NORTHWESTERN UNIVERSITY

Assessing Contributions of Muscular Imbalance to Shoulder Osteoarthritis

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF PHILOSOPHY

Field of Biomedical Engineering

By

Margaret Sarah Coats-Thomas

EVANSTON, ILLINOIS

August 2022

Abstract

Assessing Contributions of Muscular Imbalance to Shoulder Osteoarthritis

Margaret Sarah Coats-Thomas

Shoulder (glenohumeral joint) osteoarthritis causes pain, limits daily activities, and frequently requires joint replacement surgery. In shoulder osteoarthritis, the glenoid bone surface erodes in one of two ways: symmetrically (concentric deformity) or asymmetrically (eccentric deformity). Shoulder replacements in patients with eccentric deformities fail and require additional, revision surgery more often than replacements in patients with concentric deformities. These failures are thought to result from imbalances between the anterior and posterior rotator cuff muscles, which surround and stabilize the shoulder, specifically with posterior deficiency. Muscle deficiency in the posterior rotator cuff would manifest functionally as relative weakness; however, strength has not been evaluated and compared between patients with eccentric and concentric deformities. Furthermore, clinical strength measurement tools may be limited to detect imbalances. In this thesis, I addressed these gaps by first comparing clinical and laboratory tools for assessing strength. I then used laboratory tools to quantify and compare strength, along with its determinants, muscle size and activity, between patients with eccentric and concentric deformities. When comparing laboratory three-dimensional methods and clinical one-dimensional methods for measuring strength, I found that one-dimensional measurements overestimate strength due to greater off-axis torque generation. Given these results, I evaluated three-dimensional strength in patients before surgery, as well as rotator cuff muscle size, but found no differences between deformity groups. A remaining unknown was whether strength or muscle activity deficiencies exist following surgery in patients with pre-operative eccentric deformities. Therefore, I quantified

three-dimensional strength and muscle activity in patients after shoulder replacement. While strength was reduced in patients following surgery compared to healthy adults, it did not differ by deformity type. However, patients with eccentric deformities demonstrated reduced posterior rotator cuff muscle activity, suggestive of a posterior deficiency that may be related to post-operative failures. Together, this work characterized three-dimensional strength and its determinants in patients with shoulder osteoarthritis, providing important insight into mechanisms that potentially contribute to shoulder replacement failures.

Acknowledgments

The last four years unfolded in ways I never could have imagined. I owe my deepest gratitude to the many people who contributed to making it all possible.

To my research advisor, **Amee Seitz**: Most importantly, thank you for sharing my passion for the shoulder. Thank you for your dedication to supporting me and ensuring that the work we produced was something we were proud of. Thank you for always finding something to laugh about, even when the obstacles we faced seemed insurmountable. There are more lessons than I can count that you have taught me over the last four years, and I know that they will all make me into a better clinician-scientist.

To my co-advisor, **Eric Perreault**: Thank you for pushing me beyond what I thought I could achieve. Thank you for teaching me more than I ever thought I could learn about biomechanics, motor control, and the various experimental tools at our disposal to explore these fields.

To my clinical mentor and dissertation committee member, **Dr. Guido Marra**: Thank you for supporting my passion for orthopaedics and for quite literally making this work possible, as without you and your patients this work would never have happened. I look forward to continuing to learn from you as I get back onto the wards and prepare for my future as an aspiring orthopaedic surgeon.

To my dissertation committee member, **Todd Parrish**: Your assistance identifying the optimal imaging technique to achieve our goal when we first began this work was instrumental in making the work possible. Your feedback always brought new perspectives that made my work stronger as a whole. Thank you for asking thought-provoking questions and for providing your support.

To **Dr. Matthew Saltzman**, thank you for asking insightful questions in the early phases of this project as we were trying to finalize our research question. Thank you also for your willingness to let us recruit your patients to participate, making this work possible.

To **Dr. Ankur Garg**, thank you for teaching me about shoulder ultrasound and for helping us to read the images collected as a part of this work.

To **Rachael Young** at **the Center for Translational Imaging**: Thank you for your flexibility and assistance during all of the data collection I did at CTI. I always enjoyed the opportunity to talk about what was going on in our lives during the scans.

To the **Neuromuscular Control Laboratory**: Thank you to everyone for being there through it all. To Daniel, thank you for answering all of my questions, explaining things for me often times more than once, and for always providing your guidance when I was unsure of what to do next. Thank you for also always helping me to keep things in perspective when I got overwhelmed. To Emma, thank you for serving as an incredible role model and for always being there (even after you left!) – whether it was to work through code or for a much-needed pep talk. To Kosta, thank you for weekly wellness checks, for believing I could do this when I didn't, and for assuring me that things would work out every single time (there were many) I needed that reminder. To Zoe, thank you for being there to listen to my word vomit on more occasions than I can count, and for helping to problem solve whenever the load cell got stuck or something else wasn't working. To Kristen, thank you for always being one of the first people I went to when I had a question or concern about something in the lab, and for always providing a helpful and insightful answer. Thank you also for always understanding the trials and tribulations of life with two dogs. To Bing, thank you for schlepping with me out to Elmhurst and for helping troubleshoot when things went awry in lab. To Kristen and Bing, thank you both for helping to support and guide me through this stressful and momentous final stage – I am so glad we went through it all together. To Anna, thank you for all the insight you provided during shoulder group meetings – I can't wait to see where your project goes after PT school! To Tim, thank you for being there to fix things whenever they went wrong, and for always doing so in such a calm manner. I certainly would not have made it to this point without all of your contributions.

To the **Northwestern Medical Scientist Training Program**: Thank you for believing in my ability to succeed as a physician scientist and for giving me the opportunity to train to become one. To Jayms, Becca, Marisa, Lindsey, and Joyce, thank you for always being there for whatever it was that I needed, be it a simple question or a pep talk. To my classmates, thank you for riding along this journey with me. Particularly to Roger, Cooper, Karthik, Mihai, and Zack, thank you for teaching me new things, pushing me intellectually, taking on international adventures, and always making time for fun.

To **Ebony**, **Cheryl**, **Amy**, and the **rest of the Elmhurst team**: Thank you for your flexibility and for welcoming me into your space on so many occasions.

To the **NIH** and **NIAMS**, the **American Society of Biomechanics**, the **Northwestern Department of Orthopaedic Surgery,** the **Northwestern Department of Physical Therapy & Human Movement Science**s, and **The Graduate School at Northwestern University**: Thank you for providing the financial support that made my training and these experiments possible.

To **those who participated in my research studies**: Thank you for your interest in my research and your willingness to donate your time to participate in my studies. It brought me so

much joy meeting all of you along the way and hearing your different stories. This work never would have happened without your generosity, and for that I am very grateful.

To **Nanny**: Thank you for brightening my day anytime we had a chance to talk on the phone or see each other in person, for always asking me how school was going, and for providing unwavering encouragement.

To **my mom, dad, Katherine, Andrew, and Owen**: Thank you for supporting my dreams even when it meant I'd be moving halfway across the country for 8 years. We already made it to year 6! Thank you for instilling in me the dedication and work ethic that allowed me to get to this point and for always motivating me to keep striving to achieve my goals. Thank you for always checking in to see how I was doing and for understanding and offering your support during the busiest times.

To **Sandy and Howard**: Thank you for taking an interest in learning what my research was all about and for sending much-appreciated and much-enjoyed baked goods.

To **Zach**: Thank you for being there, always. Through the highs and lows over the past 6 years, and the last 4 especially, you have been my sounding board and constant source of support. Thank you for encouraging me to have more confidence in my clinical and scientific abilities and for reminding me about the importance of balance.

To **Alissa**: Thank you for being there every step along the way and always being willing to provide a listening ear, even when you were in the depths of residency in the middle of COVID. Thank you for sharing an appreciation for the little things like Taylor Swift and grocery shopping, as it is the little things that help us to keep going.

To **Maisey and Munch**: Thank you for the constant butt wiggles and kisses, for giving me a reason to get some fresh air each day, and for always brightening my day.

Finally, to **Mike**: It is nearly impossible to put into words how much I have to thank you for. Thank you for supporting me along this journey in so many different ways. Thank you for always reminding me that I could do it, especially when I most doubted it to be true. During the busiest and most stressful times, thank you for your patience and understanding and for always trying to bring a smile to my face. Most importantly, thank you for making sure I was fed, as we know nothing is quite as bad as a stressed and hangry Maggie. This accomplishment is for both of us, as it quite literally would not have happened without you by my side.

List of Abbreviations

ABD: Shoulder abduction
ADD: Shoulder adduction
CI: Confidence interval
EMG: Electromyography
ER: Shoulder external rotation
EXT: Shoulder extension
FLEX: Shoulder flexion
IR: Shoulder internal rotation
OA: Osteoarthritis
TSA: Total shoulder arthroplasty
1D: One-dimensional
3D: Three-dimensional
SD: Standard deviation

Dedication

To Mike, for your unwavering support. We did it!

Table of Contents

List of Tables and Figures

Chapter 1: Introduction

Shoulder function is necessary for completion of numerous daily tasks, including eating, dressing, and combing one's hair. Beyond activities of daily living, impaired shoulder function can hamper one's ability to participate in employment or hobbies such as golfing, painting, or gardening. Patients affected by glenohumeral, or shoulder, osteoarthritis (OA), which causes pain and limits function, often are unable to complete these tasks that many of us take for granted.

