ACKNOWLEDGMENTS

I would like to thank first and foremost my Lord Jesus Christ for keeping me and sustaining my strength for this process. It is through his strength that I had the ability to accomplish such a formidable task. I would then like to thank my advisor Dr. Scott Arthur Banks for all his undying help over the last 4.5 years. He has been instrumental in guiding and developing my skills. It was his ability to trust in my ability to run the studies being presented in thesis that allowed me to persevere and accomplish this task. I would then like to thank Dr. Thomas Wright for also trusting in my ability to accomplish the task of running these studies. Dr. Wright also served as a mentor in understanding the shoulder anatomy as well as the reverse prosthesis function. I would like to also thank Aimee Struk for her instrumental recruitment and aiding to test all of the subjects. She has been a pleasure to work with and instrumental to getting this studies complete. I would like to thank Dr. Bryan Conrad for all his assistance and mentorship. His training of use of the motion capture lab was instrumental in the successful completion of the studies presented. I would like to thank Dr. Bo Gao who mentored and was instrumental in the development of the initial analysis tools for both kinematic and EMG analysis. I would like to thank Lyneesha Sweeney, Courtney Cox, Mpho Sello, and Adori for their hard work in shape matching images for kinematic analysis. I would like to thank Ms. Jennifer Jones for her instrumental help in digitizing motion data captured by the motion capture system. I would like to thank Ms. Eve Culbreth for her moral support through this time. Lastly I would like to thank my mother (Ms. Audrey Fisher) for her encouraging words and support through this whole process.
TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................. 3

LIST OF FIGURES ...................................................................................................................... 5

ABSTRACT ..................................................................................................................................... 6

CHAPTER

1 INTRODUCTION ......................................................................................................................... 8

Shoulder Anatomy ....................................................................................................................... 8
Shoulder Joint Injuries ................................................................................................................ 8
Reverse Total Shoulder Arthroplasty ......................................................................................... 8
Scapulohumeral Rhythm (SHR) ............................................................................................... 9
Muscle Activation and Function ................................................................................................. 10

2 SCAPULOHUMERAL RHYTHM OF REVERSE TOTAL SHOULDER ARTHROPLASTIES DURING NON-WEIGHTED SHOULDER ABDUCTION ..........16

Testing Protocol ........................................................................................................................ 16
Image Acquisition and 3D Modeling ......................................................................................... 17
Model-Image Registration ....................................................................................................... 17
Data Processing ....................................................................................................................... 18
Statistical Analysis .................................................................................................................. 18

3 REVERSE TOTAL SHOULDER ARTHROPLASTY SIMPLIFIES MUSCLE FUNCTION DURING ABDUCTION, FLEXION AND EXTERNAL ROTATION ..........24

Testing Protocol ........................................................................................................................ 25
Apparatus Set Up ..................................................................................................................... 25
Lateral Deltoid ........................................................................................................................... 26
Anterior Deltoid ........................................................................................................................ 26
Posterior Deltoid ....................................................................................................................... 27
General Observations ............................................................................................................. 27

4 CONCLUSION ........................................................................................................................... 35

Abduction ................................................................................................................................... 35
Flexion ........................................................................................................................................ 36

LIST OF REFERENCES ............................................................................................................... 37

BIOGRAPHICAL SKETCH ......................................................................................................... 40
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>The human shoulder girdle consists of the humerus, scapula and clavicle</td>
<td>11</td>
</tr>
<tr>
<td>1-2</td>
<td>The shoulder musculature is multilayered and complex</td>
<td>12</td>
</tr>
<tr>
<td>1-3</td>
<td>A typical rotator cuff tear. From southwest orthopaedics medical center.</td>
<td>13</td>
</tr>
<tr>
<td>1-4</td>
<td>Implanted reverse shoulder prostheses can change significantly the medial/lateral location of the shoulder center of rotation.</td>
<td>14</td>
</tr>
<tr>
<td>1-5</td>
<td>Rotator cuff deficient shoulders often lack sufficient stability to elevate without superior translation and impingement with an anatomic total shoulder arthroplasty</td>
<td>15</td>
</tr>
<tr>
<td>2-1</td>
<td>Protocol of weighted abduction during fluoroscopy. Photo courtesy of David Walker at the Orthopaedic Sports and Medical Institute (OSMI).</td>
<td>20</td>
</tr>
<tr>
<td>2-2</td>
<td>Humeral and scapular coordinate systems and degrees of freedom.</td>
<td>21</td>
</tr>
<tr>
<td>2-3</td>
<td>Reverse implant designs A. medial type implant B. neutral type implant C. Lateral type implant</td>
<td>22</td>
</tr>
<tr>
<td>2-4</td>
<td>Scapulahumeral rhythm of RTSA (medial vs. lateral) vs. normal population.</td>
<td>23</td>
</tr>
<tr>
<td>3-1</td>
<td>Surface electromyography placement.</td>
<td>31</td>
</tr>
<tr>
<td>3-2</td>
<td>Muscle activation of the implanted side lateral deltoid during un-weighted abduction.</td>
<td>31</td>
</tr>
<tr>
<td>3-3</td>
<td>Muscle activation of the non-implanted side lateral deltoid during un-weighted abduction</td>
<td>32</td>
</tr>
<tr>
<td>3-4</td>
<td>Muscle activation of the implanted anterior deltoid during weighted flexion.</td>
<td>32</td>
</tr>
<tr>
<td>3-5</td>
<td>Muscle activation of the non-implanted anterior deltoid during weighted flexion.</td>
<td>33</td>
</tr>
<tr>
<td>3-6</td>
<td>Muscle activation of the implanted posterior deltoid during un-weighted external rotation</td>
<td>33</td>
</tr>
<tr>
<td>3-7</td>
<td>Muscle activation of the implanted posterior deltoid during weighted flexion.</td>
<td>34</td>
</tr>
<tr>
<td>3-8</td>
<td>Muscle activation of the non-implanted posterior deltoid during un-weighted abduction</td>
<td>34</td>
</tr>
</tbody>
</table>
Abstract of Thesis Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Master of Science

