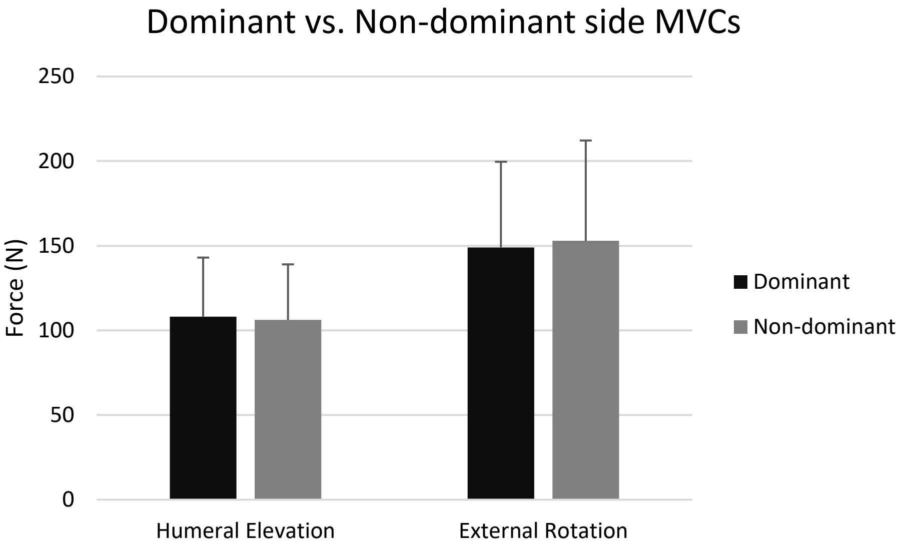

Figure 2.3. Graph of Dominant and Non-Dominant Shoulder MVC Forces on day 1 of testing. Dominant (black) and non-dominant (grey) mean values and associated standard deviations are displayed for each of the two contractions used. No significant differences were observed between dominant and non-dominant sides. Flexion $p = 0.85$, external rotation $p = 0.83$.

Normalization to MVC also provides analytical challenges when the MVC changes (Halaki & Ginn, 2012; Yang & Winter, 1983). Some of these challenges can be managed by referencing a contraction that can be more readily repeated (Allison et al., 1998; Halaki & Ginn, 2012; Norcross et al., 2010).

The normalization of EMG, by nature, relies upon the repeatability of the reference contraction (Burden, 2010). While referencing MVC is the most common normalization technique (Burden, 2010), studies have shown maximal contractions to be less reliable than submaximal contractions (Dankaerts et al., 2004; Netto & Burnett, 2006; Yang & Winter, 1983). They have also shown that patients’ ability to perform a maximal contraction differs from that of healthy subjects (Allison et al., 1998; Ettinger, Weiss, Shapiro, & Karduna, 2016), and that it is influenced by pain (Ettinger, Shapiro, & Karduna, 2017; Park et al., 2008).

Attempts at determining an appropriate submaximal value to which to normalize EMG have been widespread and include a variety of techniques. Many attempts have used mean or peak EMG values measured during movement (Bolgla & Uhl, 2007) or stabilization (Norcross et al., 2010). Different techniques have displayed advantages and disadvantages that depend, in part, on the goal of the analysis (Burden, 2010; Yang & Winter, 1984). When two groups were being compared, the variability within each group was aimed to be minimized in order to highlight differences between the groups. But this minimization of variability within a group would decrease the ability to detect differences within each group, either between subjects or across time (Burden, 2010; Hsu et al., 2006; Yang & Winter, 1984). Considering the different goals of analyses, different measures of reliability are considered and different normalization techniques might be appropriate (Burden, 2010).

Few studies have investigated the use of a submaximal isometric contraction for normalization purposes. Of those that have, most have used either a limb held against gravity or while holding an absolute weight (Allison et al., 1998; Chapman, Vicenzino, Blanch, Knox, & Hodges, 2010; Dankaerts et al., 2004). Two studies have investigated a submaximal load being moved in an isokinetic (Netto & Burnett, 2006) or isotonic (Allison, Marshall, & Singer, 1993) manner. Only three other studies have investigated the reliability of an isometric contraction at a set submaximal percentage (Burnett, Green, Netto, & Rodrigues, 2007; Yang & Winter, 1983; Yang & Winter, 1984). Yang & Winter (1983) first compared both 30% and 50% isometric contractions to MVCs and found both submaximal contractions to have higher reliability than the MVCs for surface EMG of the triceps brachii, the one muscle being monitored (Yang & Winter, 1983). Yang & Winter (1984) later compared a 50% isometric contraction with other surface EMG measures, not including MVC (Yang & Winter, 1984). They found an increase in inter-subject variability (relative to raw EMG values), without an assessment of reliability, in leg muscles (Yang & Winter, 1984). Burnett et al. (2007) compared 60% isometric contractions to MVCs and found that both were highly reliable, with submaximal contractions being no less reliable than MVCs (Burnett et al., 2007). They used both surface and fine-wire EMG of neck muscles. The present study is the first assessment of reliability of submaximal isometric contractions of shoulder muscles and is partially in agreement with previous studies with respect to high reliability relative to maximal contractions.

A large potential for outliers could be detrimental to a technique; it could detract from the reliability when reliability is the main goal of normalization. For that reason, results here are considered both excluding and retaining potential outliers. The intent with this dual analysis is to provide the ability to compare the results in the two conditions (excluding and retaining outliers) and determine the extent to which the potential outliers affect the reliability of the technique being assessed.

The reliability of the submaximal normalization methods varied. While some muscles and percentages were as reliable or more reliable than normalization to MVC, others were less. When potential outliers were removed, 19 of the 32 ICC values were higher using submaximal percentages, the remaining 13 values being higher using MVC. When those potential outliers were retained, 17 of the 32 ICC values were higher using submaximal percentages, the remaining 15 values being higher using MVC. This is an indication that keeping or removing the potential outliers had little effect relative to MVC. Additionally, when the ICC values were compared between outlier removal and retention, 6 of the ICCs were higher when values were removed, while 9 of the ICCs were higher when values were retained. This, again, shows that any potentially outlying values had minimal effect on the overall results.

Four submaximal levels were used: 15%, 30%, 45%, and 60%. Each of those can be compared to MVC in both the outliers excluded and outliers retained scenarios. For 15% and 60%, the ICCs for MVC tended to be higher (15%: 6 of 8 removed, 7 of 8 retained; 60%: 5 of 8 removed, 4 of 8 retained). For 30% and 45%, the ICCs for submaximal contractions tended to be higher than for MVC (both: 4 of 8 removed, 6 of 8 retained). Considering all of these results, the most reliable techniques were 30% and 45% with outliers retained.

The results can be broken down further into individual muscles. Across submaximal percentages and outlier retention techniques, MVC was more reliable than submaximal percentages for the upper trapezius and the latissimus dorsi. Using MVC was less reliable, in all cases, for the supraspinatus. The infraspinatus results displayed consistently higher reliability using MVC than using submaximal percentages, with the exception of 30 and 45% when outliers were retained. For other muscles, the relative reliability depended upon the submaximal percentage and whether outlying data were retained.

The SEM overall displays lower error in the submaximal normalization techniques than in normalization to MVC. When potential outliers were removed, 18 of the 32 SEM values were lower using the submaximal percentages. When those potential outliers were retained, 24 of the 32 SEM values were lower using the submaximal percentages. In all cases, the SEM values were lower using submaximal percentages for the middle deltoid, serratus anterior, and supraspinatus. The SEM values were higher using submaximal percentages for the latissimus dorsi. For other muscles, the error depended upon the submaximal percentage and whether outlying data were retained.

This study was not without limitations. Only four submaximal percentages were assessed; another percentage might be more reliable. The EMG of the latissimus dorsi and serratus anterior were both collected using surface sensors; considering the extent to which these muscles slide beneath the skin, fine wire EMG might have been more appropriate. Lastly, the data analysis was performed with the assumption that the prescribed submaximal percent was achieved; the actual force might have been up to two percent higher or lower. A more precise analysis would have used the actual percent of maximum achieved rather than using the target percentage.

The fact that the MVCs on the dominant and non-dominant sides did not differ indicates that one arm, presumably a healthy one, could be used to determine a submaximal target force for the other, presumably injured, arm. This technique could help prevent further injury or pain on the involved side.

2.6. Conclusions

These results demonstrate that EMG normalization to a submaximal percentage may be a viable technique that has reliability similar to normalization to MVC. Additionally, the maximal force exerted by one shoulder can be used to calculate a target force for a submaximal contraction using the other shoulder. This technique could be useful when assessing muscle activity in cases of an acute injury or a chronic condition.

2.7. Bridge

The present study (Chapter II) demonstrates the manner in which a specified submaximal contraction can be used for electromyographical comparisons between subjects, between days, or between conditions. This result was used to inform the techniques used in the next study. In Chapter III, we investigate the acute effects of experimental pain. While pain has been shown previously to impact maximal voluntary contractions, it has been less clear how muscle pain would affect the accomplishment of a given submaximal task. The results from Chapter II indicate relatively high reliability of isometric contractions performed at 30% of maximum, so that percentage was selected for comparison between three conditions: before, during, and after acute muscle pain, in Chapter III.

CHAPTER III

ACUTE PAIN

3.1. Abstract

Shoulder pain is a complex, prevalent problem that is multifactorial in nature. While there are many potential causes, one common suspect is the rotator cuff musculature. The purpose of the present study was to induce pain in the supraspinatus muscle of healthy subjects and observe the resulting changes in muscle activity. Eight muscles on twenty-three subjects were assessed using electromyography: anterior, middle, and posterior deltoid; pectoralis major; upper trapezius; latissimus dorsi; serratus anterior; supraspinatus; infraspinatus. It was hypothesized that the rotator cuff muscles would display reduced activity during pain, and that reductions in activity would remain after the pain had dissipated. Both of the rotator cuff muscles measured did indeed display reduced activity in a majority of the dynamic, isometric, and maximal contractions. Many of those reductions remained after pain had subsided.

3.2. Introduction

Shoulder pain is common and is experienced by approximately one in three people at some point in their lives (Chester, Smith, Hooper, & Dixon, 2010). The various sources and types of shoulder pain make it challenging to study. Experimentally-induced pain can be more tightly controlled than naturally-occurring pain (Castelein et al., 2016); this control allows for a clear observation of the pain’s effects (Castelein et al., 2016).

The injection of hypertonic saline into soft tissues is one method of inducing acute pain, as it stimulates the local receptors to a nociceptive level and causes localized, temporary pain (Gerber, Galantay, & Hersche, 1998). This experimental technique has been used to determine the effects of acute pain in muscles as well as in neighboring spaces (Castelein et al., 2016; Diederichsen, Winther, et al., 2009; Leffler, Kosek, & Hansson, 2000; Madeleine et al., 1999; Mista et al., 2015; Sole, Osborne, & Wassinger, 2014). The results of such experiments have varied, with some studies showing a decrease in muscle activity of the injected and surrounding muscles (Castelein et al., 2016; Diederichsen, Winther, et al., 2009; Falla et al., 2007; Le Pera et al., 2001; Stackhouse et al., 2013; Wassinger, Sole, & Osborne, 2012), some studies an increase in muscle activity (Diederichsen, Winther, et al., 2009; Mista et al., 2015; Sole et al., 2014), and some no change (Castelein et al., 2016; Khan, McNeil, Gandevia, & Taylor, 2011; Le Pera et al., 2001; Madeleine et al., 1999; Mista et al., 2015; Schulte et al., 2004; Sole et al., 2014). These differences could be in part due to the role of the muscle being investigated, particularly whether it is serving as an agonist or antagonist to movement (Diederichsen, Winther, et al., 2009; Lund et al., 1991). Even with this aspect considered, there are conflicting results.

Pain has been shown to be associated with a decrease in maximal force generated during an isometric contraction (Brox, Roe, Saugen, & Vollestad, 1997; Graven-Nielsen et al., 1997; Graven-Nielsen et al., 2002; Khan et al., 2011; Wassinger et al., 2012) and in endurance time of a submaximal contraction (Graven-Nielsen et al., 1997). Experimentally-induced muscle pain has been associated with a decrease in motor unit firing rate (Farina et al., 2004) and a decrease in motor evoked potential (Farina et al., 2001; Le Pera et al., 2001), which are both likely contributors to decreased muscle activity, force, and endurance. Other studies showed no change in electrically-stimulated twitch torque (Graven-Nielsen et al., 2002; Nijs et al., 2012), implying a more central mechanism behind reductions in activity.

Specific to the shoulder, hypertonic saline has been used to induce acute pain in multiple structures. Muscle pain of the supraspinatus (Bandholm et al., 2008; Castelein et al., 2016; Diederichsen, Winther, et al., 2009), infraspinatus (Leffler et al., 2000), trapezius (Falla, Arendt-Nielsen, & Farina, 2009; Falla et al., 2007; Madeleine et al., 2008; Samani et al., 2009), and anterior deltoid (Muceli et al., 2014) have all been studied, but with differing results. Hypertonic saline has also been injected in the subacromial space (Sole et al., 2014; Stackhouse et al., 2013; Wassinger et al., 2012, 2013). Results of these experiments have varied. Some have shown a lack of change in EMG activity of the injected muscle (Castelein et al., 2016), others a decrease (Muceli et al., 2014; Stackhouse et al., 2013). Supraspinatus pain was associated with no change in supraspinatus activity but an increase (Bandholm et al., 2008) or a decrease (Castelein et al., 2016) in infraspinatus activity, depending on the study referenced. At this point it is unclear whether acute pain in the rotator cuff musculature consistently causes a decrease in rotator cuff muscle activity, as might be expected considering the oft-referenced pain adaptation model (Lund et al., 1991).

Additionally, studies have shown a prolonged effect of acute pain. One study used hypertonic saline in the longissimus muscle and the effects did not resolve during the post-pain period (Hodges, Moseley, Gabrielsson, & Gandevia, 2003). Another, using hypertonic saline in both the supraspinatus muscle and the subacromial space, displayed decreased EMG activity in multiple muscles during a post test (Diederichsen, Winther, et al., 2009). While most studies involving acute experimental pain did not investigate muscle activity after pain had resolved, these results indicate that the effects of pain may last longer than the pain itself.

The aim of the present study was to investigate the effect of acute supraspinatus pain on the EMG activity of both the supraspinatus and infraspinatus muscles. It was hypothesized that the EMG amplitude of the supraspinatus and infraspinatus would be lower during the pain phase than during the pre-pain phase. Additionally, it was hypothesized that reductions in muscle activity would remain in the post-pain phase.

3.3. Methods

3.3.1. Subjects

Twenty-three subjects were recruited for this study. Subject age range was 18-42 years (mean 29.1, SD 7.7). Eleven of the subjects were female, twelve male; nineteen subjects reported right hand dominance, four left hand. All subjects were healthy, with no current or previous shoulder injury. Exclusion criteria were any history of surgery or rotator cuff tear in either shoulder, needle-induced syncope, pain while performing any of the prescribed movements, any neurological disorder, or another condition the investigator deemed would make the candidate a poor fit for the study. The University of Oregon Institutional Review Board approved the project and all subjects signed an informed consent form before participating.

3.3.2. Protocol Overview

The dominant arm was used for this protocol. The subject performed MVCs followed by sub-maximal isometric contractions, after which the subject completed dynamic humeral elevation in the scapular plane. Pain was then induced by the injection of hypertonic saline into the belly of the supraspinatus muscle. While in pain, the subject repeated one of the sub-maximal isometric contractions and the dynamic humeral elevation in the scapular plane. After the pain subsided, the subject again completed all the sub-maximal isometric contractions and humeral elevation in the scapular plane, and also the MVCs performed initially (Figure 3.1).

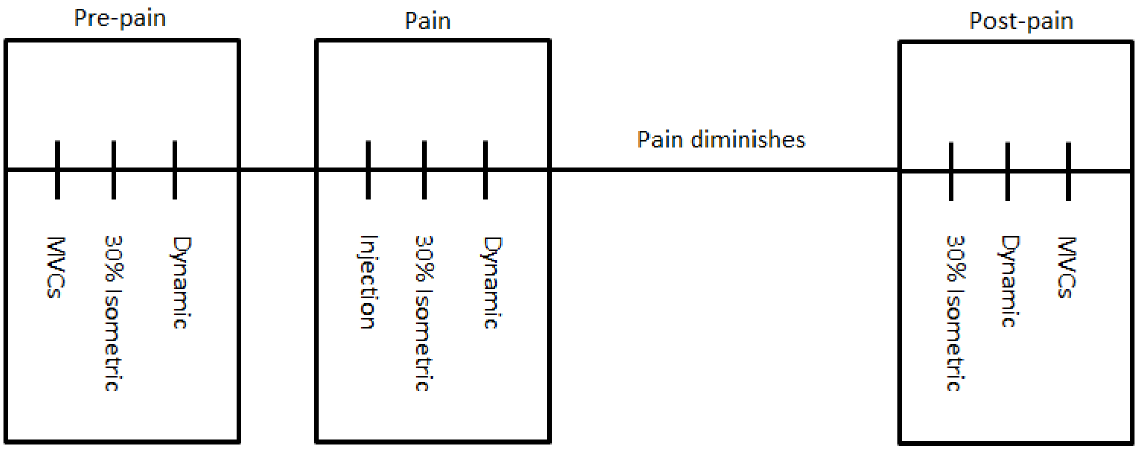

Figure 3.1 General Scheme for Acute Pain Study

3.3.3. Experimental Set-up

All instrumentation and data collection were conducted by a single investigator. The subject's dominant side was instrumented with wireless Trigno EMG electrodes (Delsys Inc., Boston, MA) and wireless MTi inertia measurement unit (IMU) sensors

(Xsens Technologies, The Netherlands) to collect muscle activity and kinematic data, respectively. The skin on the dominant shoulder and arm was abraded and cleaned with alcohol, then insertion points for fine-wire EMG data collection were determined for the supraspinatus and infraspinatus muscles (Delagi et al., 2005; Geiringer, 1999). Wires (Chalgren Enterprise, Inc, Gilroy, CA) were inserted into the bellies of these two muscles using sterilized, hollow 25-gauge needles, and then connected to spring sensors for fine-wire EMG data collection (Basmajian & De Luca, 1985; Kelly et al., 1997). Surface EMG sensors were placed over the bellies of the anterior, middle, and posterior deltoid, upper trapezius, latissimus dorsi, and serratus anterior (Cram et al., 1998).

One IMU was placed on the lateral aspect of the dominant arm, superior to the elbow. The other IMU was placed on the contralateral torso at the level of the xiphoid process. All EMG and kinematic data were collected at 2000 Hz using custom Motion Monitor software (Innovative Sports Training, Inc., Chicago, IL). The EMG data were bandpass filtered (20 – 450 Hz) and analyzed using a Root Mean Square (RMS) with a 200-millisecond sliding window. After the completion of the day’s protocol, the sensors and wires were removed. The wire insertion sites were cleaned with alcohol before the subject was excused.

3.3.4. Maximal Voluntary Contractions

Two positions were used for isometric contractions: humeral elevation in the scapular plane and external rotation, both conducted while seated. Humeral elevation was performed at 90 degrees of elevation and approximately 30 degrees forward of the frontal plane, with the elbow extended. External rotation was performed at approximately 10 degrees of abduction, elbow flexed to 90 degrees. The order of contractions (humeral elevation and external rotation) was randomized for each subject. The MVCs were completed only on the dominant side, with strong verbal encouragement being provided during each attempt. The subject performed each MVC for approximately three seconds with a minimum of two minutes between attempts. Each MVC was performed twice in the pre-pain phase. The MVCs were repeated in the post-pain phase but were not performed during the pain phase.

3.3.5. Submaximal and Dynamic Contractions

A thirty percent target force was calculated from the highest force produced during the MVCs in each position. Using the custom Motion Monitor software, the subject was provided with a computer screen that displayed a visual range of +/- 2% around the target force, i.e. 28-32%, and a line indicating the force currently being exerted. The subject was instructed to press against the load cell hard enough to get between the lines and to hold that force for approximately three seconds. Each submaximal contraction was performed twice in each position, humeral elevation and external rotation, using the dominant side.

Once the submaximal contractions were complete, the subject was given a description of the dynamic contraction, humeral elevation in the scapular plane. The subject performed this movement in a single three-repetition trial.

3.3.6. Pain Induction and Subsequent Testing

Prior to the induction of pain, the subject reported pain level using a visual analog scale ranging from 0 (no pain) to 10 (worst pain imaginable) (Castelein et al., 2016; Diederichsen, Winther, et al., 2009). Pain was then induced in the supraspinatus by injecting a 1 milliliter bolus of 5% hypertonic saline solution into the belly of the muscle (Castelein et al., 2016; Diederichsen, Winther, et al., 2009). A syringe with a 22-gauge needle was inserted approximately 3 cm lateral to the fine-wire insertion site and then guided through the muscle belly until the scapular fossa was contacted (Castelein et al., 2016). The needle was then backed out approximately 2-3 mm and the injection was performed smoothly over approximately 15 seconds; the needle was then removed. The subject immediately began to report pain level and continued to do so every thirty seconds until the end of the protocol.