A primary treatment aimed at restoring function and eliminating pain in patients with shoulder OA, total shoulder arthroplasty (TSA), does not demonstrate equivalent success rates across all patients with shoulder OA. In fact, TSAs in patients with a certain pattern of bony erosion have been shown to fail more often, necessitating additional surgery. Failures were originally thought to be due to inadequate surgical correction of the bony erosion. However, a new theory has proposed that imbalances between muscles that surround and stabilize the shoulder, the rotator cuff muscles, may play a role in TSA failures.

Muscular imbalances would manifest functionally as alterations in strength. Thus, to determine whether muscular imbalances exist in patients with certain patterns of bony erosion, a necessary first step is quantifying strength in patients with shoulder OA demonstrating different bony erosion patterns. Of additional importance is exploring mechanisms contributing to strength, including the size of muscles surrounding the shoulder and the activity of these muscles. While strength has been measured in patients with OA, relative strength measurements needed to evaluate for imbalances have not yet been compared specifically between patients with different bony erosion patterns. Additionally, muscle size and activity have yet to be measured as potential determinants of strength and function. Finally, existing knowledge on strength in patients with OA may be limited by existing measurement methods typically used in clinical settings.

There are two goals of this dissertation. The first goal is to determine whether laboratory methods for assessing strength overcome limitations of clinical methods. The second goal is to comprehensively quantify shoulder strength, muscle size, and muscle activity in patients with shoulder OA who exhibit various patterns of bony erosion to determine if muscular imbalances exist. If imbalances exist and are detected, targeted rehabilitation may be implemented in efforts to reduce TSA failure rates.

In this chapter, I first provide background on OA and its management. Next, I introduce the variation of TSA outcomes across patients with different bony erosion patterns and explore theories for why this is the case. Third, I discuss existing evidence on strength, muscle size, and muscle activity in patients with shoulder OA and the limitations associated with this evidence, thus highlighting the remaining gaps in knowledge. Finally, I summarize the objectives of this dissertation aimed at determining whether muscular imbalances exist in patients with shoulder OA and identifying the underlying mechanisms.

Prevalence and management of osteoarthritis

Disorders of the musculoskeletal system are a common cause of disability in adults in the United States (*National Center for Complementary and Integrative Health 2016 Strategic Plan*, 2016). The most common disorder of joints, OA (Storheim & Zwart, 2014), is projected to affect 67 million people in the U.S. by the year 2030 (Ashford & Williard, 2014). Not only does OA negatively affect the daily lives of many people, but also it carries a large financial burden. Specifically, the average annual costs attributed to OA were calculated to be $486.4 billion across the six-year period from 2008 to 2014 ("US Bone and Joint Initiative: The Burden of Musculoskeletal Diseases in the United States," 2014).

All joints in the body may be affected by OA, including the hips, knees, and shoulders. Healthy joints are lined by articular cartilage, which reduces friction, protects the underlying bone, and distributes loads (Ashford & Williard, 2014). In a joint affected by OA, the articular cartilage is destroyed. With this loss of cartilage, the joint space narrows and contact may occur between the bones making up the joint, which can lead to bony erosion. Patients with OA often present with symptoms of pain, swelling, stiffness, and functional limitations (Ashford & Williard, 2014). When end-stage OA fails to respond to conservative management, a primary treatment option is total joint arthroplasty, in which the bony surfaces within the joint are replaced with prosthetic implants. The goal of total joint arthroplasty is to eliminate bone-on-bone contact, alleviate pain, and restore function. Of specific interest for this dissertation is total joint arthroplasty performed for shoulder OA, with the annual number of TSAs increasing at a rate 30-50% above that of lower extremity (hip/knee) arthroplasty (Cancienne et al., 2017).

Types of shoulder osteoarthritis and theories for total shoulder arthroplasty failures

Patients with shoulder OA may be classified based upon the manner in which bony erosion, or wear, occurs. Specifically, the glenohumeral joint of the shoulder is comprised of the humerus bone and the glenoid bone. The most widely used system for classifying erosion of the glenoid in patients with shoulder OA is the Walch classification (Walch et al., 1999). Walch et al. studied the precise morphology of the glenoid in 113 patients with primary shoulder OA using computed tomography and defined three main glenoid types: Type A, Type B, and Type C. Patients with glenoids classified as Type A demonstrate a well-centered humeral head with symmetric erosion about the glenoid center. Within the Type A classification, there are two subcategories: Type A1, in which there is minor erosion, and Type A2, in which there is major erosion. Patients with Type

B glenoids exhibit posterior subluxation of the humeral head and asymmetric erosion about the glenoid center with exaggerated posterior wear. Within the Type B classification, there are two subcategories including Type B1, in which there is posterior subluxation but the glenoid remains concave, and Type B2, in which the glenoid develops a biconcavity due to posterior wear. Finally, patients with Type C glenoids exhibit glenoid retroversion (posterior angulation) exceeding 25°, which is typically of dysplastic origin. (Walch et al., 1999) Accurate classification of glenoid type is crucial for surgical planning when patients choose to pursue TSA. Radiographs alone are inferior to advanced imaging techniques, including computed tomography or magnetic resonance imaging, which provide the most accurate assessment of glenoid type (Kopka et al., 2017). For the purpose of this dissertation, we will focus on Types A and B, which may be described as either concentric (Type A1/A2) or eccentric (Type B1/B2) deformities.

The different types of glenoid deformities are of particular interest because outcomes following TSA vary depending on deformity type. One way to evaluate TSA outcomes is to consider the revision rate, which refers to how frequently patients require subsequent surgery. Additionally, the rate of prosthetic glenoid component loosening can be considered. In studies examining outcomes across all patients with shoulder OA where the deformity type was not specified, the revision rate has been found to range from 0% to 11% (Bohsali et al., 2017; Deshmukh et al., 2005; Kasten et al., 2010; Kiet et al., 2015; Norris & Iannotti, 2002; Raiss et al., 2008). Furthermore, the rate of glenoid component loosening has been found to range from 0% to 9%. In studies focused on patients with eccentric deformities, on the other hand, the revision rate has ranged from 0% to 16.3% and the rate of glenoid component loosening has ranged from 12.2% to 20.6% (Hussey et al., 2015; Luedke et al., 2018; Walch et al., 2012). Thus, revision rates are up to 48% higher and particularly the rates of glenoid component loosening are up to 128% higher in patients with eccentric deformities. Revision surgery is not only an inconvenience to the patient, but also is costly, leads to increased complications, and results in inferior outcomes (Hussey et al., 2015; Shields & Wiater, 2019). To date, it is not fully understood why revision rates are higher in patients with pre-operative eccentric deformities who undergo TSA; however, two theories have been proposed.

The first, original theory is that inadequate surgical correction of the eccentric deformity may cause more revisions in these patients (Sears et al., 2012). The ideal positioning of the glenoid component is in neutral version (no anterior or posterior angulation). Neutral version can be especially challenging to achieve in patients with eccentric deformities given the posterior wear and resulting posterior angulation that can occur. Historically, asymmetric reaming has been the most common treatment method to correct glenoid deformities and achieve neutral glenoid version. For patients with eccentric deformities, and thus posterior wear, asymmetric reaming of the anterior glenoid is performed in an attempt to restore neutral version. If neutral version is not achieved, glenoid component malpositioning will result. Component malpositioning increases stress forces and contact pressures across the glenoid component and decreases glenohumeral contact area, all of which threaten glenoid component survival (Luedke et al., 2018; Sears et al., 2012). Furthermore, if there is inadequate bone support for fixation of the glenoid component or if the glenoid component is not fully supported underneath its surface, incomplete seating of the prosthetic component on the native glenoid surface may occur. Incomplete seating may lead to asymmetric loading across the implant and increased stress levels at the bone-implant interface, which may reduce implant longevity (Sears et al., 2012).

Given the challenges of successfully correcting eccentric deformities solely with asymmetric reaming, new surgical techniques have been developed including posterior glenoid bone grafting and posterior glenoid augmentation (Luedke et al., 2018). These new methods use either a bone graft or an augmented glenoid component to fill the posterior defect that may be seen in the setting of eccentric deformities. Despite these advancements, high revision rates are still observed depending upon the surgical technique: 15.6% for asymmetric reaming and 9.5% for posterior glenoid bone grafting. Posterior glenoid augmentation is the newest alternative with only short-term follow-up and, therefore, unknown long-term results. (Luedke et al., 2018) Thus, despite surgical advances, high revision rates persist, which leads one to question if another mechanism may be contributing to increased revision rates in patients with eccentric deformities.