KINETIC AND KINETIC ANALYSIS OF THE REVERSE SHOULDER JOINT: AN IN VIVO ANALYSIS

By

David R. Walker

May 2012

Chair: Scott Arthur Banks
Major: Mechanical Engineering

Reverse Total shoulder arthroplasty (RTSA) is utilized to restore shoulder function in patients with osteoarthritis and rotator cuff deficiency. The purpose of this study was to assess the behavior of RTSA shoulder subjects as compared to healthy shouldered subjects. Scapulohumeral rhythm (SHR) of patients with RTSA during unloaded shoulder abduction and deltoid muscle activity during active shoulder abduction, flexion and external rotation were measured to give insight into the function of RTSA shoulders compared to normal shoulders.

We studied 33 subjects at least 6 months post unilateral reverse total shoulder arthroplasty. Seventeen subjects (11-medial, 6- lateral) performed shoulder abduction (elevation and lowering) during fluoroscopic imaging. SHR was calculated from the slope of the humeral and scapular elevation angles. Subjects then performed both weighted (1.5kg) and un-weighted abduction (coronal plane) and forward flexion (sagittal plane), and un-weighted external rotation. Activation of the anterior, lateral and posterior aspects of the deltoid and upper trapezius muscles were recorded bilaterally using bipolar surface electrodes. Motion capture using passive reflective markers was used to quantify three-dimensional motions of both shoulders.
For abduction above 40°, shoulders with RTSA exhibited an average SHR of 1.2:1. There were significant differences in SHR between medial and lateral offset groups of RTSA shoulders (p<<0.05).

During abduction, lateral deltoid activity was significantly higher in implanted than in non-implanted shoulders for the medial group. During flexion, the anterior deltoid was significantly more active in the lateral group during weighted and un-weighted flexion. Posterior deltoid was not activated over 40% of MVIC.

SHR in RTSA shoulders is significantly different from normal shoulders. Significant differences also occur between RTSA groups (medial/lateral). The muscle recruitment data suggest reverse total shoulder arthroplasty simplifies deltoid muscle activation. We observed higher muscle activation in the portion of the deltoid directly in line with the task, but reduced muscle function in the out-of-line portions of the muscle. This information will be useful to guide refinement in the geometric design of the prosthetic components, surgical alignment of the implants, intraoperative soft-tissue tensioning, and the design of muscle strengthening programs.
CHAPTER 1
INTRODUCTION

Shoulder Anatomy

The shoulder joint is comprised of three bones, the humerus, the scapula and the clavicle (Figure 1-1) [20]. The shoulder is controlled by a variety of muscles (Figure 1-2) [20]. The rotator cuff muscles, the trapezius and the deltoid serve to lift and stabilize the arm. The joint achieves great mobility under coordinated control of these muscles. An irreparable tear of the rotator cuff muscles may functionally immobilize the shoulder. There are several different disorders that lead to immobilization of the shoulder.

Shoulder Joint Injuries

Shoulder joint related problems are a common reason for visits to the Orthopaedic surgeon. In 2003, 14 million people in the United States visited a doctor for a shoulder-related injury [27]. These people suffered from a variety of disorders such as rotator cuff arthropathy (Figure 1-3), frozen shoulder, and shoulder impingement syndrome [27]. Irreparable tears of the rotator cuff muscles (Teres minor, supraspinatus, infraspinatus, and subscapularis) will cause the development of osteoarthritis (Figure 1-3) and impairment of motion of the shoulder [ref]. In the event of an irreparable rotator cuff (Figure 1-3) the Reverse Total Shoulder Arthroplasty (RTSA) is an increasingly popular option to restore mobility in the shoulder.