The subject repeated submaximal isometric and dynamic contractions previously described, thirty percent isometric in the humeral elevation position (at time thirty seconds post-injection) and three cycles of humeral elevation in the scapular plane (at time one minute post-injection). The isometric external rotation contraction was not performed due to the short duration of maximal pain.

Twelve minutes after injection, the post-pain testing was begun. At this point the pain had diminished to the reported pre-pain level (time was determined from pilot testing). All four submaximal contractions, two in each position, were completed. These were followed by the same three cycles of humeral elevation in the scapular plane, then four more MVCs, two in each position. Once the data collection was complete, the sensors and wires were removed. The wire and needle insertion sites were cleaned with alcohol and the subject was excused.

3.3.7. Data Analysis

The EMG data were filtered through the Delsys hardware. The Common Mode Rejection Ratio of the system was greater than 80 dB. A custom LabVIEW program (National Instruments Corporation, Austin, TX, USA) was used to perform the data processing.

Three aspects of the muscle activity were analyzed: activity during the isometric sub-maximal contraction, activity during humeral elevation, and activity during MVC. The EMG amplitude during the sub-maximal contraction was averaged between the two trials in each of the first and third phases, pre-pain and post-pain; only one trial was conducted during the pain phase. The EMG amplitude during humeral elevation was averaged across the three cycles in each of the same three pain phases.

The half-second around the highest force produced in each MVC position, pre-pain, was used for EMG normalization of the dynamic contractions. The humeral elevation MVC was used to normalize the anterior, middle and posterior deltoid, upper trapezius, supraspinatus, and serratus anterior. The external rotation MVC was used for the infraspinatus and latissimus dorsi. The submaximal isometric contractions in the pain and post-pain conditions were normalized to the pre-pain submaximal isometric contraction.

IMU data were processed using the ISB standard for humerothoracic kinematics (YXY Euler angle rotation sequence) (Wu et al., 2005), generating plane, elevation, and internal/external rotation of the humerus relative to the thorax.

3.3.8. Statistical Analysis

The hypothesis that rotator cuff muscle activity would be lower with pain was tested using a One-Dimensional Statistical Parametric Mapping (SPM1d) analysis (Pataky, 2012; Robinson, Vanrenterghem, & Pataky, 2015), comparing the pre-pain to the pain phase and also comparing the pre-pain to the post-pain phase. An SPM1d two-tailed paired *t*-test was used to compare the activation of each muscle between conditions (Pataky, 2012). This method is similar to a scalar two-tailed paired *t*-test with the additional benefit of Random Field Theory as a means to handle the relatively smooth, interdependent EMG data points (Pataky, 2012; Robinson et al., 2015). Open source SPM1d Matlab code (The Mathworks, Inc., Natick, MA, USA) was used to run these analyses.

Potential changes in activity during isometric submaximal and maximal contractions were assessed using paired *t*-tests, as was the force generated during MVCs. In all cases, an alpha level of 0.05 was used to determine significant difference.

3.4. Results

3.4.1. Data Exclusions

Data from two subjects were excluded in total, prior to analysis, due to investigator error during data collection. In addition to those data sets, exclusions were made for outlying data for each muscle. The outlying nature for dynamic contractions was determined by the average value during concentric or eccentric humeral elevation in the scapular plane. Where a value exceeded three standard deviations from the mean, in any of the three conditions (pre-pain, pain, post-pain), the data for that muscle were excluded in all three conditions. For the dynamic concentric portion, six values were excluded. For the dynamic eccentric portion, five values were excluded. For the submaximal contractions, seven values were excluded. For the maximal contractions, five values were excluded.

3.4.2. Further SPM detail

An example of the results of the SPM1d analysis is provided below (Figure 3.2). For reference, these are the results associated with the eccentric portion of unweighted humeral elevation in the scapular plane for the anterior deltoid muscle, as shown in Figure 3.4B and Table 3.1. In Figure 3.2, the *x*-axis displays the portion of the movement, 0 - 100% being from 120 - 30° of elevation. The *y*-axis displays the *t*-value, as determined with the SPM1d code. In this instance, a critical *t*-value of 3.467 (horizontal dashed line) was determined using the code (Henderson, Rubin, & Macefield, 2011; Pataky, 2012). The extent to which this *t*-value was exceeded determined the *p*-value associated with each excursion (Henderson et al., 2011; Pataky, 2012). The *p*-value calculated is the probability that a supra-threshold cluster of this size would be observed in repeated random samplings (Henderson et al., 2011; Pataky, 2012). Here, the portions of significant difference were 74.8 – 75.7% and 76.1 – 80.7% of the movement. These portions of significance are depicted by the shaded regions below the dashed line (Figure 3.2).

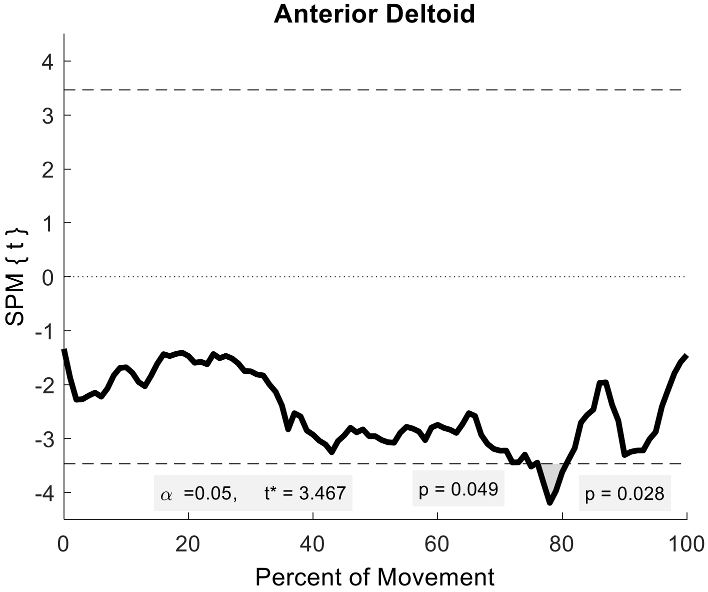

Figure 3.2. SPM1d Results Example. Results of an SPM1d two-tailed paired *t*-test, comparing anterior deltoid activity during eccentric unweighted humeral elevation in the scapular plane before and after a pain-inducing injection.

3.4.3. Acute Experimental Pain

The pain profile was similar across all subjects. The pain phase was begun at time thirty seconds and completed by time ninety seconds. For each subject, the reported pre-pain level was reached well before the post-pain testing was initiated (Figure 3.3).

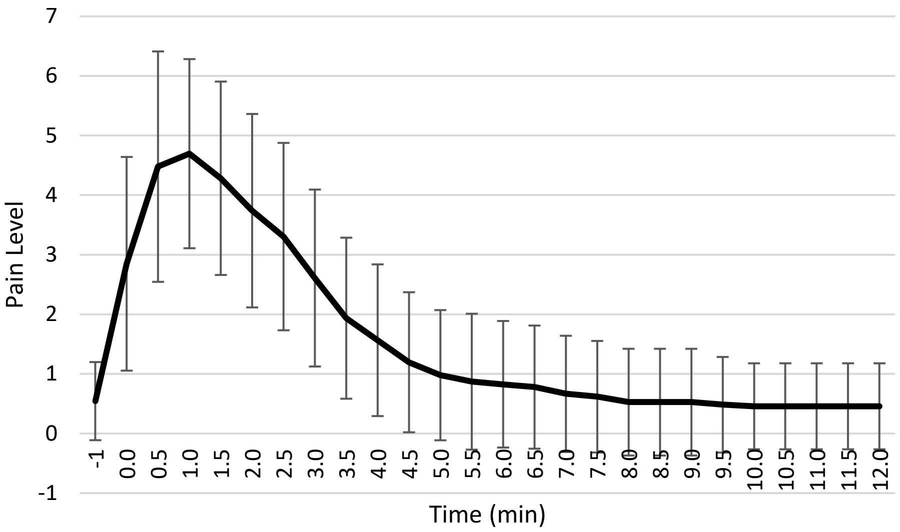

Figure 3.3. Graph of Pain vs. Time. Self-reported pain levels on a visual analog scale of 0-10. Injection was performed at time 0; the pain at time -1 is pre-injection. Data are represented as means +/- standard deviations.

3.4.4. Dynamic – Anterior, Middle, Posterior Deltoid

Humeral elevation in the scapular plane was completed in each of the three phases. There were no differences displayed during the concentric portion between the pre-pain and pain phase, nor between the pre-pain and post-pain phase, for any of the three heads of the deltoid. Differences were observed during the eccentric portion between the pre-pain and pain phase, but not between the pre-pain and post-pain phase, for all three heads of the deltoid. In each of these instances, activity was higher in the pain condition than the pre-pain condition but there was no difference between the pre-pain and the post-pain conditions (Figure 3.4, Table 3.1, Table 3.2).

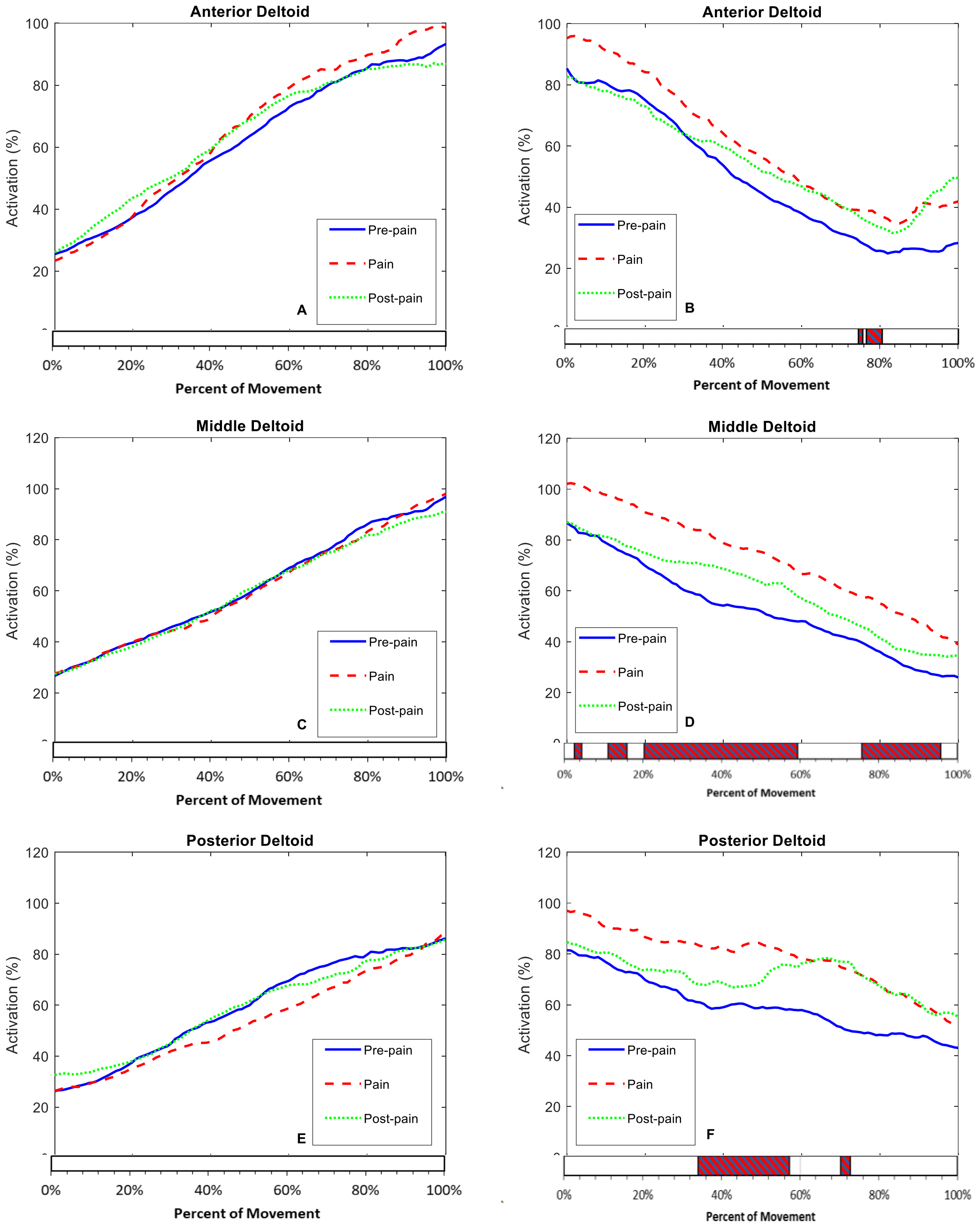

Figure 3.4. Graphs of Muscle Activation During Three Pain States for the Anterior, Middle, and Posterior Deltoid. Pre-pain (red), during pain (blue), and post-pain (green) mean values concentrically and eccentrically across 90 degrees (30°-120°) of humeral elevation in the scapular plane for each of three muscles. Differences, as displayed by diagonal fills, were observed between the pre-pain and the pain conditions in each muscle eccentrically (B, D, F) but not concentrically. No differences were observed between the pre-pain and post-pain conditions in any of these muscles.

Table 3.1. Muscle Activation Pre-Pain vs. During Pain for the Anterior, Middle, and Posterior Deltoid

Summary of Differences between Pre-Pain and During Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Anterior Deltoid	20	Concentric	-	-	-
	20	Eccentric	74.8-75.7	0.049	Pre < Pain
		Eccentric	76.1-80.7	0.028	Pre < Pain
Middle Deltoid	20	Concentric	-	-	-
	21	Eccentric	2.6-4.5	0.048	Pre < Pain
		Eccentric	11.1-16.0	0.039	Pre < Pain
		Eccentric	20.4-59.1	< 0.0001	Pre < Pain
		Eccentric	76.4-96.1	0.001	Pre < Pain
Posterior Deltoid	20	Concentric	-	-	-
	21	Eccentric	34.1-57.9	0.0001	Pre < Pain
		Eccentric	70.6-72.9	0.047	Pre < Pain
	21	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the pre-pain (Pre) and during (Pain) pain conditions.

Table 3.2. Muscle Activation Pre-Pain vs. Post-Pain for the Anterior, Middle, and Posterior Deltoid

Summary of Differences between Pre-Pain and Post-Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Anterior Deltoid	20	Concentric	-	-	-
	20	Eccentric	-	-	-
Middle Deltoid	20	Concentric	-	-	-
	21	Eccentric	-	-	-
Posterior Deltoid	20	Concentric	-	-	-
	21	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the before pre-pain and post-pain conditions.

3.4.5. Dynamic – Upper Trapezius, Latissimus Dorsi, Serratus Anterior

There were no differences displayed concentrically or eccentrically in the upper trapezius and the serratus anterior in either the pre-pain to pain comparison or the pre-pain to post-pain comparison. Differences were displayed in the latissimus dorsi in both the concentric and eccentric portions between the pre-pain and post-pain condition, but not in the pre-pain to pain condition. Where differences lay, muscle activity was higher in the pre-pain condition than in the post-pain condition (Figure 3.5, Table 3.3, Table 3.4).

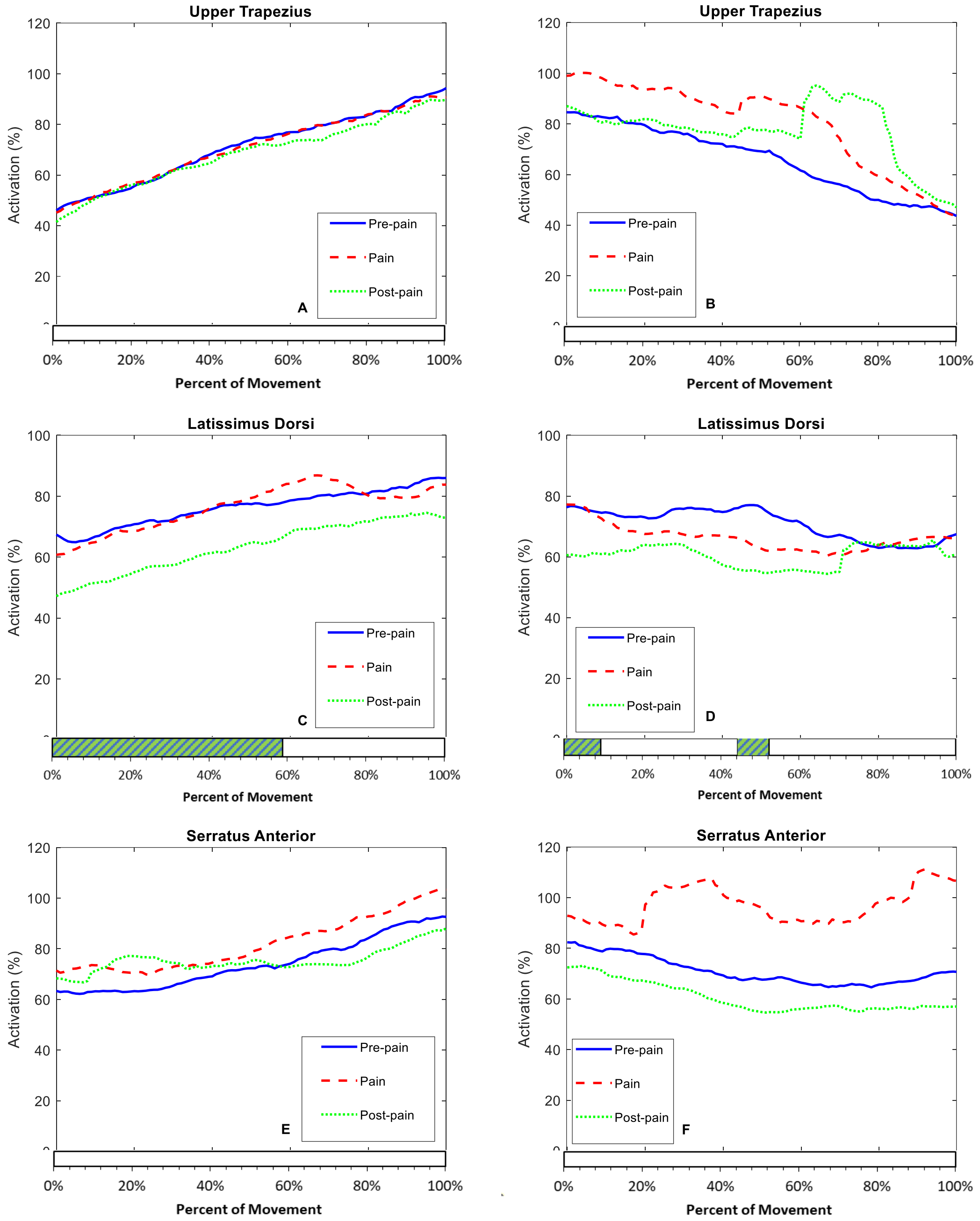

Figure 3.5. Graphs of Muscle Activation during Three Pain states for the Upper Trapezius, Latissimus Dorsi, and Serratus Anterior. Pre-pain (red), during pain (blue), and post-pain (green) mean values concentrically and eccentrically across 90 degrees (30°-120°) of humeral elevation in the scapular plane for each of three muscles. Differences, as displayed by diagonal fills, were observed between the pre-pain and the post-pain conditions in the latissimus dorsi, both concentrically (C) and eccentrically (D).

Table 3.3. Muscle Activation Pre-Pain vs. During Pain for the Upper Trapezius, Latissimus Dorsi, and Serratus Anterior

Summary of Differences between Pre-Pain and During Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Upper Trapezius	20	Concentric	-	-	-
	21	Eccentric	-	-	-
Latissimus Dorsi	20	Concentric	-	-	-
	19	Eccentric	-	-	-
Serratus Anterior	20	Concentric	-	-	-
	19	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the pre-pain and pain conditions.

Table 3.4. Muscle Activation Pre-Pain vs. Post-Pain for the Upper Trapezius, Latissimus Dorsi, and Serratus Anterior

Summary of Differences between Pre-Pain and Post-Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Upper Trapezius	20	Concentric	-	-	-
	21	Eccentric	-	-	-
Latissimus Dorsi	20	Concentric	0-58.7	< 0.0001	Pre > Post
	19	Eccentric	0-9.4	0.011	Pre > Post
		Eccentric	44.3-52.2	0.017	Pre > Post
Serratus Anterior	20	Concentric	-	-	-
	19	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the pre-pain and the post-pain conditions.

3.4.6. Dynamic – Supraspinatus and Infraspinatus

There were differences displayed concentrically between the pre-pain and pain conditions, as well as between the pre-pain and post-pain conditions, in the supraspinatus muscle. Where the differences lay, the pre-pain muscle activity was higher than the pain or post-pain muscle activity. There were no differences in the eccentric portion of movement for the supraspinatus. There were also differences in the infraspinatus between the pre-pain and post-pain conditions, with EMG in the post-pain condition being lower than EMG in the pre-pain condition. There were no differences displayed in the eccentric portion of the pre-pain to pain condition nor the pre-pain to post-pain condition for the infraspinatus (Figure 3.6, Table 3.5, Table 3.6).