A more recent theory for development of the eccentric deformity and eventual TSA failure in patients with eccentric deformities involves potential imbalances between the rotator cuff muscles. There are four rotator cuff muscles: the supraspinatus, the subscapularis, the infraspinatus, and the teres minor. The supraspinatus is located most superiorly and performs abduction. The subscapularis comprises the anterior rotator cuff and performs internal rotation. The infraspinatus and teres minor comprise the posterior rotator cuff and perform external rotation. All four rotator cuff muscles serve as primary stabilizers of the shoulder, helping to maintain symmetric loading about the glenoid center. The theorized imbalances are thought to disrupt the force couple between the anterior subscapularis and the posterior infraspinatus and teres minor (Domos et al., 2018; Donohue et al., 2018). Several studies have demonstrated increased intramuscular fat infiltration in the posterior rotator cuff in patients with eccentric deformities (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018), which would be expected to weaken these external rotators (Nakamura et al., 2017; Yoon et al., 2018). Persistent external rotation weakness may lead to asymmetric loading of the glenoid (Parsons et al., 2002; Walch et al., 1999), which may then cause bony erosion and eventual glenoid implant failure (Collins et al., 1992; Farron et al., 2006; Mansat et al., 2007). While rotator cuff muscle imbalance is a growing hypothesis to explain the higher failure rates in patients with eccentric deformities, strength has yet to be comprehensively, quantitatively measured and compared between deformity types in patients with OA. This is a significant gap because external rotation weakness that persists after surgery may contribute to initial eccentric deformity development and eventual TSA failure in patients with eccentric deformities. If strength deficits are found to exist, targeted strengthening may be implemented in efforts to reduce TSA revision rates.

Existing evidence on strength in patients with shoulder osteoarthritis

There are a few existing studies that have evaluated internal or external rotation strength in patients with shoulder OA before and after TSA. Sperling et al. measured peak forces for shoulder internal and external rotation strength in patients scheduled to undergo TSA before and 12 months after surgery (Sperling et al., 2008). Lapner et al. measured subscapularis, and thus internal rotation, strength in the affected and contralateral shoulders of patients undergoing TSA before and 12 and 24 months after surgery (Lapner et al., 2015). Finally, Baumgarten et al. measured strength with external rotation and during the liftoff, belly-press, and bear-hug tests, which target internal rotation, in patients undergoing TSA before and 12 months after surgery (Baumgarten et al., 2018). Across all three studies, strength was measured using a one-dimensional (1D) hand-held dynamometer. The results demonstrate that internal rotation strength in the operative shoulder improves after surgery but remains inferior to the contralateral shoulder (Baumgarten et al., 2018; Lapner et al., 2015) and normative values (Sperling et al., 2008). Baumgarten et al. and Sperling et al. observed the same trend for external rotation strength, with post-operative strength improving but not reaching contralateral or normative levels. Overall, these studies have enhanced our understanding of how strength measured with a hand-held dynamometer changes after TSA. However, existing works may be limited and have yet to compare strength between patients with eccentric and concentric deformities.

Two limitations of the existing strength measurements in patients with shoulder OA highlight remaining gaps in our current knowledge. The most important limitation is the measurement method that was used. As noted above, existing studies have measured strength using 1D hand-held dynamometers (Baumgarten et al., 2018; Lapner et al., 2015; Sperling et al., 2008). These devices only measure the torque generated in the given direction of interest. Prior work suggests that, as a result, 1D measures may overestimate strength as patients are likely to maximize the measured torque by generating off-axis torques (Pan et al., 2005). Additionally, when measuring strength in patients with OA before surgery, an important confounder that may impact strength measures is pain. However, to our knowledge, the potential effects of pain on strength in patients with OA have yet to be evaluated.

Recently-developed 3D methods for measuring strength may overcome limitations of 1D hand-held dynamometers. First, as 3D methods provide continuous visual feedback of the torque being generated, they may more effectively limit off-axis torque generation (Baillargeon et al., 2022). In addition, 3D methods allow for measurement of strength not only in a single direction (isolated internal/external rotation) but also in combinations of 2 or 3 directions (rotation with flexion/extension and/or adduction/abduction). Thus, 3D strength measures may be more sensitive to detect weakness in an isolated direction of interest and thus to detect potential muscular imbalances affecting relative external to internal rotation strength. To determine whether 3D measures overcome limitations of 1D measures, we compared shoulder strength measured using 1D and 3D methods. Furthermore, to overcome the methodological limitations associated with existing strength measurements in patients with OA, we used 3D measurement methods to compare strength between patients with eccentric and concentric deformities both pre-operatively and at least 1 year post-operatively. We simultaneously measured pain in patients pre-operatively to assess the potential effects of pain on strength. Overall, we sought to fill several gaps in knowledge by directly comparing 3D and clinically prevalent 1D measures and then using 3D methods to assess for strength differences between patients with eccentric and concentric deformities.

Contributions of muscle size and activity to strength in osteoarthritis

Two core determinants of strength include muscle capacity, which can be estimated from a muscle's size, and muscle activity, which can be measured using electromyography. Existing studies have measured shoulder strength, muscle size, or muscle activity independently in patients with shoulder OA. However, to understand the possible mechanisms contributing to muscular imbalances, it is crucial to comprehensively evaluate muscle capacity, activity, and strength in patients with eccentric and concentric deformities.

Muscle capacity, or the maximal force a muscle can produce when fully activated (Holzbaur et al., 2007), can be indirectly measured by muscle size. Numerous studies have measured muscle volume/cross-sectional area or quantified the amount of fat infiltration within the rotator cuff muscles to compare the extent of muscle degeneration between patients with eccentric and concentric deformities. Greater fat infiltration has been observed in the posterior rotator cuff in patients with eccentric compared to concentric deformities (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). This has been found by measuring the amount of fat within the rotator cuff muscles either using quantitative methods with specialized imaging techniques (Hansen et al., 2021) or qualitative observational methods with the Goutallier classification (Somerson et al., 2016). A greater posterior to anterior rotator cuff muscle cross-sectional area ratio was observed in patients with eccentric compared to concentric deformities (Aleem et al., 2019), yet no difference was observed in the posterior to anterior rotator cuff volume ratio (Arenas-Miquelez et al., 2021). A greater posterior to anterior rotator cuff cross-sectional area ratio would suggest a relative change in muscle size favoring the posterior rotator cuff in patients with eccentric deformities. Thus, the existing evidence conflicts, suggesting patients with eccentric deformities exhibit greater muscle degeneration based on fat infiltration, but equal or lesser muscle degeneration based on muscle area/volume.

There are a few possible explanations for the existing, conflicting evidence on rotator cuff muscle degeneration in patients with shoulder OA. Arenas-Miquelez et al. propose a difference is observed in rotator cuff cross-sectional area only because posterior humeral head subluxation in the setting of an eccentric deformity causes shortening of the posterior rotator cuff (Arenas-Miquelez et al., 2021). It is also possible that previous studies have found no association with glenoid deformity because they measured muscle area alone and did not consider intramuscular fat infiltration. This conflicting evidence highlights the importance of quantifying both muscle size and the extent of fat infiltration simultaneously. Furthermore, examination of the potential functional implications of muscle degeneration, such as on strength, is necessary to understand if differences in rotator cuff muscle size may contribute to potential strength deficits in patients with eccentric deformities. We sought to clarify the conflicting evidence by comparing rotator cuff muscle size and intramuscular fat infiltration between patients with eccentric and concentric deformities prior to TSA. Further, we examined potential functional implications of rotator cuff muscle degeneration by also comparing strength measurements in these patients.

Muscle activity, which can be measured using electromyography, defines the extent to which the nervous system can access a muscle's full capacity and may also impact measured strength. With a proposed deficiency of the posterior relative to the anterior rotator cuff in patients with eccentric deformities, differences in the activity of muscles that perform internal and external rotation would be expected. However, no studies to date have examined and compared muscle activity between patients with eccentric and concentric deformities. While muscle activity has yet to be compared between these two groups, prior work has demonstrated chronic de- and reinnervation changes within the subscapularis, the infraspinatus, and the teres minor in patients at least one year from TSA (Armstrong et al., 2016). The type of pre-operative glenoid deformity was not included or to our knowledge evaluated. However, as denervation may lead to muscle dysfunction, these findings emphasize the importance of considering the potential influence of dysfunctional muscle activity on measured strength in patients after TSA. This evidence highlights another important gap in knowledge: does muscle activity differ between patients with eccentric and concentric deformities following TSA? We sought to fill this gap by measuring both shoulder strength and muscle activity of shoulder muscles that contribute to internal and external rotation in patients following TSA.

Statement of objectives

The central aim of this dissertation was to determine if shoulder strength and two of its core determinants, muscle size and activity, differ between patients with eccentric and concentric shoulder OA before or after TSA. The work comprehensively and quantitatively explores a newly-proposed theory for the increased revision rates observed in patients with eccentric deformities: rotator cuff muscle imbalances. Furthermore, the work overcomes limitations of existing works studying 1D strength in patients with shoulder OA. In Chapter 2, I quantify strength in patients following TSA using both 1D and 3D methods to determine whether 3D methods overcome limitations of clinical 1D methods, particularly when evaluating for rotator cuff muscle imbalances. In Chapter 3, I provide the first quantification of 3D strength in patients with shoulder OA who have not yet undergone TSA and make specific comparisons between patients with eccentric and concentric deformities. Furthermore, I consider the confounding effects of pain and fat-adjusted rotator cuff muscle size on strength measurements in patients with shoulder OA. In Chapter 4, I characterize 3D strength in patients following TSA to determine if imbalances are present following surgical intervention. In addition, I explore an important determinant of strength, muscle activity, to evaluate how it may have impacted the measured strength. Finally, in Chapter 5, I explain the clinical relevance and implications of my results and outline questions that remain or were motivated by the current findings. Together, these studies strive to fill a key gap in the current literature by using 3D methods to determine whether muscular imbalances exist in patients with eccentric compared to concentric deformities that may explain TSA failures. By quantifying strength and its core determinants, this work provides a first step towards understanding if detrimental strength deficits exist in certain patients with shoulder OA and what may be causing them. Most importantly, the results may improve our ability to detect muscular imbalances and develop targeted rehabilitation that may be implemented in efforts to prevent TSA failure.