Reverse Total Shoulder Arthroplasty

The Reverse Total Shoulder Arthroplasty (RTSA) was developed in the 1980’s by surgeon Paul Grammont, who developed the principles leading to successful reverse and total shoulder prostheses [21]. A reverse prosthesis is comprised of a glenosphere, a humeral stem, and a humeral cup (Figure 1-4). The reverse prosthesis possesses several potential advantages. In a normal shoulder with an irreparable rotator cuff tear, patients often experience pain and
dislocation of the humeral head. RTSA obviates the need for rotator cuff muscles by fixing the center of rotation (COR) of the humerus relative to the scapula. This allows for stabilization of the COR without need for dynamic muscular stabilization of the joint. The implant-defined COR also allows for manipulation of the deltoid moment arm. RTSA can alleviate pain while restoring motion to shoulders with irreparable rotator cuff injuries or failed total shoulder replacements (Figure 1-5).

The optimal amount of lateral offset in RTSA remains the subject of current study and debate [refs]. Three designs of RTSA were available to study for this thesis, with each adopting a different philosophy for how far laterally the COR should be placed (medial, neutral and lateral, Figure 1-4) [21, 25]. Improper placement of the COR can lead to possible implant failure by glenoid loosening, and impingement syndrome. Therefore, information on reverse shoulder joint behavior with reference to normal shoulders is vital to identify ideal placement of the COR and minimize implant failure.

The measurement of motion and muscle function in RTSA shoulders is the primary motivation for the studies that comprise Chapters 2 and 3. The measurement of motion of the humerus and scapula will be used to calculate a parameter known as the scapulohumeral rhythm (SHR)

**Scapulohumeral Rhythm (SHR)**

The coordinated motion of the humerus and scapula has been defined as a ratio between how each of the bodies move, hence the scapulohumeral rhythm (SHR). SHR was first reported to be a constant 2:1 (humerus:scapula) ratio by Inman et al. for normal healthy subjects [27]. Many researchers have since measured SHR in normal and pathological shoulders [27-29]. To date, there has been no report of SHR for RTSA patients. Alterations in the position and movement of the scapula, called scapular dyskinesia [28-29], change the SHR and likely
manifest in various shoulder disorders, such as rotator cuff tears, impingement syndrome, frozen shoulder, osteoarthritis, throwing injuries and instability [22].

It is vital to know the SHR of the RTSA population in determining if RTSA SHR differs from normal shoulders and to assess possible points of failure for the implant. Calculating SHR of RTSA subjects during shoulder abduction will help assess how the RTSA shoulder functions with respect to a normal shoulder.

**Muscle Activation and Function**

Muscles are the actuators of the shoulder joint. They produce tension that is applied to the bones via tendons to drive motion. In RTSA patients, the primary muscles that perform lifting of the arm are the deltoids and the upper trapezius (Figure 1-2) [21,24]. How these muscles are recruited is vital to understanding the function of the RTSA shoulder. It is likely that changes in RTSA geometry directly affect the function of these muscles.

Measurements of muscle activity during abduction, flexion and external rotation will be presented in Chapter 3. By measuring muscle activity during these activities, a model of how muscle recruitment varies with different RTSA designs can be developed. These measurements can be used to assess ideal placement of the COR to optimize function in RTSA shoulders.
Figure 1-1. The human shoulder girdle consists of the humerus, scapula and clavicle (From: H.E.J. Veeger and F.C.T. van der Helm, “Shoulder function: The perfect compromise between mobility and stability” Journal of Biomechanics 40 (2007) 2119–2129)
Figure 1-2. The shoulder musculature is multilayered and complex. For RTSA shoulders, the muscles of greatest functional importance are the deltoid and trapezius. Sagittal (top) and posterior coronal views (bottom) (from: H.E.J. Veeger and F.C.T. van derHelm, “Shoulder function: The perfect compromise between mobility and stability” Journal of Biomechanics 40 (2007) 2119–2129)
Figure 1-3. A typical rotator cuff tear. From southwest orthopaedics medical center: www.southwest-ortho.com/images/sports/shoulder-rotator-cuff.jpg.
Figure 1-4. Implanted reverse shoulder prostheses can change significantly the medial/lateral location of the shoulder center of rotation. From http://www.jaaos.org/content/19/7/439/F4.expansion
Figure 1-5. Rotator cuff deficient shoulders often lack sufficient stability to elevate without superior translation and impingement with an anatomic total shoulder arthroplasty (A). Patients with reverse total shoulder arthroplasty (B) often can elevate their geometrically stable shoulder without superior translation and impingement (C). From http://www.shouldersurgeon.com/shoulder_replacement_surgery/
CHAPTER 2
SCAPULOHUMERAL RHYTHM OF REVERSE TOTAL SHOULDER ARTHROPLASTIES DURING NON-WEIGHTED SHOULDER ABDUCTION