3.4.7. Submaximal Isometric Contractions

In the pain condition, the transient nature of the experimental pain necessitated a reduction from four attempts (two in each position) to one. A single attempt was performed in the humeral elevation position. For this reason, there is no value in the pain state for the latissimus dorsi or the infraspinatus. Significant differences were detected between the pre-pain and pain conditions for the anterior deltoid (increased with pain) and the supraspinatus (decreased with pain). Significant differences were also detected between the pre-pain and post-pain conditions for the serratus anterior, supraspinatus, and infraspinatus (all three lower post-pain) (Figure 3.7).

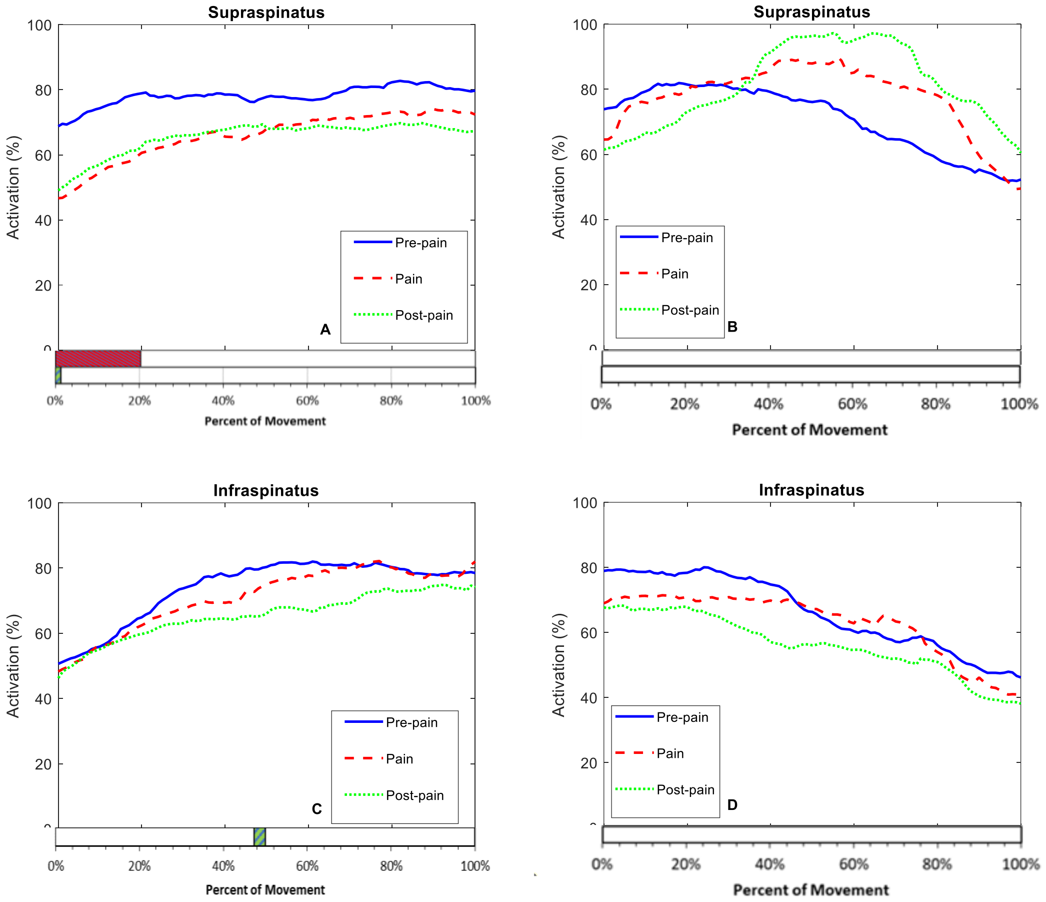

Figure 3.6. Graphs of Muscle Activation during Three Pain States for the Supraspinatus and Infraspinatus. Pre-pain (red), during pain (blue), and post-pain (green) mean values concentrically and eccentrically across 90 degrees (30°-120°) of humeral elevation in the scapular plane for two muscles. Differences, as displayed by diagonal fills, were observed between the pre-pain and the pain conditions for the supraspinatus concentrically (A), as well as between the pre-pain and post-pain conditions in the supraspinatus and the infraspinatus concentrically (A, C).

The introduction of acute pain to the supraspinatus was associated with an increase in anterior deltoid activity ($p = 0.018$) and a decrease in supraspinatus activity ($p < 0.0001$) during a submaximal isometric contraction at ninety degrees of humeral elevation in the scapular plane.

Table 3.5. Muscle Activation Pre-Pain vs. During Pain for the Supraspinatus and Infraspinatus

Summary of Differences between Pre-Pain and Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Supraspinatus	20	Concentric	0-20.5	0.002	Pre > Pain
	21	Eccentric	-	-	-
Infraspinatus	21	Concentric	-	-	-
	21	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the pre-pain and pain conditions.

Table 3.6. Muscle Activation Pre-Pain vs. Post-Pain for the Supraspinatus and Infraspinatus

Summary of Differences between Pre-Pain and Post-Pain during Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Supraspinatus	20	Concentric	0.1-1.3	0.050	Pre > Post
	21	Eccentric	-	-	-
Infraspinatus	21	Concentric	47.3-50.2	0.048	Pre > Post
	21	Eccentric	-	-	-

Note. Where no value is listed, no difference was observed between the pre-pain and post-pain conditions.

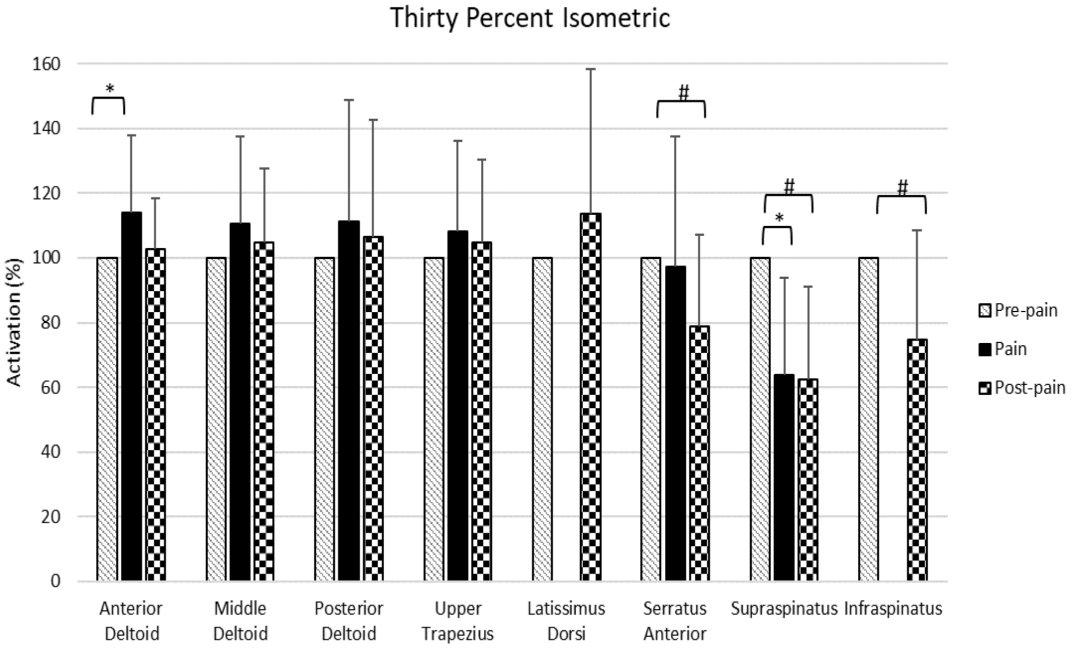

Figure 3.7. Graph of Muscle Activation during Submaximal Contractions in Three Pain States. Muscle activation mean and standard deviation for eight muscles while performing a 30% isometric contraction pre-pain (diagonals), during pain (solid), and post-pain has (checked). * significant difference between the pre-pain and pain conditions. # significant difference between the pre-pain and post-pain conditions. ($p < 0.05$)

In the post-pain phase, there was decreased activity (relative to the pre-pain phase) in the serratus anterior ($p = 0.007$) and supraspinatus ($p < 0.0001$) during a submaximal isometric contraction at ninety degrees of humeral elevation in the scapular plane, and in the infraspinatus ($p = 0.003$) during a submaximal isometric external rotation contraction (Table 3.7).

Table 3.7. Muscle Activation during Submaximal Contractions in Three Pain States

Summary of Normalized Thirty Percent Isometric Contraction Results

Muscle	*n*	Pre-pain	Pain	Post-pain	*p* (Pre to Pain)	*p* (Pre to Post)
Anterior Deltoid	20	100	113.9 (24.0)	102.6 (15.9)	0.018*	0.470
Middle Deltoid	21	100	110.6 (26.8)	104.7 (22.9)	0.084	0.361
Posterior Deltoid	20	100	111.3 (37.4)	106.4 (36.2)	0.191	0.439
Upper Trapezius	21	100	108.0 (28.1)	104.8 (25.5)	0.204	0.400
Latissimus Dorsi	20	100	-	113.5 (44.9)	-	0.207
Serratus Anterior	17	100	97.2 (40.2)	78.7 (28.6)	0.781	0.007*
Supraspinatus	21	100	63.9 (29.9)	62.4 (28.5)	< 0.0001*	< 0.0001*
Infraspinatus	21	100	-	74.9 (33.7)	-	0.003*

Note. Values listed are mean (*sd*) in Newtons. *significant difference ($p < 0.05$)

3.4.8. Maximal Isometric Contractions

The MVCs completed in the pre-pain and post-pain conditions displayed a decrease in force production for both the humeral elevation ($p = 0.003$) and the external rotation ($p = 0.010$) position (Table 3.8).

Table 3.8. Maximal Forces Pre-Pain vs. Post-Pain during MVC

Summary of Maximal Voluntary Contraction Force Results

Contraction	*n*	Pre-pain	Post-pain	*p*
Humeral Elevation	22	120.1 (39.1)	113.4 (36.6)	0.003*
External Rotation	22	145.0 (44.1)	136.3 (37.9)	0.010*

Note. Values listed are mean (*sd*) in Newtons. *significant difference ($p < 0.05$)

Muscle activity during MVC was measured via EMG in the pre-pain and post-pain conditions. For the humeral elevation MVC, there was a significant decrease in supraspinatus activity ($p = 0.0001$). For the external rotation MVC, there was a significant decrease in infraspinatus activity ($p = 0.001$) (Table 3.9).

3.5. Discussion

The purpose of this study was to investigate the effect of acute supraspinatus pain on the EMG activity of both the supraspinatus and infraspinatus muscles. It was hypothesized that the EMG amplitude of the supraspinatus and infraspinatus would be lower during the pain phase than during the pre-pain phase. Additionally, it was hypothesized that reductions in muscle activity would remain in the post-pain phase. Both of these hypotheses were well supported by the results.

Table 3.9. Muscle Activation Pre-Pain vs. Post-Pain during MVC

Summary of Maximal Voluntary Contraction Muscle Activation Results

Muscle	*n*	Pre-pain	Post-pain	*p*
Anterior Deltoid	21	0.249 (0.119)	0.259 (0.158)	0.69
Middle Deltoid	21	0.144 (0.067)	0.144 (0.114)	0.98
Posterior Deltoid	21	0.103 (0.042)	0.105 (0.060)	0.88
Upper Trapezius	21	0.251 (0.147)	0.278 (0.230)	0.47
Latissimus Dorsi	21	0.019 (0.010)	0.022 (0.015)	0.27
Serratus Anterior	21	0.060 (0.106)	0.058 (0.061)	0.97
Supraspinatus	21	0.0006 (0.0004)	0.0003 (0.0002)	0.0001*
Infraspinatus	21	0.0004 (0.0005)	0.0003 (0.0003)	0.001*

Note. Values listed are mean (*sd*) in millivolts. *significant difference ($p < 0.05$)

The subjects completed three tasks during this study: dynamic humeral elevation, submaximal isometric contractions, and MVCs. In the dynamic task, differences were detected in both the supraspinatus and infraspinatus. The supraspinatus displayed a decrease in activity concentrically with pain and a portion of that decrease remained in the post-pain phase. The infraspinatus, on the other hand, did not display any dynamic differences initially; it did, however, display lower activity in the post-pain phase. This lag could be an indication of one difference between an acute response to pain and a subacute initial adaptation to it.

The submaximal contractions provided very clear support for both hypotheses, with supraspinatus activity decreasing with pain and remaining decreased post-pain. The infraspinatus activity was not analyzed during the submaximal isometric attempt since there was insufficient time to perform the external rotation contraction; the activity was lower in the post-pain state, though, as expected. It is unclear whether that response was present during the pain state or whether, as in the dynamic contraction, the response lagged behind the supraspinatus response.

The MVCs, while not assessed during the pain state, support the second hypothesis; however, the results are more vulnerable. The observed decreases in force and muscle activity displayed in both the humeral elevation and external rotation MVCs, as well as in both the supraspinatus and infraspinatus muscles, occurred at the end of the protocol. Fatigue might have been a factor. The lack of change in activity for the other six muscles monitored is an indication that fatigue was likely not a significant factor, but it does not preclude the possibility.

Three other studies were found in which the supraspinatus was injected with hypertonic saline and muscle activity was collected (Bandholm et al., 2008; Castelein et al., 2016; Diederichsen, Winther, et al., 2009). None of those studies detected a decrease in supraspinatus activity during pain (Bandholm et al., 2008; Castelein et al., 2016; Diederichsen, Winther, et al., 2009), but one detected a decrease in infraspinatus activity (Castelein et al., 2016) and one an increase in infraspinatus activity (Bandholm et al., 2008). The first, decrease, used a similar arm movement and activity was collected via MRI (Castelein et al., 2016); the second, increase, had subjects perform humeral abduction (Bandholm et al., 2008). Neither of these studies presented the post-pain muscle activity during movements. The third study using supraspinatus pain displayed no change in the supraspinatus but a decrease in infraspinatus activity during pain, with the subjects performing abduction (Diederichsen, Winther, et al., 2009). This study did include post-pain assessments and there detected decreased EMG activity in the supraspinatus but not the infraspinatus (Diederichsen, Winther, et al., 2009). This is counter to the current study, in which the infraspinatus decrease followed the supraspinatus decrease. That study differed additionally in that a second hypertonic saline injection, one performed subacromially, was included before the post-pain assessments were made. It is unclear whether that second injection affected the post-pain condition.

Pain in the supraspinatus muscle has been speculated to be a potential initiator of a sequence of events leading to a chronic shoulder condition (Michaud, Arsenault, Gravel, Tremblay, & Simard, 1987; Michener et al., 2003). Pain in the muscle could lead to a decrease in rotator cuff muscle activity, for which more superficial musculature might compensate. There has been some evidence of this occurring with acute, experimental pain. In the present study, there were increases observed in all three heads of the deltoid in the pain condition. This is noteworthy since the deltoid can compensate for reduced rotator cuff activity. It is also potentially interesting that these increases were observed not in the concentric portion of humeral elevation, but the eccentric portion during which the deltoid served as an antagonist. These changes had reduced to an insignificant level by the post-pain phase. During the submaximal isometric contraction, there was increased anterior deltoid activity; again, that could be compensating for reduced supraspinatus activity. This compensation was not observed during MVCs, likely because the muscle was maximally activated initially and had no remaining compensatory potential.

The three studies discussed above, involving supraspinatus injections, reported different changes in deltoid activity (Bandholm et al., 2008; Castelein et al., 2016; Diederichsen, Winther, et al., 2009). One did not monitor the deltoid (Castelein et al., 2016). One detected a decrease in anterior deltoid activity but not the middle deltoid during abduction, then lower activity in the anterior and middle deltoid in the post-pain state (Diederichsen, Winther, et al., 2009). The third study, also using abduction, reported increased activity in the middle deltoid (isometrically but not dynamically) and no change in the anterior deltoid (Bandholm et al., 2008).

Raising of the arm, regardless of the plane and rotation thereof, involves scapular tilting and rotation. While these were not tracked kinematically in the present study, upper trapezius and serratus anterior activity could provide hints as to potential changes with the pain and post-pain states. Upward rotation of the scapula is generally accepted to contribute approximately one third of humerothoracic elevation, with the remaining two thirds being provided by the glenohumeral joint (Scibek & Carcia, 2012). This configuration may be disrupted by a number of factors, including subacromial or supraspinatus pain. Increased upward rotation of the scapula increases subacromial space, the reduction of which has been implicated in subacromial pain syndrome (Michener et al., 2003). While the present study did not include an assessment of scapular kinematics, it did include EMG measurement of upper trapezius and serratus anterior activity, both of which contribute to upward rotation of the scapula. Of these, though, the only change observed in the present study was reduced serratus anterior activity during the submaximal isometric contractions in the post-pain condition. This is not evidence of changes to scapular kinematics. This result is somewhat in agreement with the other three studies (Bandholm et al., 2008; Castelein et al., 2016; Diederichsen, Winther, et al., 2009), with two of them showing no changes in the upper trapezius or serratus anterior (Bandholm et al., 2008; Castelein et al., 2016) and one displaying a decrease in the upper trapezius activity during pain that remained in the post-pain state (Diederichsen, Winther, et al., 2009).

Another potential factor from the pain adaptation model (Lund et al., 1991) is antagonist coactivation, which might be expected with pain. This would presumably be occurring to reduce the range and rate of motion of injured structures (Lund et al., 1991). The potential for this phenomenon was the reason the latissimus dorsi was monitored in the present study, as it could serve as an antagonist to humeral elevation in the scapular plane. However, where an increase in activity might be expected during the concentric portion of movement, there was no change in the pain state and a decrease, both concentrically and eccentrically, in the post-pain state. No changes were detected isometrically. Considering previous studies, the latissimus dorsi displayed no change during abduction in one (Bandholm et al., 2008), increased activity during abduction in another (insignificant by the post-pain state) (Diederichsen, Winther, et al., 2009), and was not monitored in the third (Castelein et al., 2016). This combination of results provides minimal support for antagonist coactivation by the latissimus dorsi during painful humerothoracic movements.

A fourth study not yet mentioned in this discussion involved an injection that was performed not into the supraspinatus but into the neighboring subacromial space (Sole et al., 2014). This has been shown to generate a similar pain profile (Diederichsen, Winther, et al., 2009) and the subjects performed humeral elevation in the scapular plane (Sole et al., 2014). While this study detected no EMG changes in the middle deltoid, upper trapezius, serratus anterior, or infraspinatus during the concentric portion of movement, it did detect increases during the eccentric portion for the middle deltoid (in agreement), serratus anterior, and infraspinatus (present study no change).

3.6. Conclusions

The wide nature of potential causes of pain and the complex nature of the shoulder structures contribute to a poor understanding of the transition from an acute injury to a chronic condition. While this transition varies with the specific nature of injuries, one potential initiator of an unhealthy spiral is insult to the rotator cuff musculature. Injury to the rotator cuff could lead to a maladaptation that results in further injury and the possibility of chronic shoulder pain, even after the initial insult has been resolved. Considering this potential cascade, further investigation into the acute and subacute effects of pain in the rotator cuff could help to illuminate the transition to a chronic condition.

3.7. Bridge

This chapter investigated the acute effects of experimental pain in the supraspinatus. The function of this muscle, regardless of the initial insult, is often in question when a chronic shoulder condition presents. While this chapter (Chapter III) investigated the effects of acute pain, the next chapter (Chapter IV) investigates the acute relief of chronic pain in a similar area of the shoulder.

CHAPTER IV

CHRONIC PAIN

4.1. Abstract

Shoulder pain is common and potentially multifactorial. The purpose of the present study was to investigate the effect of the acute removal of chronic pain on shoulder muscle activity in patients diagnosed with impingement syndrome. This was accomplished by reducing pain via anesthetic injection in the subacromial space. Eight muscles on twenty subjects were assessed using surface and fine-wire electromyography: the anterior, middle, and posterior deltoid; upper trapezius; latissimus dorsi; serratus anterior; supraspinatus; and infraspinatus. It was hypothesized that rotator cuff muscle activity would be higher after the injection. Dynamic and isometric contractions were performed while muscle activity was recorded. One-dimensional Statistical Parametric Mapping was used to determine muscle activity differences during the dynamic contractions. The results displayed a decrease rather than an increase in the activity of both rotator cuff muscles instrumented. Further investigation regarding the effects of chronic pain, and the relief thereof, on muscle activity could provide additional insight and guidance regarding recovery.

4.2. Introduction

Shoulder pain is one of the leading reasons people seek orthopedic assistance (Greving et al., 2012; Michener et al., 2003). The most common cause of shoulder pain is rotator cuff tendinopathy (Greving et al., 2012; Michener et al., 2003; Mitchell, Adebajo, Hay, & Carr, 2005). Many patients are diagnosed with more than one issue; over half the shoulder patients in one study received a diagnosis including both tendinosis and impingement (Mitchell et al., 2005). Impingement syndrome is a condition in which there is insufficient space below the acromion process for the soft tissues to move freely. There are three primary potential causes of impingement syndrome: soft tissues expanding inside the subacromial space, hard tissues encroaching on the space, and internal structures colliding during movement (Michener et al., 2003). The standard therapeutic approach for impingement syndrome begins with a subacromial injection consisting of both an anesthetic and a corticosteroid (Dong et al., 2015). The purpose of this injection is threefold: reduce pain, decrease inflammation, and provide an opportunity for tissue healing (Dong et al., 2015).