Chapter 2: One-dimensional hand-held dynamometry overestimates external and internal rotation strength

Margaret S. Coats-Thomas[1-3]; Daniel Ludvig, PhD[1,2]; Guido Marra, MD[4]; Eric J. Perreault, PhD[1,2,5]; Amee L. Seitz, DPT, PhD[3,6]

[1]Biomedical Engineering, Northwestern University, Evanston IL 60208, USA
[2]Shirley Ryan AbilityLab, Chicago IL 60611, USA
[3]Feinberg School of Medicine, Northwestern University, Chicago IL 60611, USA
[4]Orthopaedic Surgery, Northwestern University, Chicago IL 60611, USA
[5]Physical Medicine & Rehabilitation, Northwestern University, Chicago IL 60611, USA
[6]Physical Therapy & Human Movement Sciences, Northwestern University, Chicago IL 60611, USA

This study was supported by the National Institutes of Arthritis and Musculoskeletal and Skin Diseases (NIAMS, F31AR077426), the American Society of Biomechanics, the Department of Physical Therapy and Human Movement Sciences at Northwestern University, and the Department of Orthopaedic Surgery at Northwestern University. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We would like to acknowledge Matthew Saltzman, MD, for his assistance with patient recruitment and Timothy Haswell, MS, for his technical assistance during data collection.

Abstract

Eccentric glenoid component loading resulting from disruption of the force couple between the anterior and posterior rotator cuff muscles may cause glenoid loosening and ultimate total shoulder arthroplasty (TSA) failure. Thus, accurate measurements of internal and external rotation strength are essential to direct post-operative rehabilitation. Accuracy of clinical strength measurements made using one-dimensional (1D) hand-held dynamometry relies on feedback provided by the clinician to minimize off-axis torques. Thus, 1D measures may elicit greater off-axis torques and overestimate rotational strength compared to robust 3D methods that provide continuous feedback to prevent off-axis contributions. We tested this hypothesis in patients following TSA by quantifying strength using 1D and 3D methods. To determine whether patients attempted to perform the same motion during 1D compared to 3D testing, shoulder muscle activity was also recorded. Internal and external rotation torques measured using 1D methods exceeded those measured using 3D methods. Muscle activity of abductors, extensors, and external rotators was greater when measuring isolated external rotation strength using 1D compared to 3D methods. In contrast, muscle activity of internal rotators, flexors, and adductors was increased when measuring isolated internal rotation strength using 1D compared to 3D methods. Finally, a model was derived relating measured EMG to torque and was used to predict torques generated during 1D compared to 3D testing. The predictions suggested that greater off-axis torques were generated in the 1D case. Overall, these results highlight the importance of careful evaluation of existing literature on strength recovery after TSA, as hand-held dynamometry may not fully isolate torque generation in internal and external rotation and may falsely portray greater rotational strength.

Statement of Clinical Significance: These results directly inform clinicians' interpretation of existing knowledge on strength recovery following TSA and suggest that 3D methods may provide additional clinical information regarding isolated internal and external rotation strength in patients following TSA.

Introduction

Glenohumeral osteoarthritis (OA) affects approximately 20-30% of adults over age 60 (Kerr et al., 1985; Petersson, 1983). An anatomic total shoulder arthroplasty (TSA) is a viable option for patients with end-stage glenohumeral OA who experience persistent pain and disability despite conservative management. A leading cause of TSA failure is glenoid loosening (Matsen et al., 2008; Papadonikolakis et al., 2013), which can result from eccentric loading of the glenoid component (Collins et al., 1992). Eccentric loading may be caused by disruption of the force couple between the anterior and posterior rotator cuff muscles (Parsons et al., 2002; Walch et al., 1999), which normally maintains the humeral head centered on the glenoid surface. To avoid this complication, post-operative rehabilitation focuses on maintenance of the anterior to posterior rotator cuff force couple by targeting internal and external rotation strength, respectively (Wilcox et al., 2005). Therefore, accurate assessment of internal and external rotation strength post-operatively is vital as detection and rehabilitation of any deficiencies may help prevent glenoid loosening and ultimate TSA failure.

While assessment of internal and external rotation strength following TSA is crucial, methods for accurately measuring strength in these isolated directions may be limited. Strength measurements in patients who have undergone TSA are typically performed using one-dimensional (1D) hand-held dynamometers (Baumgarten et al., 2018; Lapner et al., 2015; Sperling et al., 2008), which are cost effective, accessible, and efficient for measuring strength in clinical settings. The accuracy of external and internal rotation strength measurements obtained using 1D methods relies on the patient's ability to follow feedback provided by the clinician and generate torque only in the desired direction while minimizing off-axis contributions. When measuring strength with a 1D dynamometer, contributions in off-axis directions, such as along the adduction/abduction axis, may mask underlying deficits in isolated internal or external rotation. It has been shown that the component of strength measured in a direction of interest can often be much larger than the actual strength in that direction when individuals are constrained to limit off-axis torque production (Pan et al., 2005). In fact, individuals are likely to generate off-axis torques to maximize the measure being made. This is a significant limitation of 1D strength assessments that must be considered when interpreting prior literature documenting normal recovery of internal and external rotation strength following TSA.

More recently, methods to quantify strength in three dimensions (3D) have been developed (Baillargeon et al., 2022). These have been shown to be repeatable in asymptomatic adults. Further, musculoskeletal simulations suggest the methods are robust, detecting strength differences between modeled shoulders with rotator cuff tears and with an intact rotator cuff (Baillargeon et al., 2022). Additionally, these methods have demonstrated greater strength in external relative to internal rotation in patients after TSA [Chapter 3]. This stands in contrast to a study that used hand-held dynamometry and found greater strength in internal than external rotation in patients following TSA (Sperling et al., 2008). An important factor that may explain these conflicting findings is the variation in the method (3D versus 1D) used to quantify strength.

In contrast to 1D methods, 3D methods quantify contributions along all three axes, and thus can distinguish between isolated torques generated in internal or external rotation and accessory torques produced along the off axes. When using 3D methods, patients are provided with continuous visual feedback of torque generated along all three axes and consequently must limit off-axis contributions. Therefore, unlike 1D methods, 3D methods do not rely on the clinician's ability to monitor and control patient performance. Due to the additional restrictions imposed, 3D methods may be less likely to elicit off-axis torques and overestimate isolated internal or external rotation torque. Additionally, 3D methods allow one to assess the specific contribution of rotational strength in combined, more functional directions. For example, external rotation is commonly coupled with abduction and/or extension. With 3D methods, one can determine the specific contribution of external rotation torque to this coupled motion. Consequently, 3D strength measurements may provide more accurate and functional assessments of isolated rotational strength. Thus, 3D methods may offer additional, clinically pertinent information regarding isolated internal and external rotation strength in patients after TSA.

Therefore, the primary goal of this study was to determine whether 1D measurements of internal and external rotation strength deviate from 3D measurements in patients following TSA. As an explanatory factor, we measured shoulder muscle activity to determine whether patients attempted to perform the same task during 1D and 3D testing. Establishing whether and why 1D strength assessments deviate from 3D assessments is crucial as this would inform clinicians' interpretation of existing knowledge on strength recovery following TSA. Further, this knowledge may highlight methods that provide clinically informative internal and external rotation strength measurements and thus may help prevent post-operative complications leading to TSA failure.

Methods

Patients

All study procedures for this prospective, cross-sectional study were approved by the Northwestern University institutional review board before initiating recruitment and all patients provided written informed consent for participation. Patients who had an anatomic TSA for primary glenohumeral OA at least 1 year ago by one of two fellowship-trained orthopaedic surgeons were recruited for testing from January to March 2022. Patients were excluded if they had another shoulder surgery before or after the TSA, prior shoulder fracture/infection, neurological disease, a systemic inflammatory condition, prior breast cancer treatment, or active cancer. Eligible patients were scheduled, consented, and then further excluded from the study if current resting shoulder pain was greater than a 6 out of 10 or if cervical spine active range of motion reproduced shoulder symptoms. Given complications associated with subscapularis healing following TSA, all eligible patients underwent ultrasound imaging. Only patients deemed by a musculoskeletal radiologist to have intact subscapularis and supraspinatus tendons were included.

In total, 24 patients enrolled, completed informed consent, and were included. Patient demographic information and self-reported pain, satisfaction and function using the Penn shoulder score (Leggin et al., 2006) were recorded (Table 2.1).

Table 2.1. Patient demographics

Characteristic	Patients
Number of patients	24
Age in years, mean [SD][c]	68 [7.6]
Gender, n (% men)[b]	13 (54)
Hand dominance, n (% right)[b]	20 (83)
Side tested, n (% dominant)[b]	13 (54)
Follow-up in months, mean [SD][c]	41 [23]
BMI in kg/m^2, mean [SD][c]	29 [5.1]
Resting pain, median [IQR][a]	0.0 [0.0 0.5]
Total Penn shoulder score, mean [SD][c]	91 [9.5]
Pain subscore (0-30), mean [SD][c]	28 [1.8]
Satisfaction subscore (0-10), mean [SD][c]	9.2 [1.4]
Function subscore (0-60), mean [SD][c]	53 [9.3]

SD = standard deviation. IQR = [25th quartile 75th quartile].