Reverse total shoulder arthroplasty (RTSA) is an effective treatment option for patients with symptomatic glenohumeral arthritis and a deficient rotator cuff. RTSA has been reported to produce early satisfactory clinical outcomes in terms of pain relief and restoration of active forward flexion and abduction [21, 23, and 24]. However, deltoid tensioning and potential instability, humeral fixation, glenosphere fixation, scapular notching and polyethylene wear are currently unsolved challenges that may lead to a significant decrease in the functional outcomes and increase the risk of RTSA failure [24]. There is currently little known about shoulder function after RTSA or if differences in surgical technique or implant design affect shoulder performance [21, 23, 24]. A better understanding of the motion of the shoulder after RTSA is critical to understand how shoulders with RTSA function and how to address these challenges and improve functional outcomes and longevity. The purpose of this study was to quantify scapulohumeral rhythm (SHR) in patients with RTSA during unloaded shoulder abduction.

Testing Protocol

Seventeen subjects gave informed written consent to participate in an Institutional Review Board (IRB) approved protocol. These subjects had uni- or bi-lateral RTSA and performed shoulder abduction (elevation and lowering) with and without a handheld 1.36 kg weight (Figure 2-1). Subjects received one of three RTSA designs (Aequalis®, Tornier, Inc., Edina, MN; Equinoxe® Reverse Shoulder, Exactech Inc., Gainesville, FL; RSP®, DJO Surgical, Austin TX). The Aequalis® (n=6) and Equinoxe® (n=5) shoulders composed the Medial Group, while the RSP® shoulders (n=6) composed the Lateral Group based upon the lateral offset of the glenosphere center of rotation.
A group of young healthy shoulders examined using the same protocol and measurement methods served as a Control Group [33 Matsuki et al].

**Image Acquisition and 3D Modeling**

Fluoroscopic images of the implanted shoulder for each subject were captured during non-weighted abduction (recorded at 7.5 Hz) using a C-arm fluoroscopy machine (give model name and maker, city). The subject stood parallel to the plane of the image intensifier. Elevation and lowering in the frontal plane were performed, at approximately eight seconds per cycle, with the elbow fully extended and the arm externally rotated. Subjects were allowed to move their arms naturally, their bodies were not constrained, and the speed of motion was not strictly controlled. Subjects performed the activity while it was demonstrated by the testing staff.

Three dimensional implant surface models were acquired from the manufacturers of all implant designs. The models were oriented and translated to establish consistent component origins and alignment (Figure 2-1). The Y-axis was parallel to the humeral shaft, and Z-axis was defined as a line through the intertubercular groove from the origin. The scapular component’s X-axis was horizontal pointed medially toward the center of the body and Y- and Z-axes was pointed superiorly and anteriorly, respectively (Figure 2-2).

**Model-Image Registration**

The 3D position and orientation of the humeral and the scapular components were determined using model-image registration techniques (Figure 2-3) [26]. The implant model was projected onto the distortion-corrected fluoroscopic image, and its three-dimensional pose was iteratively adjusted to match its silhouette with the silhouette of the fluoroscopic image (Figure 2-3).
Data Processing

The kinematics of the humerus and the scapula components of the implant relative to the x-ray coordinate system were determined using Cardan angles [30]. Elevation of the humeral component was defined as rotation about the Z-axis. Motion of the scapular component was defined as anterior-posterior tilt about the X-axis, internal-external rotation about the Y-axis, and upward-downward rotation about the Z-axis (Figure 2-2).

Scapular elevation was plotted as a function of humeral elevation, and a best-fit polynomial regression curve was used to interpolate scapular elevation values in 15° increments of the humeral elevation angle [31].

SHR was calculated from arm at side to maximum elevation positions using the expression SHR = (ΔH–ΔS)/ΔS, where ΔH is the increment in humeral component elevation angle and ΔS is the increment in scapular component upward rotation angle [27]. SHR was computed at 15° increments of humeral elevation in two steps: First, ΔS /ΔH was computed as the slope of the polynomial regression line using scapular upward rotation as the independent value and humeral elevation angle as the dependent value. Then, SHR was calculated as (ΔS /ΔH)^1 – 1.