It has been shown that patients diagnosed with impingement syndrome have lower rotator cuff muscle strength than healthy controls (Reddy, Mohr, Pink, & Jobe, 2000), but this weakness and the associated pain may be causing the pathology or may be a result of it (Castelein et al., 2016). Studies have shown some differences in rotator cuff muscle activity, as measured with electromyography (EMG), between patients diagnosed with impingement syndrome and healthy controls (Diederichsen, Nørregaard, et al., 2009; Larsen et al., 2014; Reddy et al., 2000). The patients displayed higher supraspinatus activity during abduction (Diederichsen, Nørregaard, et al., 2009), lower infraspinatus activity during humeral elevation in the scapular plane (Reddy et al., 2000), and lower infraspinatus activity during external rotation (Diederichsen, Nørregaard, et al., 2009).

Chronic pain is a complex phenomenon that is difficult to study; it can be challenging to determine when a pathology is causing pain and when pain is causing a pathology (Castelein et al., 2016; Lawrence et al., 2014; Wassinger et al., 2013).

Impingement syndrome is one such example, with pain potentially contributing to further dysfunction (Castelein et al., 2016; Lawrence et al., 2014). Pain could be reducing the activity of an injured muscle, and continued disuse could lead to muscle weakness and changes in motor recruitment patterns (Lund et al., 1991). If pain in the rotator cuff musculature is indeed reducing muscle activity, which would be in line with the pain adaptation model, removal of that pain might diminish the reduction in activity (Lund et al., 1991). A reduction in pain could be a first step in recovery from impingement syndrome, allowing an increase in muscle activity that had been previously diminished. Of the benefits expected from a subacromial injection, the only one immediately observable is the reduction in pain.

The purpose of the present study is to observe the immediate effects on rotator cuff muscle activity of a subacromial injection in patients diagnosed with impingement syndrome. It is hypothesized that the EMG amplitude of the supraspinatus and infraspinatus will be higher during isometric and dynamic contractions after pain relief than prior to it.

4.3. Methods

4.3.1. Subjects

Patients diagnosed with impingement syndrome were recruited for this study. Inclusion criteria were an age of 21 - 65 years, pain with passive provocative maneuvers (Hawkins or Neer) (Michener, Walsworth, Doukas, & Murphy, 2009; Yung, Asavasopon, & Godges, 2010), pain with active elevation, pain with isometric resisted movements

(Jobe’s “empty can” or shoulder external rotation) (Michener et al., 2009; Yung et al., 2010), and the plan to receive a subacromial injection. Aside from age, these inclusion criteria were assessed by a participating orthopedic surgeon. Exclusion criteria were a history of shoulder surgery, a history of shoulder fracture, traumatic shoulder dislocation or instability in the previous three months, shoulder injection in the previous three months, a positive Spurling test (Yung et al., 2010), reproduction of shoulder pain with active or passive cervical range of motion, or signs of a rotator cuff tear on the symptomatic side.

Thirty-three patients fitting the above criteria were recruited for a larger study. The patients were recruited from the Slocum Center, which is an orthopedic facility in Eugene, Oregon. Of those thirty-three patients, one was later excluded for a rotator cuff tear, one was subjected to a different protocol, one failed to experience pain relief, six did not move fully through the required range of motion for this study, and three had faulty readings from the supraspinatus sensor. This resulted in twenty subjects for analysis.

Subject age range was 25-61 years (mean 47.9, SD 10.3). Nine of the subjects were female, eleven male; nineteen subjects reported right hand dominance, one left hand. Twelve subjects had the left shoulder involved, eight the right shoulder. The University of Oregon Institutional Review Board approved this project and all subjects signed an informed consent form before participating.

4.3.2. Experimental Set-up

All instrumentation and data collection were conducted by a single investigator. The subject’s involved side was instrumented with wireless Trigno EMG electrodes

(Delsys Inc., Boston, MA) and wireless MTi inertia measurement unit (IMU) sensors (Xsens Technologies, The Netherlands) to collect muscle activity and kinematic data, respectively. The skin on the involved shoulder and arm was abraded and cleaned with alcohol, then insertion points for fine-wire EMG data collection were determined for the supraspinatus and infraspinatus muscles (Delagi et al., 2005; Geiringer, 1999). Wires (Chalgren Enterprise, Inc, Gilroy, CA) were inserted into the bellies of these two muscles, using sterilized, hollow 25-gauge needles, and then connected to spring sensors for fine-wire EMG data collection (Basmajian & De Luca, 1985). Additionally, surface EMG sensors were placed over the bellies of the anterior, middle, and posterior deltoid, upper trapezius, latissimus dorsi, and serratus anterior (Cram et al., 1998).

One IMU was placed on the lateral aspect of the involved arm, superior to the elbow. The other IMU was placed on the contralateral torso at the level of the xiphoid process. All EMG and kinematic data were collected at 2000 Hz using custom Motion Monitor software (Innovative Sports Training, Inc., Chicago, IL). The EMG data were bandpass filtered (20 – 450 Hz) and analyzed using a Root Mean Square (RMS) with a 200-millisecond sliding window. After the completion of the day’s protocol, the sensors and wires were removed. The wire insertion sites were cleaned with alcohol before the subject was excused.

4.3.3. Initial Testing

All testing was performed using the affected arm only. The initial testing consisted of the subject reporting pain levels, performing maximal voluntary isometric contractions (MVCs), and dynamic contractions: humeral elevation in the scapular plane, weighted humeral elevation in the scapular plane, lifting a gallon jug of water, a circular motion against a wall, and simulating the combing of one's own hair. The scapular plane was defined as thirty degrees anterior to the frontal plane. Each of these components is described below.

The subject first rated pain (at rest, during activity, and at night) and pointed to location of pain if and when it occurs. The pain rating was based on a visual analog scale ranging from 0 (no pain) to 10 (worst pain imaginable) (Castelein et al., 2016; Diederichsen, Winther, et al., 2009) The researcher also performed the Neer's, Hawkin's, and Jobe's tests (Yung et al., 2010) with pain ratings as additional quantifications of initial pain.

All MVCs were performed against a mounted load cell (Omega Engineering Inc., Norwalk, CT), which continuously relayed the force being produced. Two MVCs were performed in the external rotation position followed by two in the humeral elevation position (Escamilla, Yamashiro, Paulos, & Andrews, 2009), all while seated. The external rotation position was ninety degrees of elbow flexion, with the forearm parallel to the sagittal plane and rotated externally. The humeral elevation position was ninety degrees of elevation in the scapular plane with the elbow extended (Escamilla et al., 2009). Each MVC was held for approximately three seconds. A minimum of two minutes of rest was provided between subsequent attempts. The half-second around the highest force produced in each position was used for analysis.

The humeral elevation in the scapular plane movement consisted of the subject beginning with his/her arm at the side, then raising it overhead at an angle approximately

30° forward of the frontal plane with the arm externally rotated, then lowering back to the starting position. This movement was performed three times, smoothly, over an approximately six-second period per cycle (three seconds raising, three seconds lowering). Weighted humeral elevation in the scapular plane was performed in the same manner, but with the subject holding a 2.3-kg dumbbell (Figure 4.1).

Figure 4.1. Demonstration of Weighted Humeral Elevation in the Scapular Plane.

The gallon-lifting movement began with a one-gallon jug of water resting on a counter 91 centimeters high. The subject grasped the jug by the handle and placed it on a shelf above the counter, 137 centimeters high. Without letting go of the handle, the subject then lifted the jug from the shelf and placed it back on the counter. This cycle was performed three times.

The circular motion against the wall began with the subject placing his/her palm flat against the wall in front of him/her. This was done to determine the center of a circumductive motion. The subject then traced a circle with his/her palm against the wall, beginning at the top and moving laterally and down, then medially and down to the bottom, medially and up, then laterally and up to the top. This movement was performed five times, each time tracing a circle of a 122-centimeter diameter.

The hair combing movement was a simulation of the subject combing his/her hair. It began at the top of the forehead and ended at the nape of the neck. This movement was performed three times.

4.3.4. Pain Relief

The injection consisted of one of four concoctions: 6 cc 0.5% Marcaine and 1 cc DepoMedrol; 8 cc 0.25% Marcaine and 2 cc DepoMedrol; 4 cc 0.25% Marcaine, 1 cc dexamethasone sodium phosphate and 1 cc betamethasone sodium phosphate and betamethasone acetate; or 3 cc 1% Lidocaine and 2 cc betamethasone sodium phosphate and betamethasone acetate, depending on which physician was performing the injection. The approach to the subacromial space (anterior or lateral) also depended on the physician. Shortly after the injection, the physician had the subject move his/her arm and report qualitatively whether or not there was any relief of pain. If there was no pain relief and the injection appeared ineffective, as determined by the physician, the subject completed the testing but was excluded from this analysis.

4.3.5. Subsequent Testing

After a 15-minute rest period, the subsequent testing commenced. This consisted of the same components as the initial testing, but with the addition of submaximal isometric contractions.

The subject again rated pain at rest and during activity (as determined by moving the arm) and pointed to location of pain if and when it occured. The researcher again performed the Neer's, Hawkin's, and Jobe's tests (Yung et al., 2010) and the patient provided pain quantification.

Two MVCs were again performed in the external rotation position followed by two in the humeral elevation position (Escamilla et al., 2009). As an aspect of a related study, the subject performed four brief submaximal (30%) isometric contractions. These contractions are not included in this study.

After the isometric contractions were completed, the same dynamic contractions as in the initial testing (humeral elevation in the scapular plane, weighted humeral elevation in the scapular plane, gallon lift, circumduction, combing) were performed, in the same manner as during the initial testing. The IMUs and EMG sensors were then removed from the subject, the wires were extracted, wire insertion sites were cleaned with alcohol, and the subject was excused.

4.3.6. Data Analysis

The EMG data were filtered through the Delsys hardware. The Common Mode Rejection Ratio of the system was greater than 80 dB. A custom LabVIEW program (National Instruments Corporation, Austin, TX, USA) was used to perform the data processing.

The EMG data for dynamic contractions were normalized for each subject to the maximum value displayed while performing the movement in the initial, pre-injection condition. Neither the EMG sensors nor the IMUs were removed between the pre-injection and the post-injection testing sessions.

IMU data were processed using the ISB standard for humerothoracic kinematics (YXY Euler angle rotation sequence) (Wu et al., 2005), generating plane, elevation, and internal/external rotation of the humerus relative to the thorax. Elevation was used to determine the range of motion for humeral elevation in the scapular plane, weighted humeral elevation in the scapular plane, the gallon lift, wall circumduction, and combing movements.

4.3.7. Statistical Analysis

The hypothesis that rotator cuff muscle activity would increase with the acute relief of chronic pain was tested by using One-Dimensional Statistical Parametric Mapping (SPM1d) (Pataky, 2012; Robinson et al., 2015), comparing the pre-injection phase to the post-injection phase. A separate analysis was performed for each movement.

An SPM1d two-tailed paired *t*-test was used to compare the activation of each muscle in the pre-injection condition to the post-injection condition (Pataky, 2012; Robinson et al., 2015). This method is similar to a scalar two-tailed paired *t*-test with the additional benefit of Random Field Theory as a means to handle the relatively smooth, interdependent EMG data points (Pataky, 2012; Robinson et al., 2015). An alpha level of 0.05 was used to determine significant difference. Open source SPM1d Matlab code (The Mathworks, Inc., Natick, MA, USA) was used to run these analyses. The results for the rotator cuff muscles are presented here, while the results for the surface musculature are presented in the Appendix.

Potential changes in MVC forces were assessed using a paired *t*-test. Muscle activity for each of the eight muscles monitored was also compared in the two conditions using a paired *t*-test. Each of these assessments also used an alpha level of 0.05.

4.4. Results

4.4.1. Data Exclusions

Exclusions were made for outlying data sets, as determined by the average value (across the full range of motion) exceeding three standard deviations from the mean average value. One supraspinatus data set for the gallon lift was determined to be an outlier and was thus excluded. No other exclusions of supraspinatus or infraspinatus data were made.

4.4.2. Further SPM Detail

An example of the results of the SPM1d analysis is provided below (Figure 4.2). For reference, these are the results associated with the concentric portion of unweighted humeral elevation in the scapular plane for the supraspinatus muscle, as shown in Figure 4.3A and Table 4.1.

In Figure 4.2, the *x*-axis displays the portion of the movement, 0 - 100% being from 30 - 120° of elevation. The *y*-axis displays the *t*-value, as determined with the SPM1d code. In this instance a critical *t*-value of 3.390 (horizontal dashed line) was determined using the code (Henderson et al., 2011; Pataky, 2012). The extent to which this *t*-value was exceeded determined the *p*-value associated with each excursion (Henderson et al., 2011; Pataky, 2012). The *p*-value calculated is the probability that a supra-threshold cluster of this size would be observed in repeated random samplings (Henderson et al., 2011; Pataky, 2012). Here, the portions of significant difference were 21.7 – 44.4% and 88.3 – 97.6% of the movement. These portions of significance are depicted by the shaded regions above the dashed line (Figure 4.2).

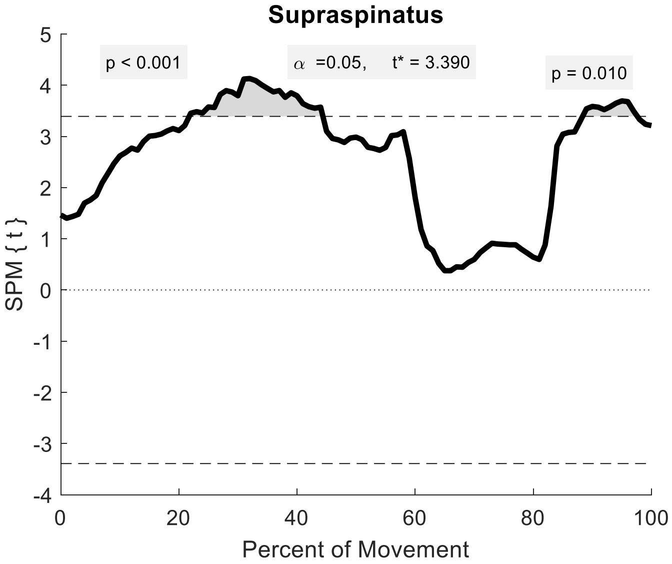

Figure 4.2. SPM1d Results Example. Results of an SPM1d two-tailed paired *t*-test, comparing supraspinatus activity during concentric unweighted humeral elevation in the scapular plane before and after a pain-relieving injection.

4.4.3. Unweighted Humeral Elevation in the Scapular Plane

Humeral elevation in the scapular plane has been divided into two sections for each muscle: concentric (30 - 120°) and eccentric (120 - 30°) portions. For each subject, the mean of the three repetitions was used. Significant differences ($p < 0.05$) are shown with black bars along the *x*-axis across the range for which the difference exists. There were significant decreases observed in the activity of both the supraspinatus and the infraspinatus with the acute relief of chronic pain, in both the concentric and eccentric portions (Figure 4.3, Table 4.1).

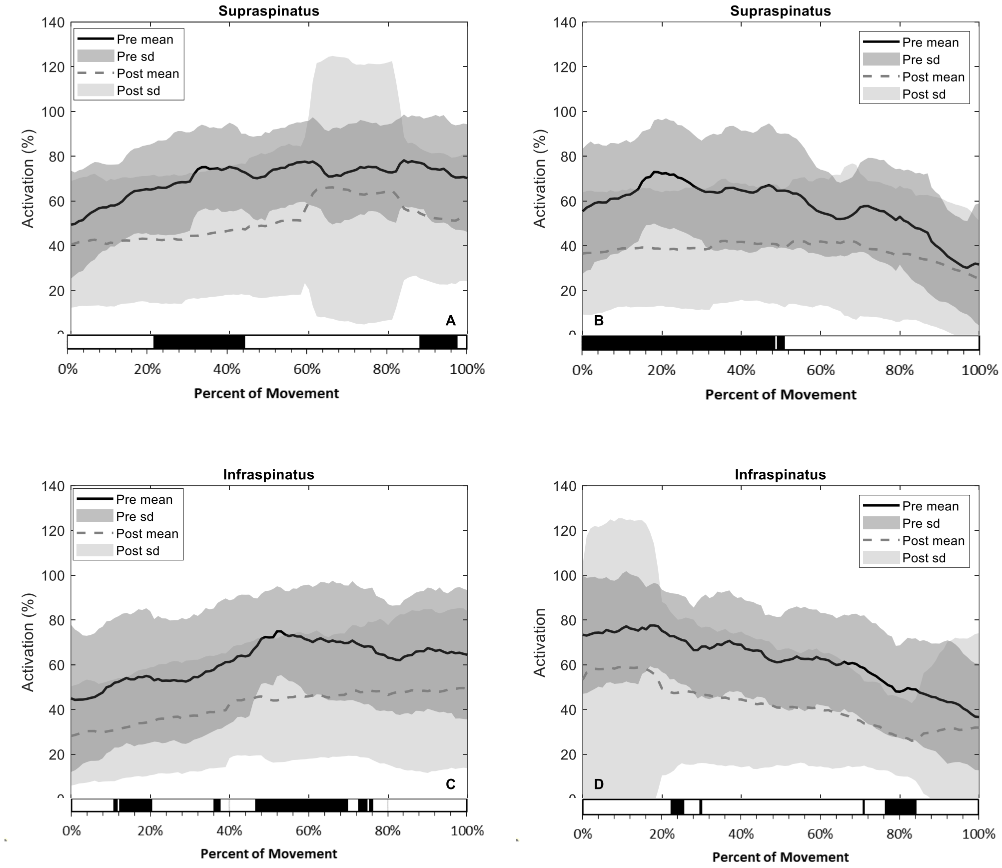

Figure 4.3. Graphs of Supraspinatus and Infraspinatus Activation during Unweighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean values and associated standard deviations (*sd*) concentrically (A,C) and eccentrically (B,D) across 90 degrees (30°-120°) of unweighted humeral elevation in the scapular plane for the supraspinatus and infraspinatus muscles. Differences, as displayed by black bars, were observed in both muscles, both concentrically and eccentrically.

Table 4.1. Muscle Activation Before vs. After Injection for the Supraspinatus and Infraspinatus during Unweighted Humeral Elevation

Summary of Means and Differences between Before and After Pain Relief during Unweighted Humeral Elevation

Muscle	*n*	Direction	Range (%)	*p*	Change
Supraspinatus	20	Concentric	21.7-44.4	< 0.0001	Pre > Post
		Concentric	88.3-97.6	0.01	Pre > Post
	18	Eccentric	0.4-48.5	< 0.0001	Pre > Post
		Eccentric	49.2-50.8	0.047	Pre > Post
Infraspinatus	20	Concentric	10.8-11.6	0.049	Pre > Post
		Concentric	12.3-20.2	0.011	Pre > Post
		Concentric	36.1-37.6	0.047	Pre > Post
		Concentric	46.6-69.8	< 0.001	Pre > Post
		Concentric	72.8-74.8	0.045	Pre > Post
		Concentric	75.4-76.2	0.049	Pre > Post
	18	Eccentric	22.3-25.5	0.039	Pre > Post
		Eccentric	29.7-30.1	0.050	Pre > Post
		Eccentric	70.8-71.1	0.050	Pre > Post
		Eccentric	76.6-77.9	0.048	Pre > Post
		Eccentric	78.1-84.1	0.021	Pre > Post

Note. An alpha level of 0.05 was used.

4.4.4. Weighted Humeral Elevation in the Scapular Plane

During weighted humeral elevation in the scapular plane, there were significant decreases observed in the activity of the supraspinatus with the acute relief of chronic pain but no changes in the infraspinatus (Figure 4.4, Table 4.2).