Strength testing

All patients completed strength testing in a position designed to replicate clinical strength assessments for shoulder internal and external rotation (Hannah et al., 2017; Hayes et al., 2002; Kelly et al., 1996; Stickley et al., 2008). Patients were seated with their back supported and the arm at 45° of shoulder elevation in the scapular plane, 90° of elbow flexion, neutral shoulder rotation, and neutral forearm supination (Fig. 2.1A,B). Either an abduction pillow (1D) or temporary cast fitted to the arm and fixed to a load cell (3D) was used to maintain the arm in the selected position. To prevent learning effects of the visual feedback provided with 3D testing from impacting performance during 1D testing, 1D strength measurements were taken before 3D measurements for all patients.

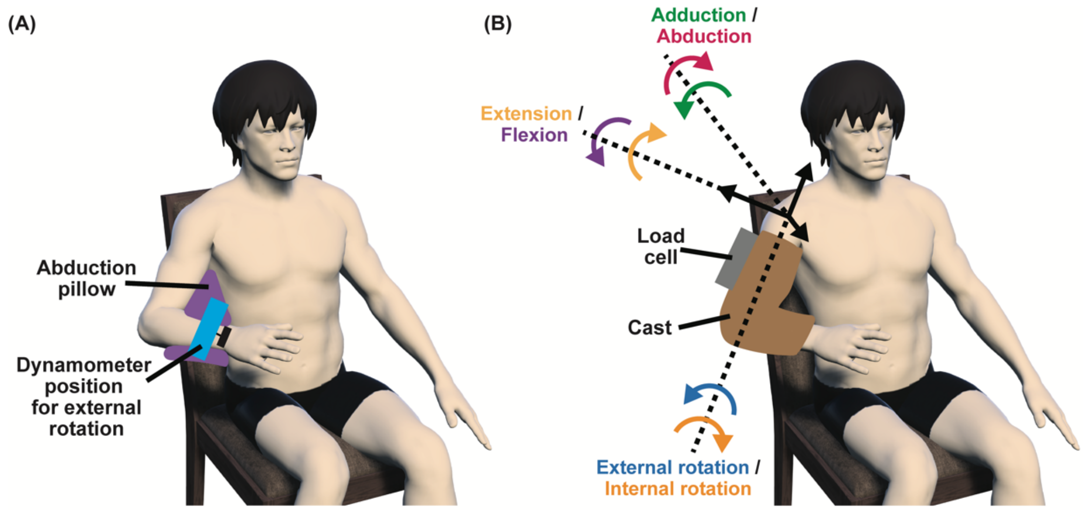

Figure 2.1. Experimental setups.
(A) For hand-held dynamometry (one-dimensional) strength testing, the arm was supported by an abduction pillow. (B) For three-dimensional strength testing, the arm was fitted with a pre-made fiberglass cast that attached to a six degree-of-freedom load cell. Straps were used to secure the torso to the chair.

<u>One-dimensional hand-held dynamometer measurements</u>

A hand-held dynamometer (microFET2, Hoggan Scientific, Salt Lake City, UT, USA) was used to measure the peak isometric contraction force generated during internal and external rotation. For internal rotation testing, the transducer pad of the dynamometer was placed on the patient's ventral forearm between the radial and ulnar styloid processes. For external rotation testing, the transducer pad of the dynamometer was placed on the patient's dorsal forearm between the radial and ulnar styloid processes. Patients were provided verbal instructions for a make test (Kim et al., 2016). Consistent with clinical practice, no visual feedback was provided. Patients first completed a submaximal practice trial for each direction, during which the examiner corrected patient form if necessary and reminded them to minimize off-axis motions. After practicing, participants completed two 5-second maximal isometric contraction trials yielding maximum force outputs within 10% of each other. The maximum of the two recorded forces (N) was converted to joint torque (Nm) by multiplying the peak force by the patient's forearm length (m ; olecranon to ulnar styloid). These joint torques represented the measured internal and external rotation torques in 1D, which were normalized to patient bodyweight for analysis.

Three-dimensional strength measurements

For 3D strength testing, each patient's arm (upper arm to wrist) was fit with a pre-made fiberglass cast maintaining the elbow in 90° flexion. The cast allowed for attachment of the arm to a six degree-of-freedom load cell (45E15A4, JR3, Woodland, CA, USA). Torque and force measurements made within the load cell's local coordinate system were transformed to a glenohumeral joint coordinate system (Wu et al., 2005) to determine torque in shoulder adduction/abduction, internal/external rotation, and flexion/extension.

Consistent with 1D testing, patients first completed submaximal practice trials, which, in the 3D condition, oriented them to the visual feedback provided (Fig. 2.2A). The visual feedback showed the torque generated along all three axes simultaneously, providing a continuous visual cue to patients to limit the amount of off-axis torque generation. After practicing, patients performed maximal isometric contractions lasting 3 seconds in 26 directions equally distributed throughout the 3D space encompassing the shoulder. The 26 randomized directions included targets involving one direction at a time (e.g. internal rotation independently), two directions at a time (e.g. extension and external rotation simultaneously), or three directions at a time (e.g. adduction, internal rotation, and flexion concurrently). All patients were provided with a 30 second rest period between each trial to minimize fatigue. Prior to further analysis, a 1-second moving average filter was applied to the torque data. For each direction tested, the maximum torque achieved in the prescribed target direction was identified (Baillargeon et al., 2022) and used for further processing (Fig. 2.2B-C). The maximum torques achieved specifically in isolated internal rotation and isolated external rotation represented the measured internal and external rotation torques in 3D, which were normalized to patient bodyweight for analysis.

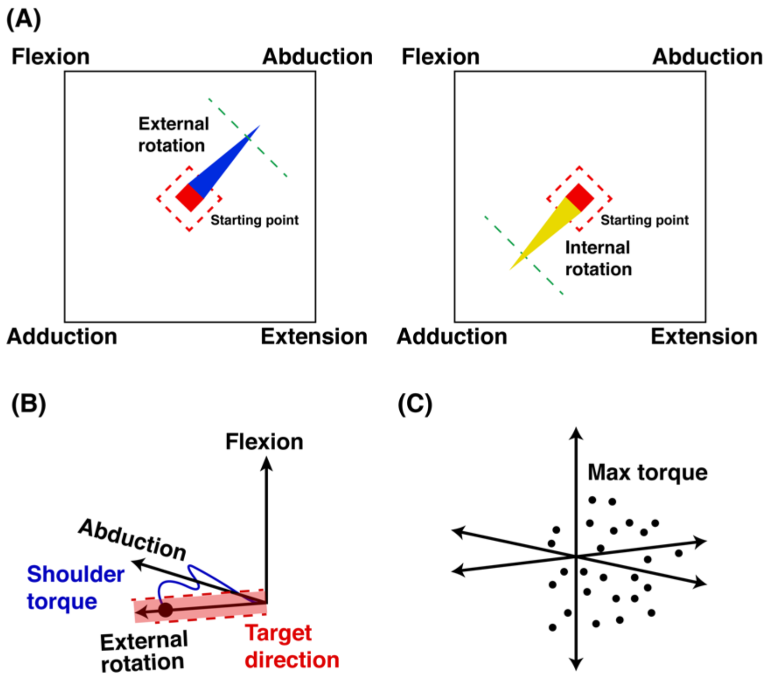

Figure 2.2. Three-dimensional (3D) strength testing
(A) Demonstration of 3D visual feedback viewed by the participant during a target in isolated external rotation (left) and isolated internal rotation (right). (B) Sample trajectory of the torque generated during an isolated external rotation trial, showing the maximum torque (black dot) achieved in the target direction (red shaded channel). (C) Illustration of the maximal torques (black dots) achieved in all 26 directions tested.

Muscle activity

To determine whether patients attempted to perform the same task when using 1D compared to 3D methods, we simultaneously recorded muscle activity during 1D and 3D strength testing and used these data in two ways. First, we compared muscle activity of shoulder muscles between 1D and 3D internal and external rotation strength testing to determine whether different muscle activity patterns were elicited. Second, we used the muscle activity data recorded during 3D strength testing across all 26 directions to generate a model that, when given muscle activity, could predict the resulting 3D torque generated during either 1D or 3D assessments. These predictions allowed us to determine whether 1D and 3D strength measurements differed not only along the axis of interest (internal/external rotation), but also along the off axes (adduction/abduction and flexion/extension) as measured by our model.

Electromyography data collection and processing

Surface electromyography (EMG) was recorded from each of the 3 aspects of the deltoid (anterior, middle, posterior), the pectoralis major, the latissimus dorsi, the teres major, the infraspinatus, and the upper trapezius (Table 2.2). Rectangular surface electrodes (Trigno Avanti, Delsys Incorporated, Natick, MA, USA) had dimensions of 27 x 37 x 13 mm, an interelectrode distance of 10 mm, and a dual on-board stabilizing reference. Additionally, 5 patients were eligible and agreed to fine-wire EMG of the subscapularis, infraspinatus, and supraspinatus muscles using bipolar, fine-wire electrodes (Motion Lab Systems, Inc, Baton Rouge, LA, USA) (Table 2.2). The muscles included were selected either because they contribute specifically to shoulder internal or external rotation or because they contribute to off-axis torque generation (e.g. ad/abduction). Before electrode application, the skin was prepared by shaving and cleaning with alcohol. For surface electrodes, an abrasive electrode gel (NuPrep) was also applied. Fine-wire electrodes were inserted using a clean technique. Confirmation of proper electrode placement was achieved by using manual palpation and visualizing muscle activity during standardized contractions. The Delsys Trigno system (Delsys Incorporated, Natick, MA, USA) was used to record all EMG signals, which were bandpass filtered by the EMG system at 20-450 Hz (surface) and 10-2000 Hz (fine-wire). Fine-wire and surface EMG data were sampled at 4370.4Hz and 2148.1Hz, respectively (Delsys Trigno system, Delsys Incorporated, Natick, MA, USA).