Statistical Analysis

Two-way repeated-measures analysis of variance (ANOVA) was used to compare the incremental data of scapular angles and SHR between between Medial and Lateral RTSA groups, and between RTSAs and Controls. The level of significance for all comparisons was set at p<0.05. Tukey’s Honestly Significant Difference was used to perform pair-wise post-hoc comparisons.

There was a significant difference between the RTSA group and the normal group SHR (p<0.05, p=0.00008). For abduction above 40°, shoulders with RTSA exhibited an average SHR
of 1.2:1 (Figure 2-4). There was significant difference in SHR between medial and lateral offset
groups of RTSA shoulders (p=0.002341). SHR was highly variable for abduction less than 40°,
with SHR ranging from a low of 1 to greater than 10 (Figures.2-4).

At arm elevation angles less than 40°, SHR in RTSA shoulders is highly variable and the
mean SHR (Figures. 2-4,) for RTSA appears higher than the SHR for normal shoulders (Figures.
2-4). At higher elevation angles, SHR in shoulders with RTSA (1-1.4) is much more consistent
and is lower than SHR in normal shoulders (2-4). At higher elevations the scapula rotates a lot
more in the reverse shoulder population (Figures. 2-4,). Medial and lateral groups within the
RTSA population have a significant difference in SHR (p=0.0002341). It can be observed that
rotator cuff-deficient, arthritic shoulders treated with RTSA do not move like healthy young
shoulders. Previous studies have looked at normal shoulder SHR [9, 27-29]. This study
purposed to calculate the SHR for RTSA patients. Significant differences were found between
the SHR for RTSA population as compared to the normal population. There were significant
differences found in the SHR between medial and lateral RTSA shoulder groups. This insight
shows that the RTSA SHR is different from normal shoulders and it is also different depending
on the RTSA design (medial/lateral). Comparison of RTSA groups (medial/lateral) to normal
shoulders may give insight to which RTSA design restores more of a normal function to the
shoulder.
Figure 2-1. Protocol of weighted abduction during fluoroscopy. Photo courtesy of David Walker at the Orthopaedic Sports and Medical Institute (OSMI)
Figure 2-2. Humeral and scapular coordinate systems and degrees of freedom. From citation 27
Tornier:
(Grammont Type) medial COR and lowering of humeral stem (Increasing Deltoid moment arm)

Exactech:
Neutral Position (able to shift COR M/L)

Encore:
(Reverse shoulder prosthesis)
• Lateral COR (diminish scapular notching)

Figure 2-3. Reverse implant designs A. medial type implant B. neutral type implant C. Lateral type implant. From exac.com, tornier.com, encore.com
Figure 2-4. Scapulahumeral rhythm of RTSA (medial vs. lateral) vs. normal population
CHAPTER 3
REVERSE TOTAL SHOULDER ARTHROPLASTY SIMPLIFIES MUSCLE FUNCTION DURING ABDUCTION, FLEXION AND EXTERNAL ROTATION

Reverse total shoulder arthroplasty (RTSA) is an effective treatment option for patients with symptomatic glenohumeral arthritis and a deficient rotator cuff. RTSA has been reported to produce early satisfactory clinical outcomes in terms of pain relief and restoration of active forward flexion and abduction [1]. However, deltoid tensioning and potential instability, humeral fixation, glenosphere fixation, scapular notching and polyethylene wear are currently unsolved challenges that may lead to a significant decrease in the functional outcomes and increase the risk of RTSA failure [24]. A better understanding of muscle activity after RTSA is critical to understand how shoulders with RTSA function and how to address these challenges and improve functional outcomes and longevity.

Most RTSA research efforts have focused on improving the design and biomechanics of reverse prostheses. Few studies have focused on the deltoid, which becomes the primary mover in the rotator cuff-deficient shoulder and RTSA. We currently lack a fundamental understanding how deltoid tension and activity relates to functional outcomes such as range of motion (ROM), arm strength and functional scores with RTSA. Insufficient deltoid tensioning may lead to prosthetic instability, whereas excessive deltoid tension may result in acromial fractures [4]. Deltoid tensioning is thought to directly affect the activation pattern and active force-generating ability of the muscle [4-6], such that active ROM and shoulder function depend on the interplay between RTSA geometry and deltoid length and tension.