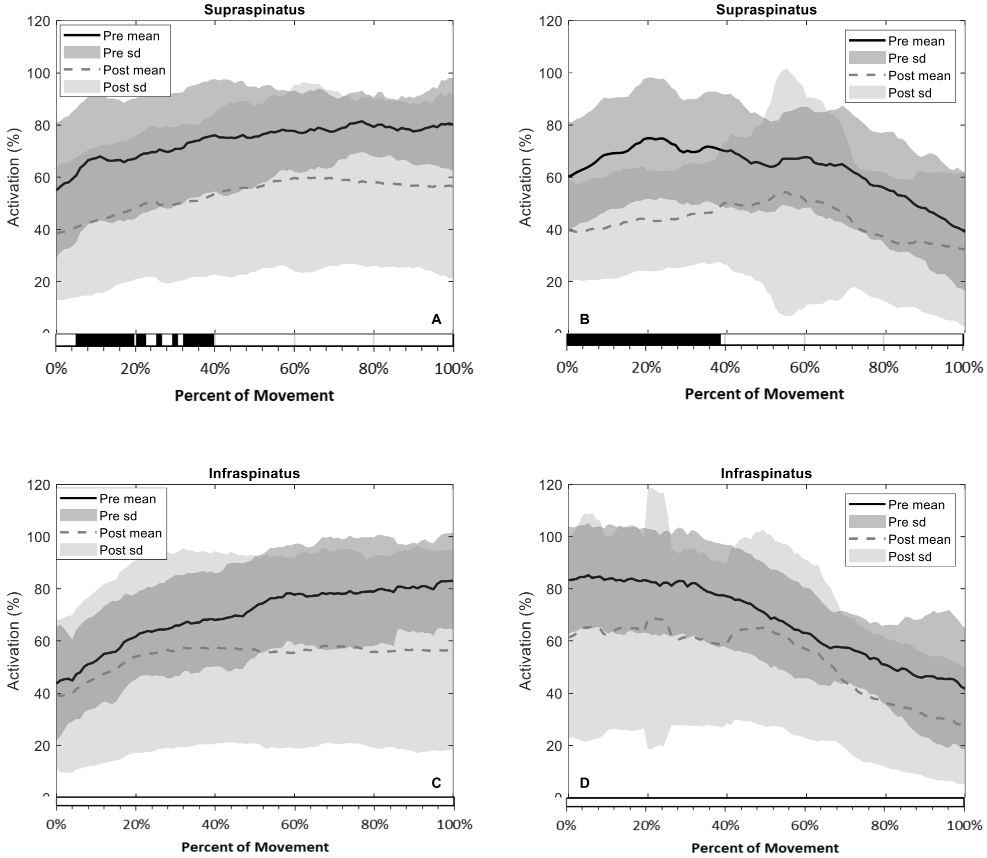

Figure 4.4. Graphs of Supraspinatus and Infraspinatus Activation during Weighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean values and associated standard deviations (*sd*) concentrically and eccentrically across 90 degrees (30°-120°) of weighted humeral elevation in the scapular plane for two muscles. Differences, as displayed by black bars, were observed in the supraspinatus, for both concentric (A) and eccentric (B) portions.

Table 4.2. Muscle Activation Before vs. After Injection for the Supraspinatus and Infraspinatus during Weighted Humeral Elevation in the Scapular Plane

Summary of Means and Differences between Before and After Pain Relief during Weighted Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Supraspinatus	17	Concentric	5.3-19.6	0.012	Pre > Post
		Concentric	20.4-22.5	0.048	Pre > Post
		Concentric	25.4-26.6	0.050	Pre > Post
		Concentric	29.6-30.6	0.050	Pre > Post
		Concentric	32.3-39.6	0.035	Pre > Post
	17	Eccentric	0-38.6	< 0.0001	Pre > Post
Infraspinatus	17	Concentric	-	-	-
	17	Eccentric	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between the before (Pre) and after (Post) pain relief conditions.

4.4.5. Gallon Lift

The gallon-lifting movement was analyzed as the mean of two repetitions, each beginning and ending as the subject held the jug at the maximum elevation achieved over the shelf, before moving it down to the counter. There were significant decreases observed in the activity of both the supraspinatus and the infraspinatus with the acute relief of chronic pain (Figure 4.5, Table 4.3).

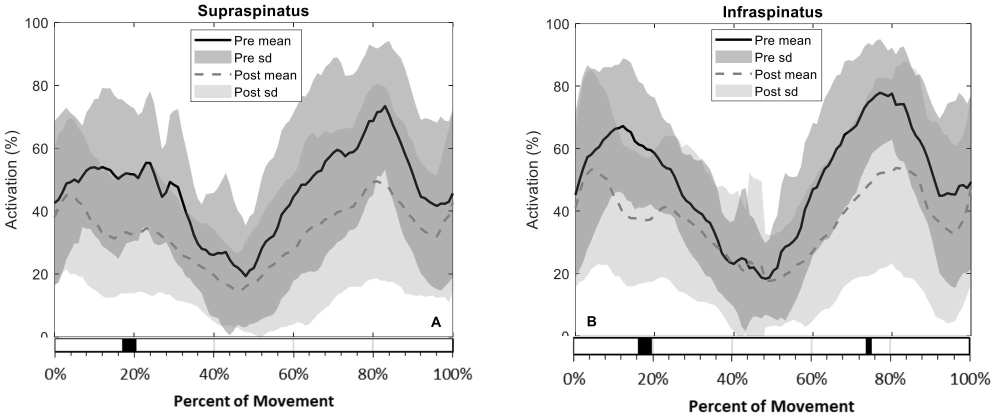

Figure 4.5. Graphs of Supraspinatus and Infraspinatus Activation during a Gallon Lift. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean values and associated standard deviations (*sd*) while lifting a gallon jug of water for two muscles. Differences, as displayed by black bars, were observed in both the supraspinatus (A) and the infraspinatus (B).

Table 4.3. Muscle Activation Before vs. After Injection for the Supraspinatus and Infraspinatus during a Gallon Lift

Summary of Means and Differences between Before and After Pain Relief while Lifting a Gallon Jug of Water

Muscle	*n*	Range (%)	*p*	Change
Supraspinatus	19	17.1-20.3	0.023	Pre > Post
Infraspinatus	20	16.2-19.4	0.021	Pre > Post
		74.3-75.3	0.046	Pre > Post

Note. An alpha level of 0.05 was used.

4.4.6. Circular Motion Against the Wall

The circumduction movement was analyzed as the mean of three repetitions, each beginning and ending as the subject achieved maximum humeral elevation. There were significant decreases observed in the activity of both the supraspinatus and the infraspinatus with the acute relief of chronic pain (Figure 4.6, Table 4.4).

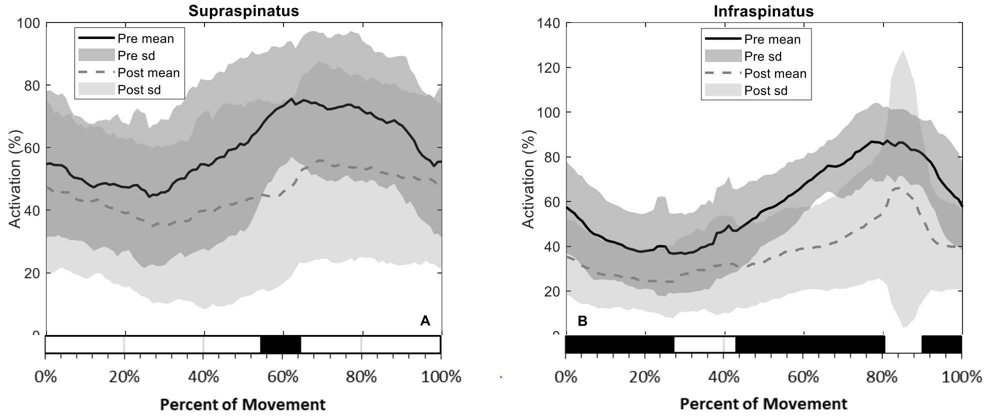

Figure 4.6. Graphs of Supraspinatus and Infraspinatus Activation during Circumduction. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean values and associated standard deviations (*sd*) while performing circumduction for two muscles. Differences, as displayed by black bars, were observed in both the supraspinatus (A) and the infraspinatus (B).

Table 4.4. Muscle Activation Before vs. After Injection for the Supraspinatus and Infraspinatus during Circumduction

Summary of Means and Differences between Before and After Pain Relief during Circumduction

Muscle	*n*	Range (%)	*p*	Change
Supraspinatus	20	54.5-64.6	0.001	Pre > Post
Infraspinatus	20	0-27.4	<0.0001	Pre > Post
		43.1-80.6	<0.0001	Pre > Post
		90.1-100	<0.001	Pre > Post

Note. An alpha level of 0.05 was used.

4.4.7. Hair-Combing Movement

The hair-combing movement was analyzed as the mean of two repetitions, each beginning and ending as the subject achieved maximum humeral elevation. There was a significant decrease observed in the activity of the infraspinatus with the acute relief of chronic pain, but no change in the supraspinatus (Figure 4.7, Table 4.5).

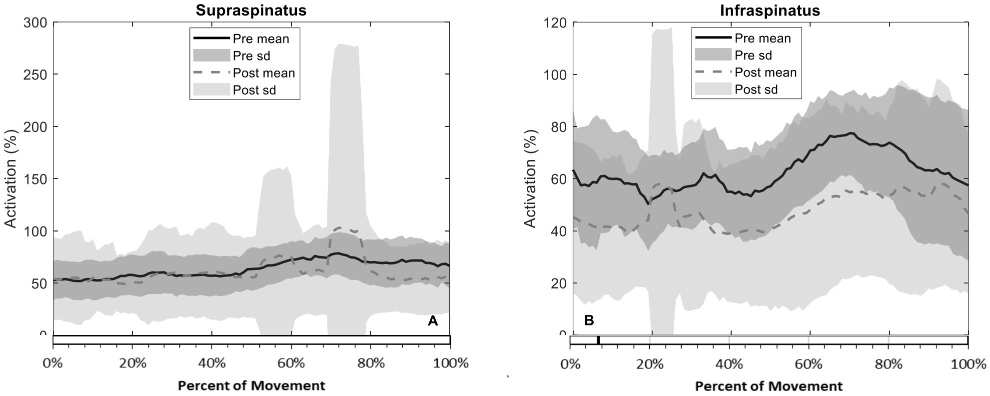

Figure 4.7. Graphs of Supraspinatus and Infraspinatus Activation during a Combing Movement. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean values and associated standard deviations (*sd*) while making a hair combing movement for two muscles. Differences, as displayed by black bars, were observed in only the infraspinatus (B).

Table 4.5. Muscle Activation Before vs. After Injection for the Supraspinatus and Infraspinatus during a Combing Movement

Summary of Means and Differences between Before and After Pain Relief while Making a Hair Combing Movement

Muscle	*n*	Range (%)	*p*	Change
Supraspinatus	17	-	-	-
Infraspinatus	17	6.9-7.4	0.049	Pre > Post

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between the before (Pre) and after (Post) pain relief conditions.

4.4.8. Maximal Voluntary Contractions

There was no change in humeral elevation force during MVC but there was a significant increase in external rotation force during MVC with the acute relief of chronic pain. Considering the humeral elevation MVC, for which there was no change in force, there was an increase in the activity of both the supraspinatus and the infraspinatus muscles. Considering the external rotation MVC, for which there was a decrease in force, there were also decreases in the activity of the supraspinatus and infraspinatus muscles (Table 4.6, Table 4.7, Table 4.8).

Table 4.6. Maximal Forces during MVC Before vs. After Injection

Summary of Maximal Voluntary Contraction Force Results

Contraction	*n*	Pre-relief	Post-relief	*p*
Humeral Elevation	20	88.3 (34.3)	88.1 (33.3)	0.939
External Rotation	20	119.7 (49.6)	139.4 (49.1)	0.002*

Note. Values listed are mean (*sd*) in Newtons. *significant difference ($p < 0.05$)

Table 4.7. Muscle Activation during Humeral Elevation MVC Before vs. After Injection

Summary of Humeral Elevation Maximal Voluntary Contraction Muscle Activity Results

Contraction	*n*	Pre-relief	Post-relief	*p*
Supraspinatus	20	0.69 (0.48)	0.39 (0.29)	0.005*
Infraspinatus	20	0.55 (0.42)	0.35 (0.30)	0.008*

Note. Values listed are mean (*sd*) in millivolts. *significant difference ($p < 0.05$)

Table 4.8. Muscle Activation during External Rotation MVC Before vs. After Injection

Summary of External Rotation Maximal Voluntary Contraction Muscle Activity Results

Contraction	*n*	Pre-relief	Post-relief	*p*
Supraspinatus	20	0.49 (0.37)	0.33 (0.28)	0.015*
Infraspinatus	20	0.50 (0.36)	0.35 (0.30)	0.034*

Note. Values listed are mean (*sd*) in millivolts. *significant difference ($p < 0.05$)

4.5. Discussion

The purpose of the present study was to assess changes in shoulder muscle EMG activity when chronic pain from the subacromial space was acutely relieved. It was hypothesized there would be higher rotator cuff muscle activation after pain relief. This hypothesis was not supported, with neither the supraspinatus nor the infraspinatus displaying an increase in activity after the injection. The results of this study not only failed to support the hypothesis, they ran directly against it. Pain relief was associated with a decrease in rotator cuff muscle activity in almost all contractions.

Previous studies have reported a variety of intermittent differences in shoulder muscle activity between patients, who had been diagnosed with subacromial pain or impingement, and the healthy population. During abduction, studies have reported EMG in patients being higher for the supraspinatus (Diederichsen, Nørregaard, et al., 2009), latissimus dorsi (Bandholm, Rasmussen, Aagaard, Jensen, & Diederichsen, 2006; Diederichsen, Nørregaard, et al., 2009), and upper trapezius (Lin et al., 2005; Ludewig &

Cook, 2000). Muscle activity has been reported to be lower in patients than in controls during abduction for the serratus anterior (Diederichsen, Nørregaard, et al., 2009; Lin et al., 2005; Ludewig & Cook, 2000) and middle deltoid (Michaud et al., 1987). During external rotation, studies have displayed lower EMG in patients than healthy controls in the infraspinatus and serratus anterior (Diederichsen, Nørregaard, et al., 2009). During humeral elevation, decreased EMG activity in patients has been observed in the supraspinatus, infraspinatus, and middle deltoid (Reddy et al., 2000). At the same time, some studies have shown no differences in the EMG activity between patients and healthy controls in the supraspinatus (Bandholm et al., 2006; Brox et al., 1997; Reddy et al., 2000), anterior deltoid (Bandholm et al., 2006), posterior deltoid (Clisby et al., 2008), and serratus anterior (Bandholm et al., 2006). These disparate results of comparisons between patient and healthy EMG activity are difficult to interpret since EMG is most often normalized to MVC (Chester et al., 2010) and that process is influenced by pain (Ettinger et al., 2016). This is one potential reason for conflicting reports regarding differences in muscle activity between the patient and healthy populations.

One presumably significant difference between the patient and healthy populations, on which studies generally agree, is superior translation of the humeral head in the patient population (Deutsch et al., 1996; Michener et al., 2003). It has been speculated that such translation could be resulting from decreased supraspinatus activity with a compensatory increase in middle deltoid activity during humeral elevation (Michener et al., 2003). This shift between the muscles would direct some of the muscular force more superiorly and less medially and potentially contribute to impingement syndrome (Michener et al., 2003). Further speculation regarding a cause of the presumed decreased supraspinatus activity includes that the muscle and its tendons could be signaling pain; supraspinatus pain could lead to a reduction in supraspinatus activity (Lund et al., 1991; Michener et al., 2003). If this is indeed occurring, a reduction in pain could lead to a decrease in that reduction of activity, which would be observed as an increase in activity. While this was hypothesized in the present study, the results indicate otherwise.

Only two other studies were found to have investigated EMG activity in patients before and after a subacromial injection (Brox et al., 1997; Ettinger et al., 2016). Both studies showed an activity increase in the middle deltoid during an MVC (Brox et al., 1997; Ettinger et al., 2016). Only one study monitored the anterior and posterior parts of the deltoid, both of which displayed an increase in activity during MVC (Ettinger et al., 2016). Both studies measured, but only one displayed an increase in, the upper trapezius during MVC (Brox et al., 1997; Ettinger et al., 2016). One study measured and displayed an increase in the lower trapezius during MVC (Ettinger et al., 2016). One study measured and displayed an increase in the infraspinatus during MVC (Brox et al., 1997). No changes were observed in the supraspinatus (Brox et al., 1997), latissimus dorsi (Ettinger et al., 2016), or serratus anterior (Ettinger et al., 2016). The results of the present study add further disparities, being the first to display a decrease in supraspinatus and infraspinatus activity after pain relief. Further results, in Appendix A, show increased EMG activity in the upper trapezius and some increased activity in the posterior deltoid, neither of which is in disagreement with previous studies (Brox et al., 1997; Ettinger et al., 2016). No changes were observed during any of the movements for the anterior or middle deltoid, nor for the latissimus dorsi or the serratus anterior.

While other studies did not assess EMG, they have displayed differences in strength and kinematics following a subacromial injection for patients. Regarding strength (two studies), one showed only modest increases in external rotation strength and no change in “empty can” (humeral elevation while internally rotated) or internal rotation strength (Park et al., 2008). The other study showed increased strength in all four positions tested: abduction, adduction, external rotation, and humeral elevation while neutrally rotated (Ben-Yishay, Zuckerman, Gallagher, & Cuomo, 1994). One study assessed proprioception and reported a decline thereof (Ettinger et al., 2017). Three studies assessed kinematics (Ettinger, Shapiro, & Karduna, 2014; Kolk et al., 2016; Scibek et al., 2008); one reported increased glenohumeral motion after the injection (Scibek et al., 2008); the remaining two studies tracked scapular movement; both reported an increase in anterior tilt (Ettinger et al., 2014; Kolk et al., 2016) and one reported increased internal rotation (Kolk et al., 2016). This latter result is puzzling in a manner similar to the results of the present study; patients already display more anterior tilting and upward rotation of the scapula relative to the healthy population (Ettinger et al., 2014) and the subacromial injection appears to, at least initially, have furthered that divide.

Similar to the increased anterior tilt, the present study displayed a further decrease in supraspinatus activity with pain relief. This is potentially surprising if one subscribes to the concept of decreased supraspinatus and increased deltoid activity leading to the previously displayed superior translation of the humeral head in the patient state (Michener et al., 2003). While the results of the present study do not provide evidence supporting that progression, there is a distinct possibility that the response to the acute relief of chronic pain does not directly reverse an adaptation to chronic pain.

Humerothoracic kinematics were analyzed in the present study. This is one potential source of ambiguity, since the humerothoracic result is a combination of the scapulothoracic and glenohumeral components. This means that the pre-injection humeral elevation and post-injection humeral elevation, while resultantly similar, might have differed in their kinematic elements. Previous work has shown an increase in glenohumeral motion after injection (Scibek et al., 2008), but that could be masked in the present study by a decrease in scapulothoracic movement. On the other hand, there could have been an increase in scapulothoracic movement and a decrease in glenohumeral motion. While this would not agree with Scibek et al. (2008), it could be supported by the observed increase in upper trapezius activity; this is further detailed in Appendix A (Scibek et al., 2008). Such an increase in scapular movement could reduce the necessity for glenohumeral muscle activity and could be a contributor to the observed decrease in rotator cuff muscle activity.

The latissimus dorsi was monitored due to its potential for antagonist coactivation during humeral elevation in the scapular plane. Had this muscle displayed a decrease in activity, that might have accounted for reduced rotator cuff muscle activity; this, however, did not occur. The lack of an observed decrease in coactivation does not preclude, though, another muscle, or another section of the latissimus dorsi, from having served as an antagonist coactivator in a manner that was not detected.

Perhaps the highly localized nature of fine-wire EMG contributed to the investigators not observing a redistribution of muscle activity within the rotator cuff muscles, with other portions of the supraspinatus and infraspinatus experiencing an increase in activity. Additionally, barring a sympathetic response, the body's initial reaction to a stimulus may generally default to a reduction in energy expenditure vice an increase. This would indicate an overall optimization strategy that could be difficult to elucidate.

A relationship has been displayed between pain and muscle activity, but the details of that relationship are not widely understood and at times appear inconsistent (Ettinger et al., 2016; Hodges, 2015; Mista et al., 2015). An adaptation to chronic pain likely differs from an acute response (Graven-Nielsen & Arendt-Nielsen, 2010; Hodges, 2015; Madeleine et al., 2008). Perhaps an adaptation to pain relief differs from the acute response to it. The direct effect of chronic pain, and chronic or acute pain relief, on muscle activity is unclear. Studies have shown that motor cortex inhibition is reduced when pain level stabilizes (Coronado, Simon, Valencia, & George, 2014; S. Farina et al., 2001; Nijs et al., 2012; Struyf et al., 2014), but also that a reduction in pain can enhance motor output (Brox et al., 1997; Ettinger et al., 2016; Nijs et al., 2012).

4.6. Conclusions

Counter to expectation, a reduction in pain in the subacromial space caused a reduction in rotator cuff muscle activity in almost all assessments, both dynamic and isometric. This does not seem to be in alignment with Lund's pain adaptation model.

What these results might indicate is that the return to a pre-pain state is not simply the reverse of a transition into a chronic pain state. The puzzling nature of these results displays room for further exploration into the effect of chronic pain on muscle activity, in both temporal directions. An improved understanding of the causal relationships involved in injury and recovery could clarify factors integral to physical therapy regimens.

CHAPTER V

CONCLUSIONS

Shoulder pain is potentially complex and multifactorial, and its nature may differ widely between subjects and conditions. The primary purpose of this dissertation was to investigate shoulder pain from two different angles: an acute condition that might initiate a cascade toward sub-acute, and a chronic condition beginning a standard treatment protocol. The goal is to help inform both the manner in which an injury becomes a chronic condition and the manner in which function is restored to a healthy, pain-free state.