Table 2.2. Electromyography recorded

Muscle	Electrode Type	Placement & Orientation
Anterior Deltoid	Surface	One finger width distal and anterior to the acromion oriented along the line between the acromion and the thumb.[1]
Middle Deltoid	Surface	Greatest bulge of the muscle between the acromion and the lateral epicondyle oriented along the line between the acromion and the hand.[1]
Posterior Deltoid	Surface	Two finger widths behind the angle of the acromion oriented along the line between the acromion and the little finger.[1]
Pectoralis Major	Surface	Two finger widths below the midpoint of the clavicle along the line between the sternoclavicular joint and the anterior axillary fold.[2]
Latissimus Dorsi	Surface	Three finger widths distal to and along the posterior axillary fold along the line between the posterior axillary fold and L3.[2]
Teres Major	Surface	Three finger widths above the inferior angle of the scapula along the lateral border along the lateral border along the line between the posterior axillary fold and inferior angle.[2]
Infraspinatus	Surface	Two to three finger widths below the scapular spine at the midpoint between the posterior acromion and the trigonum spinae parallel to the scapular spine.[2]
Upper Trapezius	Surface	Halfway between the acromion and C7 along the line between these two structures.[1]
Supraspinatus	Intramuscular	Wire placed 1-2 finger widths above the scapular spine at the midpoint between the posterior acromion and the trigonum spinae and angled towards the supraspinous fossa.[2]
Infraspinatus	Intramuscular	Wire placed 2-3 finger widths below the scapular spine at the midpoint between the posterior acromion and the trigonum spinae and angled towards the infraspinous fossa.[2]
Subscapularis	Intramuscular	Wire inserted 3 finger widths superior to the inferior angle and 2-3 finger widths anterior to the lateral border of the scapula.[3]

[1]Hermens HJ. SENIAM : European recommendations for surface electromyography : results of the SENIAM project. [Pays-Bas]: Roessingh Research and Development; 1999.
[2]Perotto A, Delagi EF. Anatomical Guide for the Electromyographer: The Limbs and Trunk: Charles C Thomas; 2005.
[3]Németh G, Kronberg M, Broström LA. Electromyogram (EMG) recordings from the subscapularis muscle: description of a technique. J Orthop Res. 1990 Jan;8(1):151-3.

Surface EMG data were digitally bandpass filtered between 20 and 500Hz prior to analysis. For fine-wire EMG, a notch filter was applied at 60Hz followed by a digital bandpass filter between 20 and 1000Hz. After filtering, data were rectified. For each muscle, the EMG data collected during 1D and 3D strength testing were normalized to the maximum activity achieved by that muscle across the 26 directions evaluated during 3D strength testing. After filtering, rectifying, and normalizing, the EMG data were further processed following the same procedure used for the torque data. A 1-second moving average filter was applied to the EMG data to ensure the torque and EMG data were aligned. For 1D strength testing, the muscle that demonstrated the highest amplitude during each trial was identified and the time at which it achieved its maximum was extracted. The EMG activity for each muscle for each trial was determined at this single timepoint. For 3D strength testing, the EMG activity was determined at the time of maximal torque production for each muscle for each target direction (Fig. 2.3). Muscle activity was compared between 3D and 1D internal and external rotation. Muscle activity comparisons were made across the 8 muscles for which surface EMG data were collected in all 24 patients. If fine-wire EMG data were also collected in a patient, these data were included in the patient-specific EMG to torque models described below.

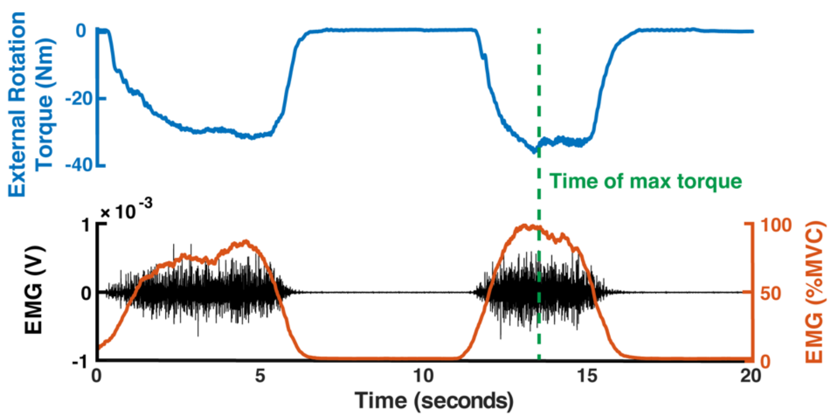

Figure 2.3. Raw and filtered EMG and torque
Example of an isolated external rotation trial for one subject, showing torque, raw EMG (V), rectified and filtered EMG (%MVC), and the time the maximal torque was achieved.

<u>EMG to torque models</u>

Patient-specific models relating EMG to torque were derived using data from 3D strength testing to determine whether differences between 1D and 3D measures existed not only along the internal/external rotation axis, but also along the off axes (adduction/abduction; flexion/extension). To generate each patient-specific model, a multivariate regression was applied with the muscle activity ($N \leq 11$) in each of the 26 target directions considered as the input and the corresponding torques in each direction ($N=3$) as the output. For each patient, backwards stepwise regression was performed on the original model to eliminate muscles without unique contributions to the model ($p>0.05$) and to minimize overfitting. On average, 2 ± 2 (mean ± SD) muscles were removed across all 24 patient models. A leave-one-out cross validation was applied to the final model for each patient and the resulting R^2 was computed. If the adduction/abduction, internal/external rotation, or flexion/extension component of the computed R^2 was less than 0.70, that patient's model was eliminated from further analysis (8/24; 33%).

Each patient's final model was used to predict the 3D torques generated during 1D and 3D strength testing. Predictions were computed from the EMG of all muscles during the 1D or 3D internal or external rotation trial. For each patient, this yielded predicted 3D torques generated during 1D and 3D internal and external rotation. The 1D and 3D predictions were normalized to patient bodyweight so that data could be combined across subjects.

Statistical Analysis

To test our primary hypothesis that 1D measurements deviate from 3D measurements, we used paired t-tests to determine if 1D external and internal rotation strength differed from 3D external and internal rotation strength, respectively. Next, we used paired t-tests to determine whether muscle activity for each of the 8 muscles differed between 3D and 1D internal and external rotation strength testing. To determine whether differences between 1D and 3D measures existed not only along the internal/external rotation axis but also along the adduction/abduction and flexion/extension axes, we used paired t-tests to test for differences along each axis between the predicted 1D and predicted 3D internal and external rotation torques. For all tests a significance level of $\alpha = 0.05$ was used. Bonferroni corrections were applied as needed to adjust for multiple comparisons.

Results

1D versus 3D strength measurements

The mean weight-normalized internal rotation torque measured in 1D (mean ± SD, 0.29 ± 0.10 Nm/kg) was 153% greater than that measured in 3D (0.11 ± 0.06 Nm/kg ; mean difference 0.17 Nm/kg, [95% CI 0.14 Nm/kg to 0.20 Nm/kg] ; $p < 0.01$) (Fig. 2.4). For external rotation, the mean weight-normalized torque measured in 1D (0.35 ± 0.10 Nm/kg) was 98% greater than that measured in 3D (0.18 ± 0.10 Nm/kg ; mean difference 0.17 Nm/kg, [95% CI 0.11 Nm/kg to 0.24 Nm/kg ; $p < 0.01$). Thus, 1D measurements of internal and external rotation torque exceeded 3D measurements.

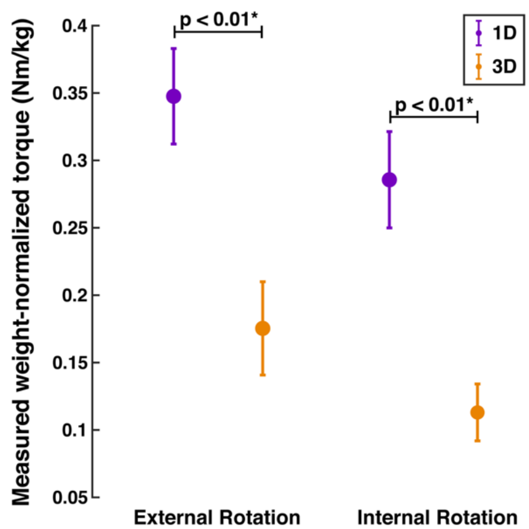

Figure 2.4. Measured 1D and 3D torques
Mean (95% CI) of measured weight-normalized torque during 1D and 3D strength testing in external and internal rotation.