In the healthy and rotator cuff deficient shoulder, muscle tension is required to dynamically stabilize the glenohumeral joint and to move the arm. RTSA provides definitive geometric stability to the replaced shoulder so that muscle tension is not required to stabilize the glenohumeral joint. Thus, we might expect muscle fibers in the most mechanically advantageous
locations to be preferentially recruited to perform functional tasks, while collateral and antagonist muscle activity is decreased compared to non-RTSA shoulders. This hypothesis is the converse of phenomena observed in the knee where joint instability results in increased antagonist muscle activity as a means to dynamically stabilize the joint [7]. The purpose of this study was to determine shoulder muscle recruitment in patients with RTSA. We measured deltoid and upper-trapezius muscle activity in the RTSA and non-involved contralateral shoulders of subjects during both weighted and un-weighted shoulder abduction and flexion, and un-weighted external rotation.

**Testing Protocol**

50 subjects (33 RTSA, 17 healthy) between 60-85 years of age gave written consent to participate in this IRB approved study. Patients were an average of 37 months post unilateral RTSA (range 12-63 months). Patients received prostheses with a medial or lateral center of rotation: The Medial Group consisted of 17 shoulders with an Aequalis® implant (Tornier Inc., Edina, MN) or an Equinoxe® implant (Exactech, Gainesville, FL), and the Lateral Group consisted of 16 shoulders with a Reverse® implant (DJO surgical, Austin TX) (Figure 2-3).

Subjects’ motions were recorded during weighted and un-weighted abduction, weighted and un-weighted flexion, and un-weighted external rotation. Motions were performed so that one cycle required approximately 15 seconds. Weighted trials utilized a 1.5kg hand-held weight. Each subject was tested bilaterally. Subjects rested for 2 minutes between activities to minimize the effects of fatigue.

**Apparatus Set Up**

A twelve-camera motion capture system was used to record the motions of fifteen skin-mounted retro-reflective markers at 60Hz (Figure 3-1) [8-9]. Eight channels of skin surface electromyography (EMG) were collected simultaneously at 1200 Hz using bipolar electrodes
placed bilaterally on the anterior, lateral, and posterior aspects of the deltoid and on the upper trapezius (Figure 3-1, Telemyo 2400, Noraxon USA Inc. Scottsdale, AZ) [10]. Maximal voluntary isometric contraction (MVIC) data and maximal activation during each functional activity performed were used to normalize the EMG signals [11]. A hand-held dynamometer was used to measure the maximum force generated at the wrist joint during MVIC trials.

Reflective marker kinematics were determined using standard software (EvaRT, Motion Analysis Corporation, Santa Rosa, CA) and filtered using a fourth-order, zero-phase-shift, low-pass Butterworth filter with a 12 Hz cutoff frequency. A custom program was used to compute shoulder abduction, flexion, and external rotation angles using an abduction-flexion-external rotation sequence [30]. EMG data were mean filtered [10] and fitted spline curves were used to determine the EMG signal magnitude at specific arm angles. Comparisons between the RTSA and contralateral shoulders were performed using two-way repeated-measures ANOVA with the level of significance chosen to be 0.05. Tukey’s Honestly Significant Difference was used to perform pair-wise post-hoc comparisons.

**Lateral Deltoid**

Activation of the lateral deltoid was significantly higher in the Medial Group of RTSA shoulders than in their contralateral shoulder during weighted and un-weighted abduction throughout the entire cycle (Figures 3-2, 3-3, middle graph). The Lateral Group of RTSA shoulders showed significantly higher activation of the lateral deltoid muscle in the first 70° of humeral elevation (Figures 3-2, 3-3, lateral graph, p<<0.05). After 70° the non-implanted side had a higher activation for the lateral deltoid muscle (Figure 13-14, top graph, p<<0.05).

**Anterior Deltoid**

Activation of the anterior deltoid was significantly higher in the implanted shoulder of Lateral Group of RTSA shoulders than in their contralateral shoulders during weighted and un-
weighted flexion throughout the entire cycle (Figures 3-4, 3-5, top graph). The Medial Group of shoulders showed significantly higher activation of the lateral deltoid muscle in the first 50° of humeral elevation during flexion (Figures 3-4, 3-5, middle graph, p<<0.05). After 50°, the contralateral shoulders showed higher lateral deltoid activation (Figures 3-4, 3-5, bottom top, p<<0.05).

Posterior Deltoid

Maximum posterior deltoid activity of 18% MVIC was observed during external rotation in RTSA shoulders and posterior deltoid activity in all activities averaged less than 40% of MVIC for both RTSA and uninvolved shoulders (Figures 3-6, 3-7 and 3-8).

General Observations

Weighted trials showed significantly higher muscle activation than un-weighted trials (Figures 3-4, 3-5). RTSA shoulders did not elevate as far as contralateral shoulders during weighted trials (Figures 3-4). During weighted trials, RTSA implanted shoulders showed significantly higher activation of muscle fibers acting in line with the motion, e.g. lateral deltoid for abduction and anterior deltoid for flexion (Figures 3-2, 3-4). Anterior and posterior deltoid activation in RTSA shoulders were comparable or lower than in contralateral shoulders during weighted abduction. Posterior deltoid was not highly active during unresisted internal/external rotator.