There is a distinct possibility that the sequence of physiological responses, be they in series or in parallel, differ by temporal directionality. That is, recovery is likely not simply the reverse of the injury progression. Regardless, there may be points along the progression at which an intervention can allow the direct recovery from aspects of an acute, subacute, or chronic condition. The results of this dissertation indicate that recovery is not simply backwards injury. If it were, the results of introducing and removing pain would not be as similar as they were, with both resulting in a decrease in rotator cuff muscle activity.

Many questions remain. The progression after an injury remains difficult to investigate in an ethical manner. A return to full function, be that a regression or a different progression, is challenging for a whole host of reasons including compliance, nutrition, rest, stress -- basically all the lifestyle and physiological differences between individuals. Additionally, therapy often uses a shotgun approach, in which multiple potential factors are addressed simultaneously; this makes is difficult to determine which aspects of the therapy were effective and which were simply performed alongside. Much further investigation is required.

APPENDIX

PATIENT SURFACE MUSCLE RESULTS

Following are the results from Chapter IV for the measured surface musculature of patients: the anterior deltoid, middle deltoid, posterior deltoid, upper trapezius, latissimus dorsi, and serratus anterior. For reader ease, both unweighted and weighted humeral elevation in the scapular plane are split into two sections, each containing three muscles, and further split inside those section into the concentric and eccentric portions of movement.

For all analyses, 13 of the 160 data sets (eight muscles for each of twenty subjects) were excluded due to the sensors either malfunctioning or running out of battery (3 anterior deltoid, 4 middle deltoid, 1 posterior deltoid, 1 upper trapezius, 3 serratus anterior, 1 latissimus dorsi).

In addition to the initial exclusions, two data sets for unweighted humeral elevation in the scapular plane were determined to be outliers and were thus excluded: one serratus anterior and one latissimus dorsi. There were no differences observed in any of the three heads of the deltoid (anterior, middle, posterior) with the acute relief of chronic pain (Figure A.1, Table A.1).

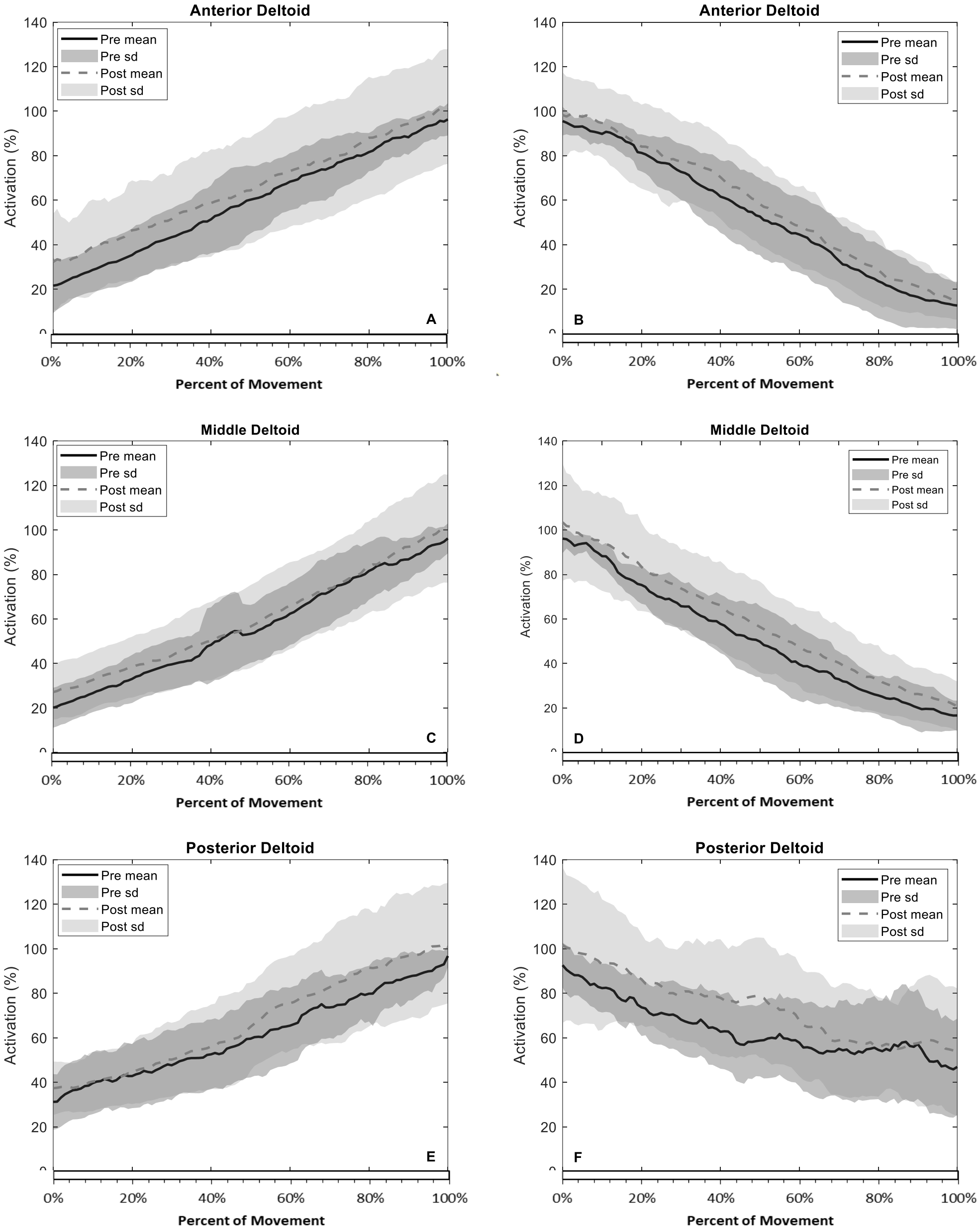

Figure A.1. Anterior, Middle, and Posterior Deltoid EMG Differences during Unweighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) concentrically (A,C,E) and eccentrically (B,D,F) across 90 degrees (30°-120°) of unweighted humeral elevation for each of three muscles. No significant differences were displayed between the pre- and post-pain relief conditions for any of the muscles.

Table A.1. Deltoid EMG during Unweighted Humeral Elevation

Summary of EMG Differences between Before and After Pain Relief during Unweighted Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Anterior Deltoid	17	Concentric	-	-	-
	15	Eccentric	-	-	-
Middle Deltoid	16	Concentric	-	-	-
	14	Eccentric	-	-	-
Posterior Deltoid	19	Concentric	-	-	-
	17	Eccentric	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

During unweighted humeral elevation in the scapular plane, there were significant increases observed in the activity of the upper trapezius with the acute relief of chronic pain but no changes in the latissimus dorsi or the serratus anterior (Figure A.2, Table A.2).

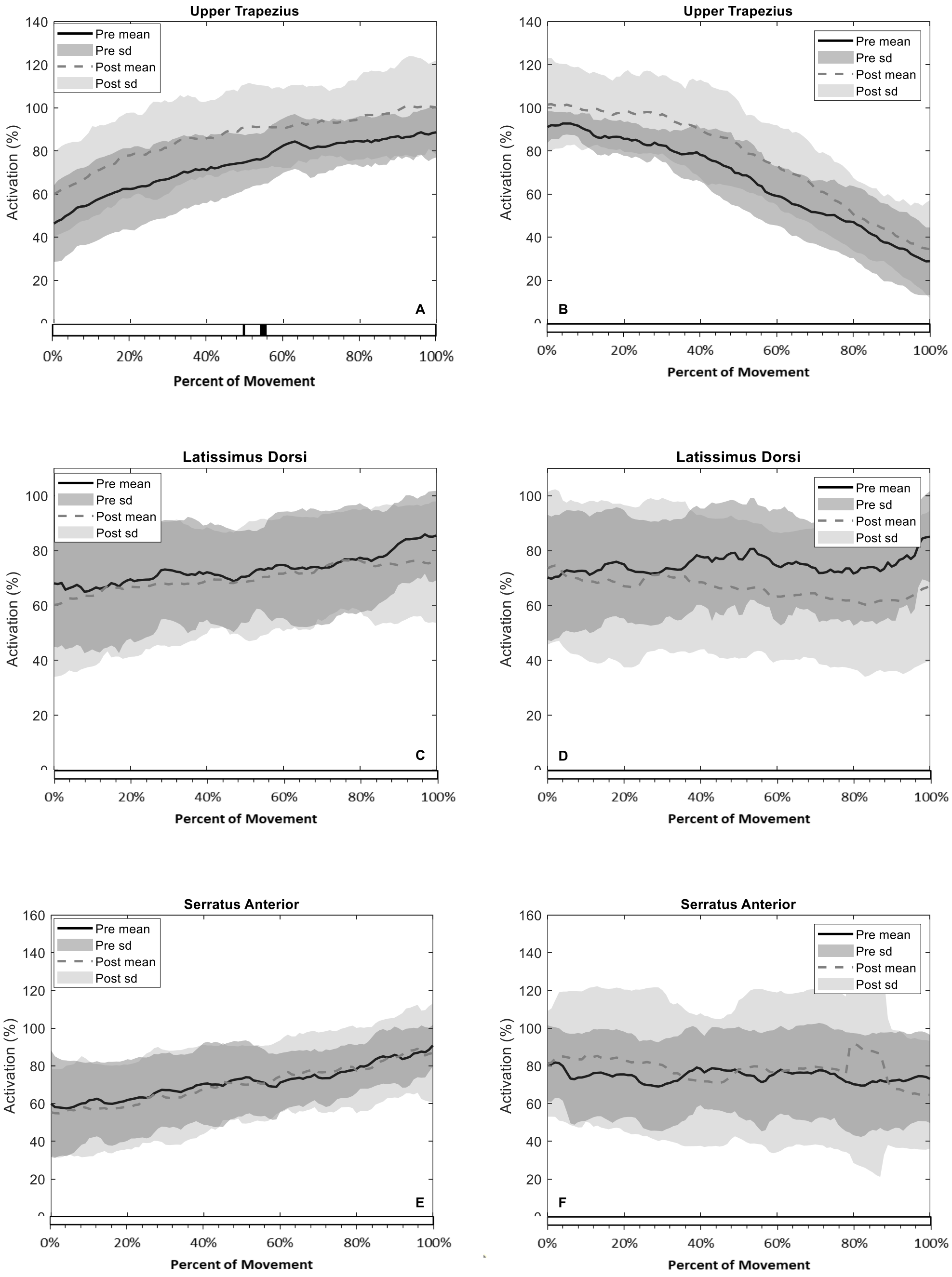

Figure A.2. Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG Differences during Unweighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) concentrically (A,C,E) and eccentrically (B,D,F) across 90 degrees (30°-120°) of unweighted humeral elevation for each of three muscles. Differences, as displayed by black bars, were observed in the upper trapezius, concentric (A).

Table A.2. Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG during Unweighted Humeral Elevation

Summary of EMG Differences between Before and After Pain Relief during Unweighted Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Upper Trapezius	19	Concentric	49.8-50.1	0.050	Pre < Post
		Concentric	54.2-55.7	0.046	Pre < Post
	17	Eccentric	-	-	-
Latissimus Dorsi	19	Concentric	-	-	-
	16	Eccentric	-	-	-
Serratus Anterior	16	Concentric	-	-	-
	14	Eccentric	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

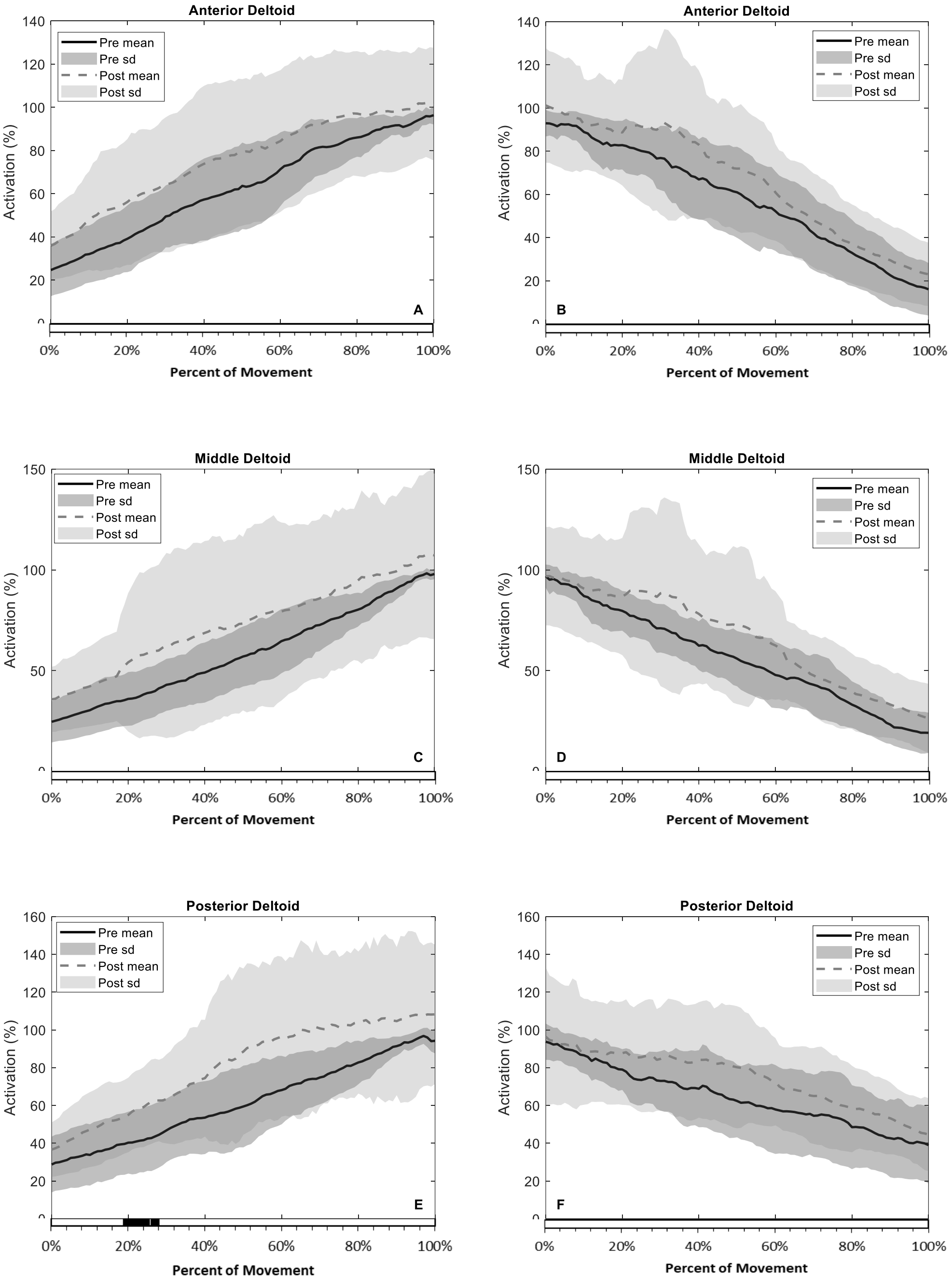

Figure A.3. Anterior, Middle, and Posterior Deltoid EMG Differences during Weighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) concentrically and eccentrically across 90 degrees (30°-120°) of weighted humeral elevation for each of three muscles. Differences, as displayed by black bars, were observed in one case: posterior deltoid, concentrically.

Table A.3. Deltoid EMG during Weighted Humeral Elevation

Summary of EMG Differences between Before and After Pain Relief during Weighted Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Anterior Deltoid	15	Concentric	-	-	-
	15	Eccentric	-	-	-
Middle Deltoid	14	Concentric	-	-	-
	14	Eccentric	-	-	-
Posterior Deltoid	16	Concentric	19.0-25.5	0.034	Pre < Post
		Concentric	26.1-28.1	0.048	Pre < Post
	16	Eccentric	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

During weighted humeral elevation in the scapular plane, there were significant increases observed in the EMG activity of the upper trapezius with the acute relief of chronic pain but no changes in the latissimus dorsi or serratus anterior (Figure A.4, Table A.4).

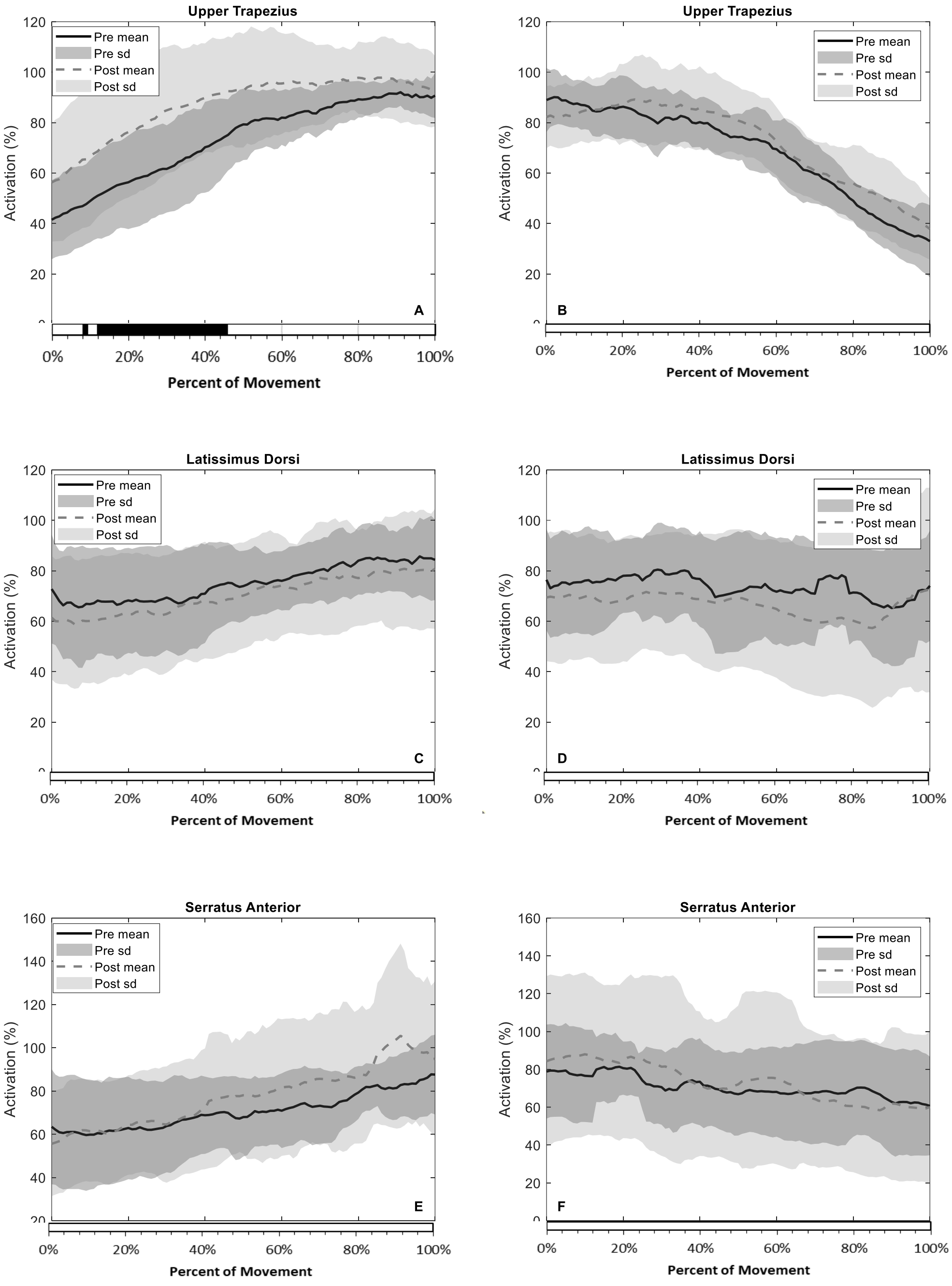

Figure A.4. Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG Differences during Weighted Humeral Elevation. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) concentrically and eccentrically across 90 degrees (30°-120°) of weighted humeral elevation in the scapular plane for each of three muscles. Differences, as displayed by black bars, were observed in one case: upper trapezius, concentric (C).

Table A.4. Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG during Weighted Humeral Elevation

Summary of EMG Differences between Before and After Pain Relief during Weighted Humeral Elevation in the Scapular Plane

Muscle	*n*	Direction	Range (%)	*p*	Change
Upper Trapezius	15	Concentric	8.1-9.1	0.050	Pre < Post
		Concentric	11.8-14.7	0.040	Pre < Post
		Concentric	15.1-41.9	<0.0001	Pre < Post
		Concentric	42.1-45.7	0.036	Pre < Post
	16	Eccentric	-	-	-
Latissimus Dorsi	15	Concentric	-	-	-
	15	Eccentric	-	-	-
Serratus Anterior	14	Concentric	-	-	-
	14	Eccentric	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

During the gallon-lifting movement, there were no differences between the pre- and post- injection conditions for any of the surface muscles (Figure A.5, Table A.5).