Muscle activity

When asked to perform isolated internal rotation, muscle activity of the pectoralis major, latissimus dorsi, and teres major was higher during 1D compared to 3D testing (Fig. 2.5) (Table 2.3). In contrast, there was lower muscle activity of the middle and posterior deltoids during 1D compared to 3D internal rotation. Muscle activity of the anterior deltoid, infraspinatus, and upper trapezius did not differ during 1D compared to 3D internal rotation. When asked to perform isolated external rotation, there was higher muscle activity of the anterior deltoid, middle deltoid, posterior deltoid, latissimus dorsi, teres major, infraspinatus, and upper trapezius during 1D compared to 3D testing. Muscle activity of the pectoralis major did not differ during 1D compared to 3D external rotation. These findings reveal that different muscle activity patterns were adopted during 1D compared to 3D testing. During 1D testing, muscles capable of performing more than just internal or external rotation were used to a greater degree.

Table 2.3. Muscle activity during 1D and 3D strength testing

	Internal Rotation				**External Rotation**			
	1D	**3D**			**1D**	**3D**		
Muscle	Mean ± SD, %MVC	Mean ± SD, %MVC	Mean difference [95% CI], %MVC	p-value	Mean ± SD, %MVC	Mean ± SD, %MVC	Mean difference [95% CI], %MVC	p-value
Anterior Deltoid	26 ± 36	17 ± 12	9.4 [-5.2 24]	0.20	52 ± 28	19 ± 12	33 [20 45]	<0.001
Latissimus Dorsi	65 ± 37	21 ± 11	44 [30 59]	<0.001	65 ± 46	26 ± 13	39 [22 57]	0.001
Pectoralis Major	105 ± 51	29 ± 12	77 [56 98]	<0.001	13 ± 11	15 ± 12	-1.7 [-4.8 1.4]	0.26
Teres Major	55 ± 27	27 ± 14	28 [17 39]	<0.001	56 ± 30	32 ± 17	24 [14 34]	<0.001
Infraspinatus	20 ± 11	15 ± 5.8	5.0 [1.6 8.4]	0.006	117 ± 52	56 ± 24	61 [36 85]	<0.001
Posterior Deltoid	8.4 ± 8.3	22 ± 9.5	-14 [-18 -9.9]	<0.001	76 ± 34	25 ± 12	51 [37 65]	<0.001
Middle Deltoid	8.8 ± 6.2	26 ± 13	-17 [-22 -12]	<0.001	69 ± 42	23 ± 12	47 [29 65]	<0.001
Upper Trapezius	21 ± 12	23 ± 18	-1.8 [-9.9 6.4]	0.66	40 ± 27	18 ± 19	22 [8.4 35]	<0.003

Internal rotators are highlighted in purple. External rotators are highlighted in orange. All p values were calculated using paired t-tests. The adjusted p-value designating significance was $p < 0.003$ (0.05/16). SD = standard deviation; CI = confidence interval; %MVC = percent maximum voluntary contraction.

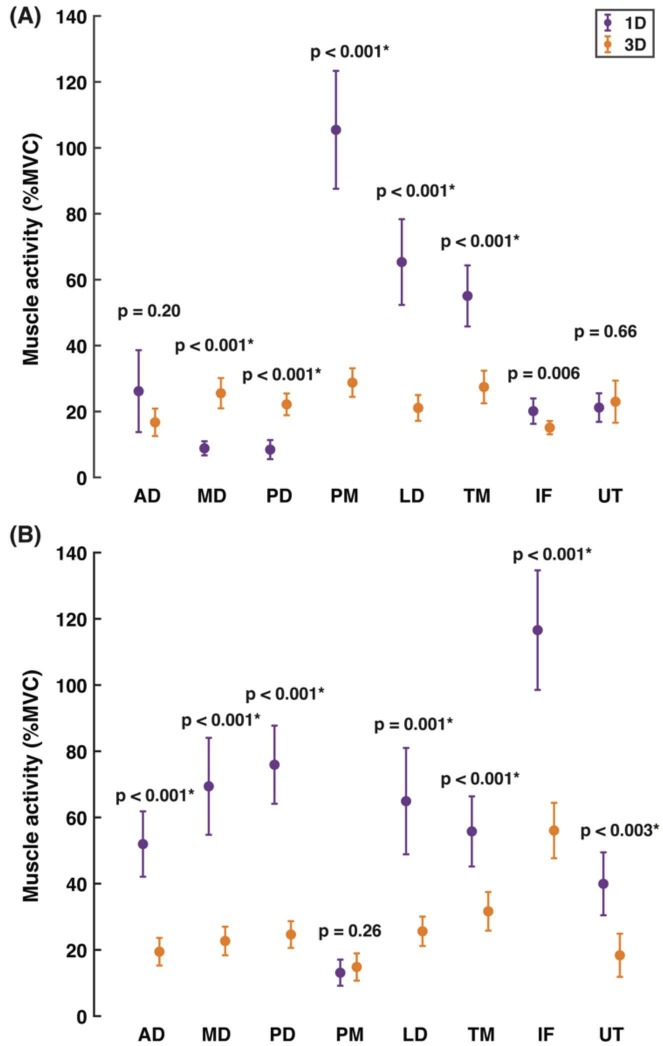

Figure 2.5. Muscle activity for each muscle during isolated internal and external rotation
Mean (95% CI) muscle activity for all muscles during 1D and 3D (A) internal rotation and (B) external rotation. AD = anterior deltoid; MD = middle deltoid; PD = posterior deltoid; PM = pectoralis major; LD = latissimus dorsi; TM = teres major; IF = infraspinatus; UT = upper trapezius.

1D versus 3D torque predictions

The mean cross-validated R^2 across the 16 patient models included was [mean±SD; X: 0.85±0.07, Y: 0.81±0.09, Z: 0.91±0.05]. A representative example demonstrating model performance for a single patient is shown in Figure 2.6. As measured by the derived EMG to torque models, the weight-normalized predicted 3D torque measured in 1D as subjects were instructed to internally rotate had larger adduction (+X), internal rotation (+Y), and flexion (+Z) components than that measured in 3D (X: mean difference 0.34, [95%CI 0.25, 0.43 Nm/kg], $p<0.001$; Y: 0.11, [0.07, 0.14 Nm/kg], $p<0.001$; Z: 0.36, [0.22, 0.51 Nm/kg], $p<0.001$) (Fig. 2.7). For external rotation, the predicted 3D torque measured in 1D had a larger extension (-Z; -0.20, [-0.29, -0.09 Nm/kg]; $p<0.001$) component than that measured in 3D. These predictions suggest greater off-axis torques are generated during 1D compared to 3D strength testing. Thus, 1D and 3D strength measures are predicted to not only differ along the internal/external rotation axis, but also along the adduction/abduction and flexion/extension axes, suggesting 3D methods more successfully limit off-axis torque generation.

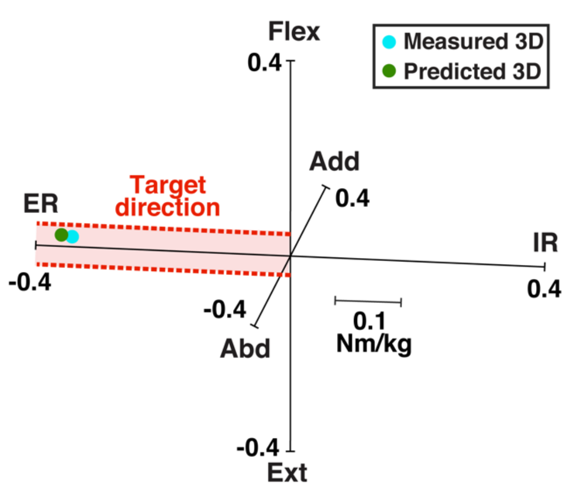

Figure 2.6. Measured and predicted 3D torques for a representative patient
Measured and predicted 3D torques generated during isolated external rotation for a representative patient. The shaded area designates the prescribed target direction.

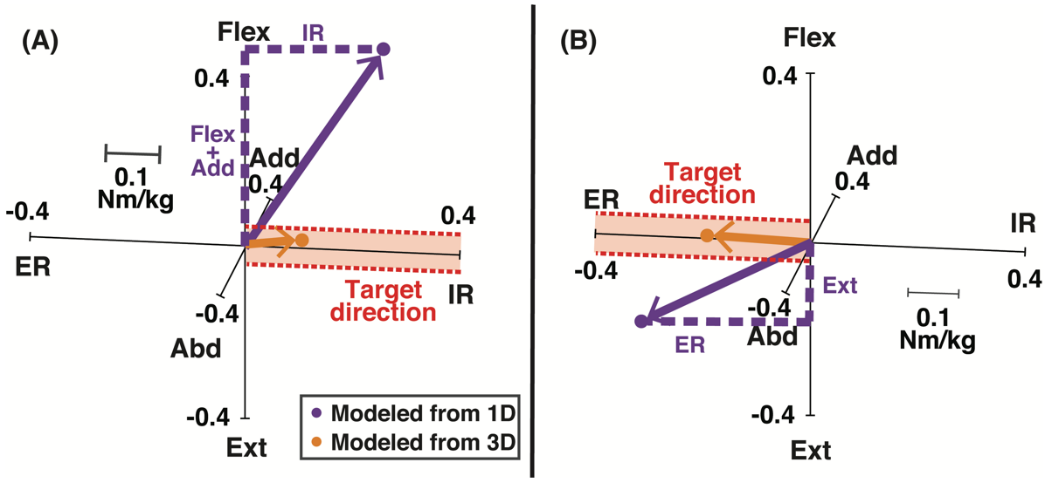

Figure 2.7. Predicted torques
For illustrative purposes, mean predicted 3D torques generated during 1D and 3D (A) internal and (B) external rotation are shown. The shaded areas designate the prescribed target direction. The 1D vectors are broken down into two components to illustrate the off-axis contributions.