Deltoid muscle function is a critical determinant of shoulder function following RTSA. It remains difficult to determine optimal deltoid tensioning during reverse shoulder surgery, and there is little objective information about how the deltoid functions in RTSA patients. The purpose of this study was to quantify deltoid and upper trapezius muscle activity in shoulders with RTSA. We found muscle function in the shoulder with RTSA is significantly different from the normal shoulder. RTSA shoulder deltoid activity is higher for fibers in line with the motion,
and lower for adjacent parts of the muscle (Figures 3-2, 3-4). As expected, muscle activity increased during weighted trials in both RTSA and contralateral shoulders (Figures 3-4, 3-5). The results suggest simplified muscle coordination post-RTSA, where muscles act to move the arm but play less of a joint stabilizing role.

This study includes 33 patients with unilateral RTSA. All subjects received RTSA devices with medial and lateral centers of rotation, and so should be representative of that patient group. We used the subjects’ contralateral shoulder for comparison, but their contralateral shoulder muscle activity may not be representative of healthy or young shoulders. We were limited to eight channels of EMG, four channels bilaterally, so it was not possible to record muscle activity for teres minor or other important shoulder muscles. We attempted to minimize experimental variability by (1) having a single examiner prepare and place the EMG electrodes for all subjects; (2) coaching subjects on how to perform the MVIC trials to get the best possible activation levels for normalization; and (3) saving for analysis only trials where the subject maintained the correct upright posture.

Our primary finding is deltoid activation is strongly related to activity, such that deltoid fibers directly causing motion are active while adjacent fibers are relatively quiet. Thus, the lateral deltoid was highly active for abduction (Fig. 3-2) while the anterior deltoid was highly active for flexion (Fig. 3-4). The posterior deltoid was minimally active during the three motions studied (Figure 3-6, 3-7, 3-8). The posterior deltoid showed only 20% activation during unresisted external rotation, which does not support the literature [13] (Figure 3-7). This might change dramatically for external rotation against resistance, with the posterior deltoid MVIC trials as an example.
In healthy shoulders the primary arm abductors are the deltoid and upper trapezius [14-17]. Increased activation of the deltoid muscles has been found in patients with impingement and/or rotator cuff deficiency [18-19]. Increased deltoid activity in cuff-deficient shoulders leads to instability and upward humeral migration. Our secondary finding was that deltoid fibers not in line with motion were significantly less active in RTSA shoulders than in the contralateral shoulders (Figure 3-7). During flexion RTSA shoulders showed high activity for anterior deltoid fibers and lower activity in lateral and posterior fibers. During abduction medial RTSA shoulders showed high lateral deltoid activity and lower activity in the anterior and posterior fibers. Lateral RTSA shoulders showed this pattern for all elevation angles during abduction. These findings suggest generalized deltoid activity in contralateral shoulders provides glenohumeral stability, while that function is less required in the intrinsically stable RTSA shoulders. These findings provide an interesting counterpoint to knee joint function, where antagonist muscle cocontraction increases as a stabilizing mechanism for knee instability after ACL tears [7].

For both abduction and flexion motions, deltoid activity reaches a plateau mid-motion with greater abduction or flexion. These patterns of muscle activation suggest an increasing contribution of scapular rotation to overall motion at higher abduction/flexion angles, or a decreasing scapulohumeral rhythm. The SHR results in Chapter 2 support this assertion. Deltoid fibers directly in line with the motion work increasingly harder at low and middle angles of motion, and then maintain a high level of activation at greater degrees of elevation. This muscle activity coincides with greater glenohumeral motion in the RTSA patients at low angles with increasing contribution of scapular-thoracic motion above 40 degrees as the upper trapezius becomes more active.
We conclude that deltoid function in shoulders with RTSA is not normal. Deltoid function appears to be greatly simplified, where the major task is arm motion with most shoulder stability provided by the implant. Opposing heads of the deltoid no longer need to work in an eccentric fashion to balance the glenohumeral joint. Lateral deltoid fibers are active for abduction and relatively quiet during flexion, while anterior fibers are active for flexion and relatively quiet for abduction. Medial and Lateral Groups of RTSA shoulders exhibit statistically distinct muscle activation patterns, which will be more fully explored in future work. Contrary to popular opinion we found little role for the posterior deltoid (only 20% activation) in unresisted external rotation in RTSA patients (Figure 3-6). The posterior deltoid was also quiet for abduction and flexion (Figures.3-7, 3-8).