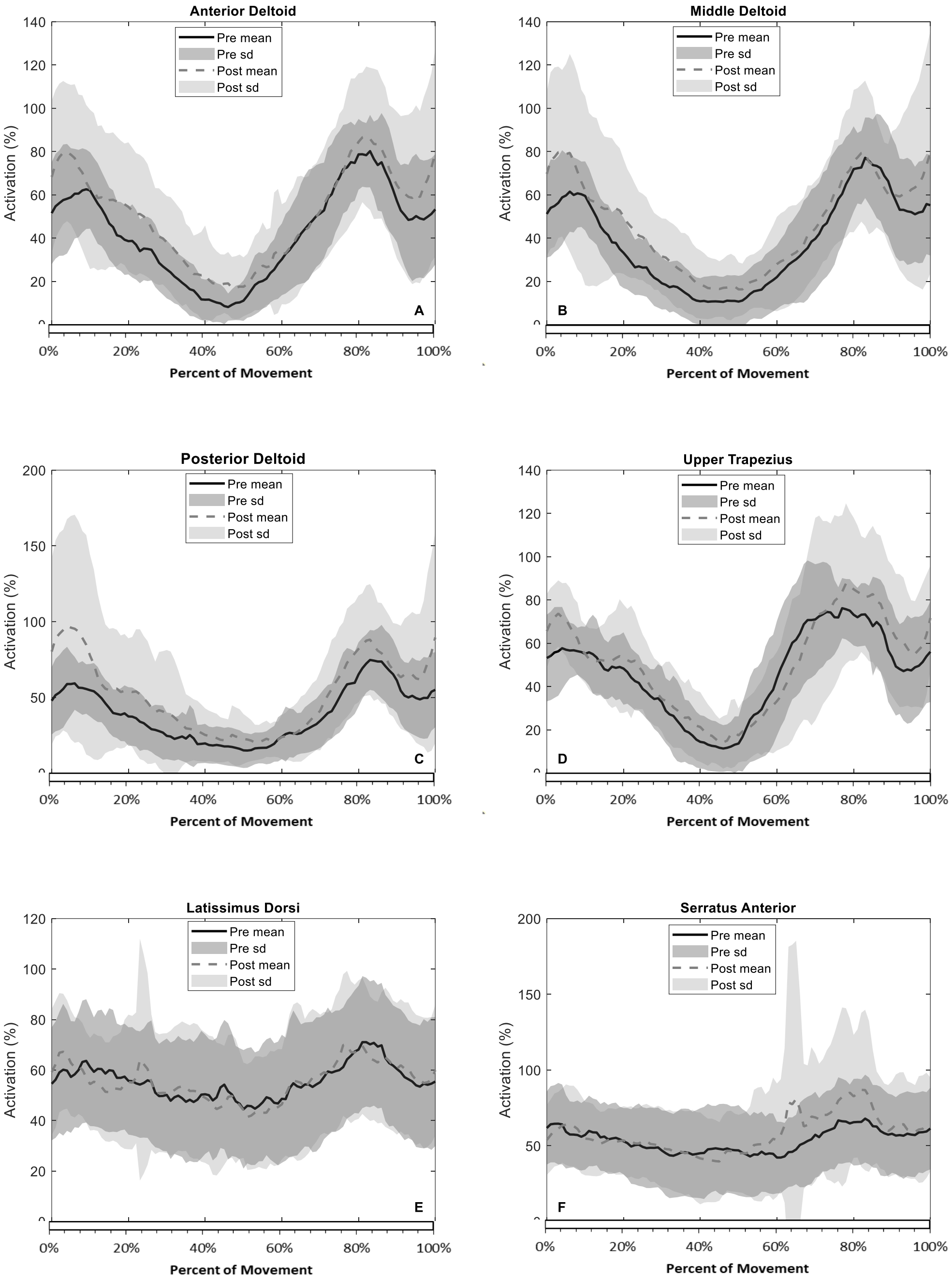

Figure A.5. Anterior, Middle, Posterior Deltoid, Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG Differences during a Gallon Lift. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) lifting a gallon jug of water for each of six muscles. No significant differences were displayed between the pre- and post-pain relief conditions.

Table A.5. Surface Muscles' EMG while Lifting a Gallon Jug of Water

Summary of EMG Differences between Before and After Pain Relief while Lifting a Gallon Jug of Water

Muscle	*n*	Range (%)	*p*	Change
Anterior Deltoid	17	-	-	-
Middle Deltoid	16	-	-	-
Posterior Deltoid	19	-	-	-
Upper Trapezius	19	-	-	-
Latissimus Dorsi	19	-	-	-
Serratus Anterior	17	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

In addition to the initial exclusions, three data sets for the circumduction movement were determined to be outliers and were thus excluded: one anterior deltoid and one posterior deltoid. There were no changes in any of the surface muscles with the acute relief of chronic pain (Figure A.6, Table A.6).

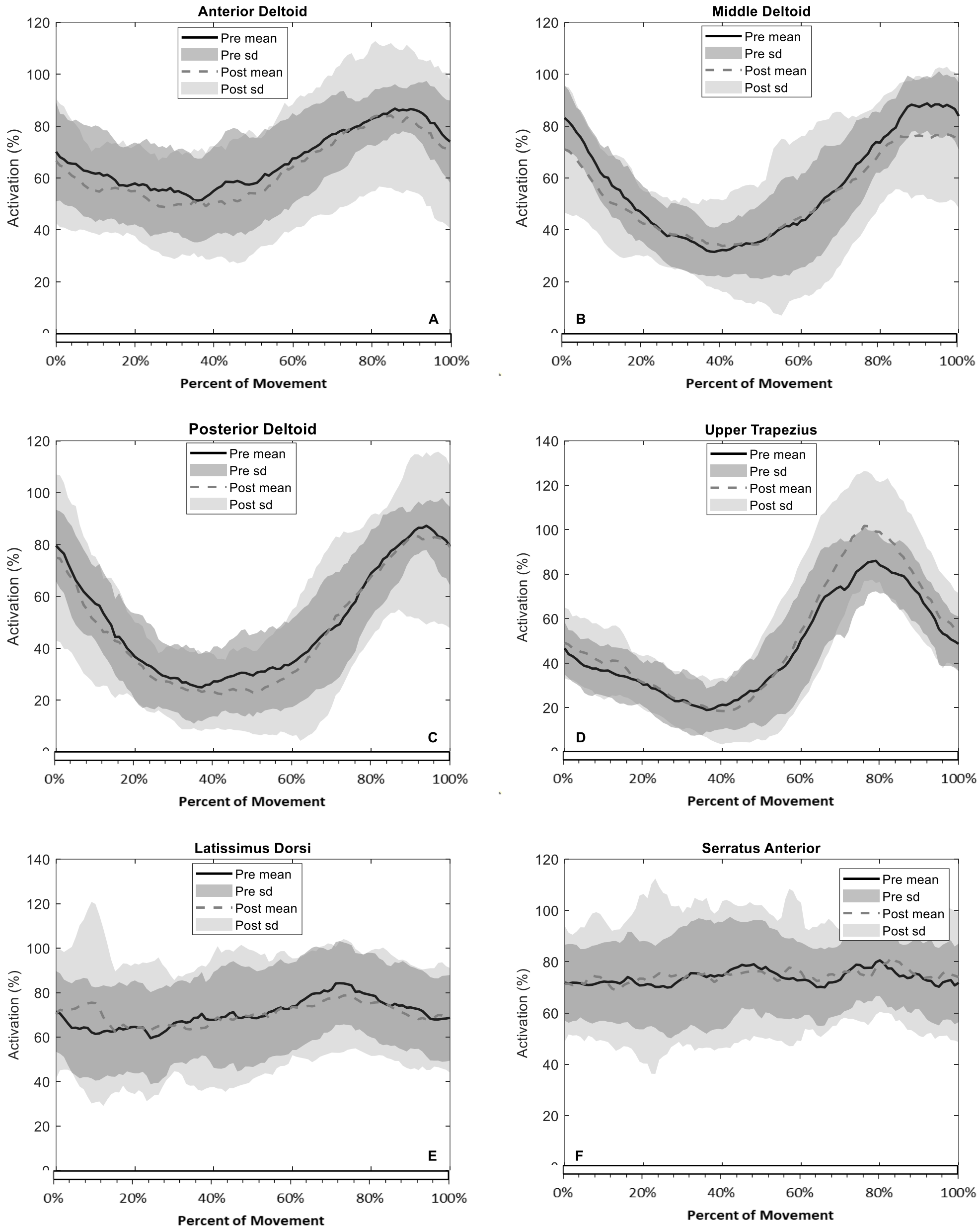

Figure A.6. Anterior, Middle, Posterior Deltoid, Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG Differences during Circumduction. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) performing circumduction for each of six muscles. No significant differences were displayed between the pre- and post-pain relief conditions.

Table A.6. Surface Muscles' EMG while Performing Circumduction

Summary of EMG Differences between Before and After Pain Relief during Circumduction

Muscle	*n*	Range (%)	*p*	Change
Anterior Deltoid	16	-	-	-
Middle Deltoid	16	-	-	-
Posterior Deltoid	18	-	-	-
Upper Trapezius	19	-	-	-
Latissimus Dorsi	19	-	-	-
Serratus Anterior	17	-	-	-

Note. An alpha level of 0.05 was used. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

After the initial exclusions, no additional data sets for the hair combing movement were determined to be outliers and thus excluded. There were no changes in any of the surface muscles with the acute relief of chronic pain (Figure A.7, Table A.7).

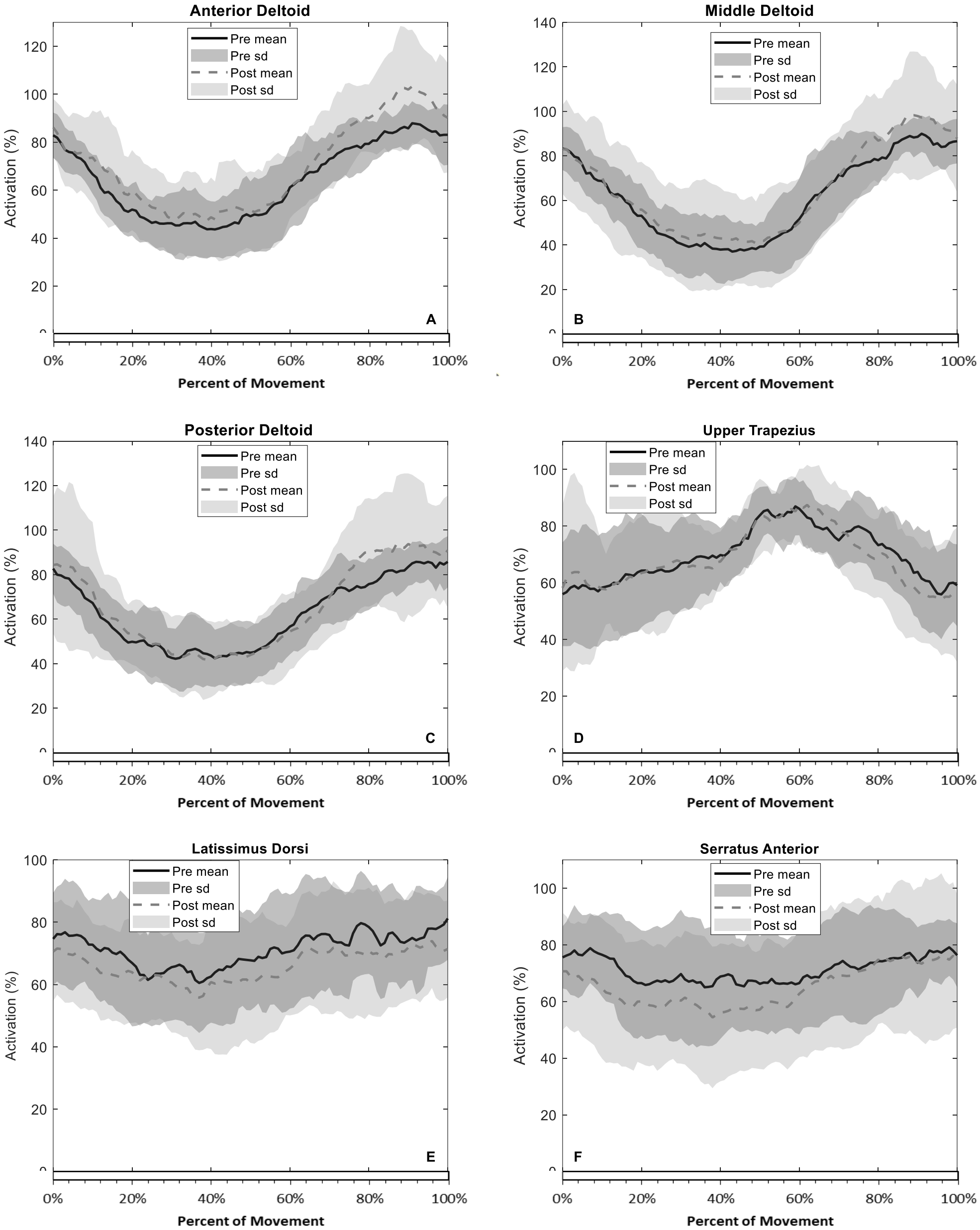

Figure A.7. Anterior, Middle, Posterior Deltoid, Upper Trapezius, Latissimus Dorsi, and Serratus Anterior EMG Differences during a Combing Movement. Before pain relief (Pre, solid black) and after pain relief (Post, dashed grey) mean EMG values and associated standard deviations (*sd*) making a hair combing movement for each of six muscles. No significant differences were displayed between the pre- and post-pain relief conditions.

Table A.7. Surface Muscles’ EMG during Hair Combing Movement

Summary of EMG Differences between Before and After Pain Relief Making a Hair Combing Movement

Muscle	*n*	Range (%)	*p*	Change
Anterior Deltoid	14	-	-	-
Middle Deltoid	14	-	-	-
Posterior Deltoid	16	-	-	-
Upper Trapezius	17	-	-	-
Latissimus Dorsi	16	-	-	-
Serratus Anterior	14	-	-	-

Note. Where no value is listed, no difference was observed between before (Pre) and after (Post) pain relief.

As displayed in the main paper, there was no change in humeral elevation force during MVC but there was a significant increase in external rotation force during MVC with the acute relief of chronic pain (Table 4.6).

Considering the humeral elevation MVC, for which there was no change in force, the only difference between the pre- and post-relief conditions was an increase in posterior deltoid EMG activity (Table A.8).

Table A.8. Surface Muscles' EMG during Humeral Elevation MVC

Summary of Humeral Elevation in the Scapular Plane Maximal Voluntary Contraction Muscle Activity Results

Contraction	*n*	Pre-relief	Post-relief	*p*
Anterior Deltoid	17	0.31 (0.25)	0.30 (0.24)	0.737
Middle Deltoid	16	0.19 (0.09)	0.20 (0.11)	0.837
Posterior Deltoid	20	0.15 (0.09)	0.17 (0.10)	0.006*
Upper Trapezius	20	0.30 (0.24)	0.31 (0.23)	0.500
Latissimus Dorsi	20	0.28 (0.79)	0.30 (0.80)	0.399
Serratus Anterior	17	0.35 (0.77)	0.34 (0.79)	0.869

Note. Values listed are mean (*sd*) in millivolts. *significant difference ($p < 0.05$)

Considering the external rotation MVC, for which there was an increase in force, there were increases in the anterior deltoid, posterior deltoid, and upper trapezius EMG with pain relief (Table A.9).

Table A.9. Surface Muscles' EMG during External Rotation MVC

Summary of External Rotation Maximal Voluntary Contraction Muscle Activity Results

Contraction	*n*	Pre-relief	Post-relief	*p*
Anterior Deltoid	17	0.12 (0.12)	0.17 (0.13)	0.029*
Middle Deltoid	16	0.15 (0.11)	0.17 (0.11)	0.304
Posterior Deltoid	20	0.20 (0.15)	0.25 (0.14)	0.012*
Upper Trapezius	20	0.08 (0.07)	0.14 (0.15)	0.004*
Latissimus Dorsi	20	0.28 (0.76)	0.32 (0.76)	0.461
Serratus Anterior	17	0.34 (0.80)	0.31 (0.77)	0.121

Note. Values listed are mean (*sd*) in millivolts. *significant difference ($p < 0.05$)

REFERENCES CITED

Allison, G. T., Godfrey, P., & Robinson, G. (1998). EMG signal amplitude assessment during abdominal bracing and hollowing. *Journal of Electromyography and Kinesiology*, *8*(1), 51–57. https://doi.org/10.1016/S1050-6411(97)00004-7

Allison, G. T., Marshall, R. N., & Singer, K. P. (1993). EMG signal amplitude normalization technique in stretch-shortening cycle movements. *Journal of Electromyography and Kinesiology*, *3*(4), 236–244.

Bandholm, T., Rasmussen, L., Aagaard, P., Diederichsen, L., & Jensen, B. R. (2008). Effects of experimental muscle pain on shoulder-abduction force steadiness and muscle activity in healthy subjects. *European Journal of Applied Physiology*, *102*(6), 643–650. https://doi.org/10.1007/s00421-007-0642-1

Bandholm, T., Rasmussen, L., Aagaard, P., Jensen, B. R., & Diederichsen, L. (2006). Force steadiness, muscle activity, and maximal muscle strength in subjects with subacromial impingement syndrome. *Muscle and Nerve*, *34*(5), 631–639. https://doi.org/10.1002/mus.20636

Basmajian, J. V., & De Luca, C. J. (1985). *Muscles Alive - Their Functions Revealed by Electromyography*.

Ben-Yishay, A., Zuckerman, J. D., Gallagher, M., & Cuomo, F. (1994). Pain Inhibition of Shoulder Strength in Patients with Impingement Syndrome. *Orthopedics*, *17*(8), 685–688. Retrieved from http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Boettcher, C. E., Ginn, K. A., & Cathers, I. (2008). Standard maximum isometric voluntary contraction tests for normalizing shoulder muscle EMG. *Journal of Orthopaedic Research*, *26*(12), 1591–1597. https://doi.org/10.1002/jor.20675

Bolgla, L. A., & Uhl, T. L. (2007). Reliability of electromyographic normalization methods for evaluating the hip musculature. *Journal of Electromyography and Kinesiology*, *17*(1), 102–111. https://doi.org/10.1016/j.jelekin.2005.11.007

Brox, J. I., Roe, C., Saugen, E., & Vollestad, N. K. (1997). Isometric abduction muscle activation in patients with rotator tendinosis of the shoulder. *Archives of Physical Medicine and Rehabilitation*, *78*(11), 1260–1267. https://doi.org/10.1016/S0003-9993(97)90341-5

Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25years of research. *Journal of Electromyography and Kinesiology*, *20*(6), 1023–1035. https://doi.org/10.1016/j.jelekin.2010.07.004

Burnett, A., Green, J., Netto, K., & Rodrigues, J. (2007). Examination of EMG normalisation methods for the study of the posterior and posterolateral neck muscles in healthy controls. *Journal of Electromyography and Kinesiology*, *17*(5), 635–641. https://doi.org/10.1016/j.jelekin.2006.06.003

Castelein, B., Cools, A., Parlevliet, T., & Cagnie, B. (2016). The influence of induced shoulder muscle pain on rotator cuff and scapulothoracic muscle activity during elevation of the arm. *Journal of Shoulder and Elbow Surgery*, *26*(3), 497–505. https://doi.org/10.1016/j.jse.2016.09.005

Chapman, A. R., Vicenzino, B., Blanch, P., Knox, J. J., & Hodges, P. W. (2010). Intramuscular fine-wire electromyography during cycling: Repeatability, normalisation and a comparison to surface electromyography. *Journal of Electromyography and Kinesiology*, *20*(1), 108–117. https://doi.org/10.1016/j.jelekin.2008.11.013

Chester, R., Smith, T. O., Hooper, L., & Dixon, J. (2010). The impact of subacromial impingement syndrome on muscle activity patterns of the shoulder complex: a systematic review of electromyographic studies. *BMC Musculoskeletal Disorders*, *11*, 45. https://doi.org/10.1186/1471-2474-11-45

Clisby, E. F., Bitter, N. L., Sandow, M. J., Jones, M. A., Magarey, M. E., & Jaberzadeh, S. (2008). Relative contributions of the infraspinatus and deltoid during external rotation in patients with symptomatic subacromial impingement. *Journal of Shoulder and Elbow Surgery*, *17*(1 SUPPL.), 87–92. https://doi.org/10.1016/j.jse.2007.05.019

Coronado, R. a, Simon, C. B., Valencia, C., & George, S. Z. (2014). Experimental pain responses support peripheral and central sensitization in patients with unilateral shoulder pain. *The Clinical Journal of Pain*, *30*(2), 143–151. https://doi.org/10.1097/AJP.0b013e318287a2a4

Cram, J. R., Kasman, G. S., & Holtz, J. (1998). *Introduction to Surface Electromyography*. Gaithersburg, MD: Aspen Publisher Inc.