These observations of muscle function in RTSA shoulders improve our understanding of joint function in rotator-cuff deficient replaced shoulders. Specific deltoid fibers in line with the desired motion act as the primary mover of the arm at low and mid angles of elevation, and this has major implications for rehabilitation, surgical technique and implant design. Based on our findings, rehabilitation might productively focus on the anterior and lateral deltoid at low and mid angles of flexion and abduction, respectively, to optimize function in patients with medialized and lateralized center of rotation RTSA. There appears to be little value in a strengthening program directed at the posterior deltoid.
Figure 3-1. Surface electromyography placement. Photo provided by David R Walker at the orthopaedic sport and medical institute.

Figure 3-2. Muscle activation of the implanted side lateral deltoid during un-weighted abduction. Provided by R software
Figure 3-3. Muscle activation of the non-implanted side lateral deltoid during un-weighted abduction

Figure 3-4. Muscle activation of the implanted anterior deltoid during weighted flexion
Figure 3-5. Muscle activation of the non-implanted anterior deltid during weighted flexion

Figure 3-6. Muscle activation of the implanted posterior deltid during un-weighted external rotation
Figure 3-7. Muscle activation of the implanted posterior deltoid during weighted flexion

Figure 3-8. Muscle activation of the non-implanted posterior deltoid during un-weighted abduction
CHAPTER 4
CONCLUSION

Understanding the function of the Reverse Total shoulder Arthroplasty (RTSA) during motion is critical to the design of preclinical plans for the placement of the implant. The studies discussed in Chapters 2 and 3 aimed to provide insight to the question “Do RTSA shoulders behave like normal shoulders?” The answer to this question was answered by quantifying scapulohumeral kinematics and muscle function.

In Chapter 2 it was found that SHR at low abduction angles in both healthy and RTSA shoulders is highly variable. SHR in RTSA shoulders decreases dramatically with abduction, such that mostly scapular elevation is observed at the extreme of abduction. Rotator cuff deficient arthritic shoulders treated with RTSA do not move like healthy young shoulders (Figure 2-4, 2-5, 2-6). Further, Medial and Lateral RTSA populations had significantly different SHR (p=0.0002341).

In Chapter 3 it was found that the lateral deltoid functioned as the primary abductor (Figure 13-14) of the arm and the anterior deltoid functioned as the primary flexor of the arm (Figures 3-4, 3-5). Posterior deltoid activity in all activities averaged less than 40% of MVIC (Figures 3-6, 3-7, 3-8). It was seen that there was a significant difference in activation between the Medial and Lateral Groups of the RTSA population.

Abduction

For abduction the Lateral RTSA Group had higher lateral deltoid activity in the implanted shoulder for early abduction. Beyond 70° elevation, the contralateral shoulders showed higher lateral deltoid activation than the implanted Lateral Group shoulders. Conversely the Medial Group did not show this behavior; the implanted side displayed a higher activation for the lateral deltoid for all degrees of elevation than the non-implanted side.
Flexion

For flexion the Medial Group had higher anterior deltoid activity in the implanted side for early angles of flexion. Above 50° degrees elevation, anterior deltoid activation for the Medial Group was higher in the contralateral shoulders than the implanted shoulders. Conversely, the Lateral Group did not show this behavior; the implanted shoulders displayed higher anterior deltoid activation for all degrees of elevation compared to the non-implanted shoulders. This muscle activation pattern is also seen in weighted and un-weighted trials of flexion in the anterior deltoid (AD: p<0.05).

The findings on shoulder muscle activation with and without RTSA provide context for assessing how geometric changes in implant design affect shoulder motion and muscle recruitment. It was found that the muscle function and kinematics of the RTSA are significantly different from normal shoulders. These insights may lead to the development of preclinical plans for placement of the implant, improved implant design, and modification of rehabilitative strategies to improve outcomes and optimize quality of life for patients who undergo RTSA.
LIST OF REFERENCES


6. Lam, F; Bhatia, DN; Mostofi, SB; van Rooyen, K;de Beer, JF. Biomechanical considerations of the normal and rotator cuff deficient shoulders and the reverse shoulder prosthesis.Orthopedics. February 2007;21:40-46


12. Uhl, TL;Carver, TJ; Mattacola, CG; Mair, SD; Nitz, AJ. Shoulder musculature activation during upper extremity weight-bearing Exercise. Journal of Orthopaedics & sports physical therapy. march 2003;33:109-117


BIOGRAPHICAL SKETCH

David Walker is from the island of Jamaica. He is the only child of Audrey Fisher. David attended the University of Florida where he received his B.Sc. in Mechanical Engineering. He received his master’s degree in mechanical engineering from the University of Florida in spring 2012. He is now pursuing a Ph.D. at the University of Florida in shoulder mechanics modeling.