Dankaerts, W., O’sullivan, P. B., Burnett, A. F., Straker, L. M., & Danneels, L. A. (2004). Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients. *Journal of Electromyography and Kinesiology*, *14*(3), 333–342. https://doi.org/10.1016/j.jelekin.2003.07.001

de Witte, P., Nagels, J., van Arkel, E. R., Visser, C. P., Nelissen, R. G., & de Groot, J. H. (2011). Study protocol subacromial impingement syndrome: the identification of pathophysiologic mechanisms (SISTIM). *BMC Musculoskeletal Disorders*, *12*(1), 282. https://doi.org/10.1186/1471-2474-12-282

Dean, B. J. F., Gwilym, S. E., & Carr, A. J. (2013). Why does my shoulder hurt ? A review of the neuroanatomical and biochemical basis of shoulder pain. *British Journal of Sports Medicine*, *47*, 1095–1104. https://doi.org/10.1136/bjsports-2012-091492

Delagi, E. F., Iazzetti, J., Perotto, A. O., & Morrison, D. (2005). Anatomical Guide for the Electromyographer - The Limbs and Trunk. In *Anatomical Guide for the Electromyographer*.

Deutsch, A., Altchek, D. W., Schwartz, E., Otis, J. C., & Warren, R. F. (1996). Radiologic measurement of superior displacement of the humeral head in the impingement syndrome. *Journal of Shoulder and Elbow Surgery / American Shoulder and Elbow Surgeons ... [et Al.]*, *5*(3), 186–193. https://doi.org/doi:10.1016/S1058-2746(05)80004-7

Diederichsen, L. P., Nørregaard, J., Dyhre-Poulsen, P., Winther, A., Tufekovic, G., Bandholm, T., … Krogsgaard, M. (2009). The activity pattern of shoulder muscles in subjects with and without subacromial impingement. *Journal of Electromyography and Kinesiology*, *19*(5), 789–799. https://doi.org/10.1016/j.jelekin.2008.08.006

Diederichsen, L. P., Winther, A., Dyhre-Poulsen, P., Krogsgaard, M. R., & Nørregaard, J. (2009). The influence of experimentally induced pain on shoulder muscle activity. *Experimental Brain Research*, *194*(3), 329–337. https://doi.org/10.1007/s00221-008-1701-5

Dong, W., Goost, H., Lin, X.-B., Burger, C., Paul, C., Wang, Z.-L., … Kabir, K. (2015). Treatments for shoulder impingement syndrome: a PRISMA systematic review and network meta-analysis. *Medicine*, *94*(10), e510. https://doi.org/10.1097/MD.0000000000000510

Escamilla, R. F., Yamashiro, K., Paulos, L., & Andrews, J. R. (2009). Shoulder muscle activity and function in common shoulder rehabilitation exercises. *Sports Medicine*, *39*(8), 663–685. https://doi.org/10.2165/00007256-200939080-00004

Ettinger, L. R., Shapiro, M., & Karduna, A. (2017). Subacromial Anesthetics Increase Proprioceptive Deficit in the Shoulder and Elbow in Patients With Subacromial Impingement Syndrome. *Clinical Medicine Insights: Arthritis and Musculoskeletal Disorders*, *10*. https://doi.org/10.1177/1179544117713196

Ettinger, Lucas, Weiss, J., Shapiro, M., & Karduna, A. (2016). Normalization to Maximal Voluntary Contraction is Influenced by Subacromial Pain. *Journal of Applied Biomechanics*, 1–10. https://doi.org/10.1123/jab.2015-0185

Ettinger, Luke, Shapiro, M., & Karduna, A. (2014). Subacromial injection results in further scapular dyskinesis. *Orthopaedic Journal of Sports Medicine*, *2*(8), 1–7. https://doi.org/10.1177/2325967114544104

Falla, D., Arendt-Nielsen, L., & Farina, D. (2009). The pain-induced change in relative activation of upper trapezius muscle regions is independent of the site of noxious stimulation. *Clinical Neurophysiology*, *120*(1), 150–157. https://doi.org/10.1016/j.clinph.2008.10.148

Falla, Deborah, Farina, D., & Graven-Nielsen, T. (2007). Experimental muscle pain results in reorganization of coordination among trapezius muscle subdivisions during repetitive shoulder flexion. *Experimental Brain Research*, *178*(3), 385–393. https://doi.org/10.1007/s00221-006-0746-6

Farina, D., Arendt-Nielsen, L., Merletti, R., & Graven-Nielsen, T. (2004). Effect of experimental muscle pain on motor unit firing rate and conduction velocity. *Journal of Neurophysiolog*, *91*(Mvc), 1250–1259. https://doi.org/10.1152/jn.00620.2003

Farina, S., Valeriani, M., Rosso, T., Aglioti, S., Tamburin, S., Fiaschi, A., & Tinazzi, M. (2001). Transient inhibition of the human motor cortex by capsaicin- induced pain . A study with transcranial magnetic stimulation. *Neuroscience Letters*, *314*, 97–101.

Geiringer, S. R. (1999). Anatomic Localization for Needle Electromyography. In *Anatomic Localization for Needle Electromyography*.

Gerber, C., Galantay, R. V, & Hersche, O. (1998). The pattern of pain produced by irritation of the acromioclavicular joint and the subacromial space. *Journal of Shoulder and Elbow Surgery / American Shoulder and Elbow Surgeons ... [et Al.]*, *7*(4), 352–355. https://doi.org/10.1016/S1058-2746(98)90022-2

Graichen, H., Bonei, H., Stammberger, T., Haubner, M., & Englmeier, K. (1999). Three-Dimensional Analysis of the Width of the Subacromial Space in Healthy Subjects and Patients with Impingement Syndrome. *AJR*, (April).

Graven-Nielsen, T., Svensson, P., & Arendt-Nielsen, L. (1997). Effects of experimental muscle pain on muscle activity and co-ordination during static and dynamic motor function. *Electroencephalography and Clinical Neurophysiology - Electromyography and Motor Control*, *105*(2), 156–164. https://doi.org/10.1016/S0924-980X(96)96554-6

Graven-Nielsen, Thomas, & Arendt-Nielsen, L. (2008). Impact of Clinical and Experimental Pain on Muscle Strength and Activity. In *Current Rheumatology Reports* (Vol. 10). https://doi.org/10.1103/PhysRevApplied.8.034004

Graven-Nielsen, Thomas, & Arendt-Nielsen, L. (2010). Assessment of mechanisms in localized and widespread musculoskeletal pain. *Nature Reviews Rheumetology*, *6*(October).

Graven-Nielsen, Thomas, Lund, H., Arendt-Nielsen, L., Danneskiold-Samsoe, B., & Bliddal, H. (2002). Inhibition of Maximal Voluntary Contraction Force by Experimental Muscle Pain: A Centrally Mediated Mechanism. *Muscle and Nerve*, *November*. https://doi.org/10.1002/mus.10225

Greving, K., Dorrestijn, O., Winters, J. C., Groenhof, F., Van Der Meer, K., Stevens, M., & Diercks, R. L. (2012). Incidence, prevalence, and consultation rates of shoulder complaints in general practice. *Scandinavian Journal of Rheumatology*, *41*(2), 150–155. https://doi.org/10.3109/03009742.2011.605390

Halaki, M., & Ginn, K. a. (2012). Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*, pp. 175–194. https://doi.org/40113

Henderson, L. a, Rubin, T. K., & Macefield, V. G. (2011). Within-limb somatotopic representation of acute muscle pain in the human contralateral dorsal posterior insula. *Human Brain Mapping*, *32*(10), 1592–1601. https://doi.org/10.1002/hbm.21131

Hodges, P. W. (2015). Pain and motor control: from the laboratory to rehabilitation. *Journal of Electromyography and Kinesiology*.

Hodges, P. W., Moseley, G. L., Gabrielsson, A., & Gandevia, S. C. (2003). Experimental muscle pain changes feedforward postural responses of the trunk muscles. *Experimental Brain Research*, *151*(2), 262–271. https://doi.org/10.1007/s00221-003-1457-x

Hsu, W. L., Krishnamoorthy, V., & Scholz, J. P. (2006). An alternative test of electromyographic normalization in patients. *Muscle and Nerve*, *33*(2), 232–241. https://doi.org/10.1002/mus.20458

Johansson, H., & Sojka, P. (1991). Pathophysiological mechanisms involved in genesis and spread of muscular tension in occupational muscle pain and in chronic musculoskeletal pain syndromes: A hypothesis. *Medical Hypotheses*, *35*(3), 196–203. https://doi.org/10.1016/0306-9877(91)90233-O

Kelly, B., Cooper, L., Kirkendall, D., & Speer, K. (1997). Technical Considerations for Electromyographic Research on the Shoulder. *Clinical Orthopaedics and Related Research*, *335*, 140–151.

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 : Official Publication of the Orthopaedic Research Society*, *14*(4), 647–653. https://doi.org/10.1002/jor.1100140421

Kelly, Bryan T., Williams, R. J., Cordasco, F. A., Backus, S. I., Otis, J. C., Weiland, D. E., … Warren, R. F. (2005). Differential patterns of muscle activation in patients with symptomatic and asymptomatic rotator cuff tears. *Journal of Shoulder and Elbow Surgery*, *14*(2), 165–171. https://doi.org/10.1016/j.jse.2004.06.010

Khan, S. I., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2011). Effect of experimental muscle pain on maximal voluntary activation of human biceps brachii muscle. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, *111*(3), 743–750. https://doi.org/10.1152/japplphysiol.00603.2011

Kolk, A., Henseler, J. F., de Witte, P. B., van Arkel, E. R. A., Visser, C. P. J., Nagels, J., … de Groot, J. H. (2016). Subacromial anaesthetics increase asymmetry of scapular kinematics in patients with subacromial pain syndrome. *Manual Therapy*, *26*, 31–37. https://doi.org/10.1016/j.math.2016.07.002

Larsen, C. M., Juul-Kristensen, B., Olsen, H. B., Holtermann, A., & Sogaard, K. (2014). Selective activation of intra-muscular compartments within the trapezius muscle in subjects with Subacromial Impingement Syndrome. A case-control study. *Journal of Electromyography and Kinesiology*, *24*(1), 58–64. https://doi.org/10.1016/j.jelekin.2013.09.008

Lawrence, R., Braman, J., Laprade, R., & Ludewig, P. (2014). Comparison of 3-dimensional Shoulder Complex Kinematics in Individuals with and without Shoulder Pain, Part I: Sternoclavicular, Acromioclavicular, and Scapulothoracic Joints.pdf. *Journal of Orthopaedic & Sports Physical Therapy*.

Le Pera, D., Graven-Nielsen, T., Valeriani, M., Oliviero, A., Di, V., Attilio, P., & Arendt-nielsen, L. (2001). *Inhibition of motor system excitability at cortical and spinal level by tonic muscle pain*. *112*, 1633–1641.

Leffler, A.-S., Kosek, E., & Hansson, P. (2000). Injection of hypertonic saline into musculus infraspinatus resulted in referred pain and sensory disturbances in the ipsilateral upper arm. *European Journal of Pain*, *4*(1), 73–82. https://doi.org/10.1053/eujp.1999.0160

Lin, J. J., Hanten, W. P., Olson, S. L., Roddey, T. S., Soto-Quijano, D. A., Lim, H. K., & Sherwood, A. M. (2005). Functional activity characteristics of individuals with shoulder dysfunctions. *Journal of Electromyography and Kinesiology*, *15*(6), 576–586. https://doi.org/10.1016/j.jelekin.2005.01.006

Ludewig, P. M., & Cook, T. M. (2000). Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Physical Therapy*, *80*(3), 276–291. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10696154

Luime, J., Koes, B., Hendriksen, I., Burdorf, A., Verhagen, A., Miedema, H., & Verhaar, J. (2004). Prevalence and incidence of shoulder pain in the general population; a systematic review. *Scand J Rheumatol*, *33*(2), 73–81. https://doi.org/16167509

Lund, J. P., Donga, R., Widmer, C. G., & Stohler, C. S. (1991). The pain-adaptation model: a discussion of the relationship between chronic musculoskeletal pain and motor activity. *Canadian Journal of Physiology and Pharmacology*, *69*(5), 683–694. https://doi.org/10.1139/y91-102

Mackenzie, T. A., Herrington, L., Horlsey, I., & Cools, A. (2015). An evidence-based review of current perceptions with regard to the subacromial space in shoulder impingement syndromes: Is it important and what influences it? *Clinical Biomechanics (Bristol, Avon)*, *30*(7), 641–648. https://doi.org/10.1016/j.clinbiomech.2015.06.001

Madeleine, P., Lundager, B., Voigt, M., & Arendt-Nielsen, L. (1999). Shoulder muscle co-ordination during chronic and acute experimental neck-shoulder pain. An occupational pain study. *European Journal of Applied Physiology and Occupational Physiology*, *79*(2), 127–140. https://doi.org/10.1007/s004210050486

Madeleine, P., Mathiassen, S. E., & Arendt-Nielsen, L. (2008). Changes in the degree of motor variability associated with experimental and chronic neck–shoulder pain during a standardised repetitive arm movement. *Experimental Brain Research*, *185*(4), 689–698. https://doi.org/10.1007/s00221-007-1199-2

Michaud, M., Arsenault, A. B., Gravel, D., GTremblay, G., & Simard, T. G. (1987). MUSCULAR COMPENSATORY MECHANISM IN THE PRESENCE OF A TENDINITIS OF THE SUPRASPINATUS. *American Journal of Physical Medicine*, *66*(3), 109–120.

Michener, L. A., McClure, P. W., & Karduna, A. R. (2003). Anatomical and biomechanical mechanisms of subacromial impingement syndrome. *Clinical Biomechanics*, *18*(5), 369–379. https://doi.org/10.1016/S0268-0033(03)00047-0

Michener, L. A., Walsworth, M. K., Doukas, W. C., & Murphy, K. P. (2009). Reliability and Diagnostic Accuracy of 5 Physical Examination Tests and Combination of Tests for Subacromial Impingement. *Archives of Physical Medicine and Rehabilitation*, *90*(11), 1898–1903. https://doi.org/10.1016/j.apmr.2009.05.015

Mista, C. A., Christensen, S. W., & Graven-Nielsen, T. (2015). Modulation of motor variability related to experimental muscle pain during elbow-flexion contractions. *Human Movement Science*, *39*, 222–235. https://doi.org/10.1016/j.humov.2014.09.006

Mitchell, C., Adebajo, A., Hay, E., & Carr, A. (2005). Shoulder pain: diagnosis and management in primary care. *Bmj*, *331*, 1124–1128. https://doi.org/10.1136/bmj.325.7368.822

Muceli, S., Falla, D., & Farina, D. (2014). Reorganization of muscle synergies during multidirectional reaching in the horizontal plane with experimental muscle pain. *Journal of Neurophysiology*, *111*(8), 1615–1630. https://doi.org/10.1152/jn.00147.2013

Netto, K. J., & Burnett, A. F. (2006). Reliability of normalisation methods for EMG analysis of neck muscles. *Work*, *26*(2), 123–130.

Nijs, J., Daenen, L., Cras, P., Struyf, F., Roussel, N., & Oostedorp, R. A. B. (2012). Nociception Affects Motor Output A Review on Sensory-motor Interaction With Focus on Clinical Implications. *Clinical Journal of Pain*, *28*(2), 175–181.

Norcross, M. F., Troy Blackburn, J., & Goerger, B. M. (2010). Reliability and interpretation of single leg stance and maximum voluntary isometric contraction methods of electromyography normalization. *Journal of Electromyography and Kinesiology*, *20*(3), 420–425. https://doi.org/10.1016/j.jelekin.2009.08.003

Park, J. Y., Lee, W. S., & Lee, S. T. (2008). The strength of the rotator cuff before and after subacromial injection of lidocaine. *Journal of Shoulder and Elbow Surgery*, *17*(1 SUPPL.), 8–11. https://doi.org/10.1016/j.jse.2007.06.010

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301. https://doi.org/10.1080/10255842.2010.527837

Reddy, A. S., Mohr, K. J., Pink, M. M., & Jobe, F. W. (2000). Electromyographic analysis of the deltoid and rotator cuff muscles in persons with subacromial impingement. *Journal of Shoulder and Elbow Surgery / American Shoulder and Elbow Surgeons ... [et Al.]*, *9*(6), 519–523. https://doi.org/10.1067/mse.2000.109410

Robinson, M. A., Vanrenterghem, J., & Pataky, T. C. (2015). Statistical Parametric Mapping (SPM) for alpha-based statistical analyses of multi-muscle EMG time-series. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *25*(1), 14–19. https://doi.org/10.1016/j.jelekin.2014.10.018

Samani, A., Holtermann, A., Søgaard, K., & Madeleine, P. (2009). Experimental pain leads to reorganisation of trapezius electromyography during computer work with active and passive pauses. *European Journal of Applied Physiology*, *106*(6), 857–866. https://doi.org/10.1007/s00421-009-1083-9

Sandlund, J., Srinivasan, D., Heiden, M., & Mathiassen, S. E. (2017). Differences in motor variability among individuals performing a standardized short-cycle manual task. *Human Movement Science*, *51*, 17–26. https://doi.org/10.1016/j.humov.2016.10.009

Schulte, E., Ciubotariu, a, Arendt-Nielsen, L., Disselhorst-Klug, C., Rau, G., & Graven-Nielsen, T. (2004). Experimental muscle pain increases trapezius muscle activity during sustained isometric contractions of arm muscles. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *115*(8), 1767–1778. https://doi.org/10.1016/j.clinph.2004.03.005

Scibek, J. S., & Carcia, C. R. (2012). Assessment of scapulohumeral rhythm for scapular plane shoulder elevation using a modified digital inclinometer. *World Journal of Orthopedics*, *3*(6), 87–94. https://doi.org/10.5312/wjo.v3.i6.87

Scibek, J. S., Mell, A. G., Downie, B. K., Carpenter, J. E., Hughes, R. E., & Arbor, A. (2008). Shoulder kinematics in patients with full-thickness rotator cuff tears after a subacromial injection. *Journal of Shoulder and Elbow Surgery*, *17*(1), 172–181. https://doi.org/10.1016/j.jse.2007.05.010

Seitz, A. L., McClure, P. W., Finucane, S., Boardman, N. D., & Michener, L. A. (2011). Mechanisms of rotator cuff tendinopathy: Intrinsic, extrinsic, or both? *Clinical Biomechanics*, *26*(1), 1–12. https://doi.org/10.1016/j.clinbiomech.2010.08.001

Sole, G., Osborne, H., & Wassinger, C. (2014). Electromyographic response of shoulder muscles to acute experimental subacromial pain. *Manual Therapy*, *19*(4), 343–348. https://doi.org/10.1016/j.math.2014.03.001

Stackhouse, S. K., Eisennagel, A., Eisennagel, J., Lenker, H., Sweitzer, B. A., & McClure, P. W. (2013). Experimental pain inhibits infraspinatus activation during isometric external rotation. *Journal of Shoulder and Elbow Surgery*, *22*(4), 478–484. https://doi.org/10.1016/j.jse.2012.05.037

Struyf, F., Lluch, E., Falla, D., Meeus, M., Noten, S., & Nijs, J. (2014). Influence of shoulder pain on muscle function: implications for the assessment and therapy of shoulder disorders. *European Journal of Applied Physiology*, *115*(2), 225–234. https://doi.org/10.1007/s00421-014-3059-7

Wassinger, C. A., Sole, G., & Osborne, H. (2012). The role of experimentally-induced subacromial pain on shoulder strength and throwing accuracy. *Manual Therapy*, *17*(5), 411–415. https://doi.org/10.1016/j.math.2012.03.008

Wassinger, C. A., Sole, G., & Osborne, H. (2013). Clinical Measurement of Scapular Upward Rotation in Response to Acute Subacromial Pain. *Journal of Orthopaedic & Sports Physical Therapy*, *43*(4), 199–203. https://doi.org/10.2519/jospt.2013.4276

Worsley, P., Warner, M., Mottram, S., Gadola, S., Veeger, H. E. J., Hermens, H., … Stokes, M. (2013). Motor control retraining exercises for shoulder impingement: Effects on function, muscle activation, and biomechanics in young adults. *Journal of Shoulder and Elbow Surgery*, *22*(4), e11–e19. https://doi.org/10.1016/j.jse.2012.06.010

Wu, G., Van Der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., … Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics*, *38*(5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042

Yang, J. F., & Winter, D. A. (1983). Electromyography Reliability in Maximal and Submaximal Isometric Contractions. *Archives of Physical Medicine and Rehabilitation*, *64*(9), 417–420.

Yang, J., & Winter, D. (1984). Electromyographic amplitude normalization methods. *Archives of Physical Medicine and Rehabilitation*, Vol. 65, pp. 517–521. https://doi.org/10.1109/TRO.2012.2211492

Yung, E., Asavasopon, S., & Godges, J. J. (2010). Screening for head, neck, and shoulder pathology in patients with upper extremity signs and symptoms. *Journal of Hand Therapy*, *23*(2), 173–186. https://doi.org/10.1016/j.jht.2009.11.004