Discussion

Eccentric glenoid component loading resulting from anterior to posterior rotator cuff force couple disruption may cause glenoid loosening and ultimate TSA failure. Thus, accurate post-operative internal and external rotation strength measurements are essential to guide rehabilitation. While robust 3D methods provide continuous visual feedback to minimize off-axis torques, 1D hand-held dynamometry relies on verbal feedback and thus may elicit greater off-axis contributions and overestimate rotational strength. We tested the hypothesis that 1D strength measures may deviate from 3D measures in patients following TSA by quantifying strength using 1D and 3D methods while measuring shoulder muscle activity. Internal and external rotation torques measured using 1D methods exceeded those measured using 3D methods. Muscle activity of abductors, extensors, and external rotators was greater when measuring external rotation strength using 1D compared to 3D methods. In contrast, muscle activity of abductors was reduced and muscle activity of internal rotators, flexors, and adductors was increased when measuring internal rotation strength using 1D compared to 3D methods. Finally, predicted torques during 1D compared to 3D testing, which were computed from the derived EMG to torque models, suggest there are greater off-axis contributions in the 1D case. Overall, these findings suggest that 1D measurements overestimate pure internal and external rotation strength in patients following TSA as patients are not as constrained to minimize off-axis contributions in the 1D compared to the 3D case. As 3D measurements effectively limit off-axis torque generation, they may provide pertinent information about isolated rotational strength.

1D versus 3D strength measurements

As anticipated, 1D measures of internal and external rotation strength exceeded 3D measures in patients following TSA. This finding may explain why results of recent studies examining strength in 3D in patients with shoulder OA differ from existing work using hand-held dynamometry. Using 3D methods, patients with OA following TSA demonstrated weakness in internal relative to external rotation compared to control participants without shoulder pain [Chapter 3]. In contrast, in an existing study using 1D hand-held dynamometry, the measure of internal rotation strength was greater than the measure of external rotation strength in patients 1 year after TSA (Sperling et al., 2008). It is possible that the 3D and 1D results deviate due to the different methodologies used to measure strength. Interestingly, in the study that used hand-held dynamometry to measure strength at 1 year post-operatively, external rotation strength was found to be 73% of normal whereas internal rotation strength was only 71% of normal (Sperling et al., 2008). This may suggest relatively greater recovery of external rotation strength post-operatively, which is more in agreement with our 3D strength results. While these findings support the hypothesis that 1D measures deviate from 3D measures, understanding why this is the case is crucial so appropriate steps may be taken to ensure accurate assessment of internal and external rotation strength after TSA.

Muscle activity

To explain why 1D measures deviated from 3D measures, we examined shoulder muscle activity using electromyography. Muscle activity was found to differ between 1D and 3D measurements of external rotation strength. When measuring external rotation strength using 1D compared to 3D methods, the deltoids (anterior, middle, posterior) and the upper trapezius, all of which are abductors (Jobe et al., 2022), demonstrated increased muscle activity. The latissimus dorsi and teres major, which are extensors (Jobe et al., 2022), exhibited increased muscle activity in the 1D case as well. As external rotation is commonly coupled with abduction and extension (Novotny et al., 1998), this finding suggests that in the 1D case there are greater contributions from muscles that perform off-axis actions. The freedom to generate these off-axis torques ultimately allowed patients to achieve greater activity of the infraspinatus, a primary external rotator (Jobe et al., 2022).

Not only did muscle activity differ between 1D and 3D measurements of external rotation strength, but also there were differences when measuring internal rotation strength. In the internal rotation case, muscle activity of the middle and posterior deltoids was reduced in the 1D compared to 3D case, whereas the pectoralis major, latissimus dorsi, and teres major demonstrated greater muscle activity. The pectoralis major is a flexor, internal rotator, and an adductor (Jobe et al., 2022). The latissimus dorsi and teres major contribute to internal rotation, extension, and adduction (Jobe et al., 2022). Internal rotation is often coupled with adduction (Kopke et al., 2021); therefore, these muscle activity changes further suggest that during 1D testing, contributions from muscles that perform off-axis actions are greater than during 3D testing. These findings are supported by existing work demonstrating that participants take advantage of kinematic constraints by applying orthogonal, off-axis torques to maximize measured torque in the prescribed direction of interest (Pan et al., 2005). Overall, based on the observed muscle activity differences, we would expect that greater off-axis torques are being generated during 1D testing, which may ultimately contribute to overestimation of strength using these methods. On the contrary, 3D strength testing limits off-axis contributions and provides an accurate measure of strength in the direction prescribed. Thus, 3D measurements may provide functional insight as to true strength in isolated rotation.

1D versus 3D torque predictions

Predictions derived from our models relating EMG to torque allowed us to determine whether 1D and 3D torque measurements differed not only along the internal/external rotation axis, but also along the off axes. As anticipated based on the muscle activity results, the predictions suggest that when trying to generate isolated external rotation torques, patients also generated off-axis torque in extension to a greater degree during 1D than 3D testing. Similarly, when attempting to perform isolated internal rotation, our predictions suggest that patients generated more off-axis torques in adduction and flexion when using 1D compared to 3D methods. Thus, across both internal and external rotation, patients could enhance the measured torque in the primary direction of interest (rotation) by taking advantage of their ability to generate off-axis torques during 1D testing. These findings are significant as they highlight the importance of careful, critical evaluation of existing literature on strength recovery after TSA. The current results suggest that studies using hand-held dynamometry may report falsely elevated internal or external rotation strength. During 3D testing, off-axis contributions were effectively minimized. Therefore, these results further emphasize the potential benefit of exploring ways to incorporate 3D measurements into the clinic alongside standard 1D measurements.

Effect of visual feedback on off-axis torque generation

To further support our theory that the freedom to generate off-axis torques contributed to the observed differences between 1D and 3D measurements, we performed an exploratory analysis on torque data collected using 3D methods with modified visual feedback. The modified feedback only showed the patient the torque they were generating along the direction of interest, thus allowing them to generate off-axis torques. When we compared the predicted torques generated during 1D testing to the measured torques generated during 3D testing with modified feedback, we found that these torques did not differ along the adduction/abduction, internal/external rotation, or flexion/extension axes for internal rotation. This suggests that the off-axis torques predicted to occur with 1D testing also occurred when 3D testing was performed with modified feedback that did not constrain off-axis torque generation. In contrast, for external rotation, the torques did not differ along the adduction/abduction or internal/external rotation axes, but the torque generated along the flexion/extension axis during 1D testing exceeded that during 3D testing with modified feedback. In other words, when measuring internal rotation strength using 3D methods with feedback that no longer constrained patients to only the internal/external rotation axis, off-axis torques generated in adduction and flexion were similar to those predicted to occur with 1D testing. When measuring external rotation using 3D methods with the modified feedback, off-axis torque generated in abduction was similar to that predicted to occur with 1D testing. Extension torque was greater during 1D testing even when compared to 3D testing with modified feedback. Overall, these findings further support the conclusion that the ability to generate off-axis torques is a major contributor to the differences between 1D and 3D strength measurements. Specifically, our results suggest that the feedback provided may be critical to ensuring accuracy of strength measurements in isolated internal and external rotation.

Limitations

There are several limitations of this study. First, 1D testing was performed before 3D testing across all patients, thus fatigue may have influenced the results. However, the choice to conduct 1D testing first was made to prevent learning effects of the feedback provided during 3D testing from influencing 1D testing. Second, strength testing was performed in a single position and thus these results cannot be generalized to other positions, as we know muscle moment arms change with arm position (Ackland et al., 2008). Additionally, 1D torques were computed using measured forearm length, which may have introduced additional error; however, the magnitude of this error (0.005 m) is small compared to that of the measured forces. Finally, while EMG was recorded from several large internal rotators, it was not recorded from the subscapularis in all patients and thus its activity could not be compared between 1D and 3D methods. Future work examining how the subscapularis may contribute differently between these two methods would be beneficial.

Conclusion

In conclusion, measurements of internal and external rotation strength made using 1D hand-held dynamometry exceed those made using 3D methods in patients following TSA. Activity of shoulder muscles that perform off-axis actions, including adduction/abduction and flexion/extension, was greater during 1D compared to 3D testing. In combination with predictions of the torques generated during 1D and 3D testing, these results suggest that off-axis torque generation occurs to a greater extent when using hand-held dynamometry. Overall, these results highlight the importance of careful evaluation of existing literature on strength recovery after TSA, as hand-held dynamometry may report falsely elevated internal or external rotation strength. As off-axis contributions were effectively limited in the 3D case, these methods may provide more insight into isolated rotational strength. Thus, our findings emphasize the potential benefit of exploring ways to make 3D measurements efficiently in the clinic alongside 1D measurements. Ultimately, these results will help to ensure accurate clinical assessment of internal and external rotation strength following TSA to avoid complications leading to failure.

Chapter 3: No strength differences despite greater posterior rotator cuff intramuscular fat in patients with eccentric glenohumeral osteoarthritis

Margaret S. Coats-Thomas[1-3]; Emma M. Baillargeon, DPT, PhD[4]; Daniel Ludvig, PhD[1,2]; Guido Marra, MD[5]; Eric J. Perreault, PhD[1,2,6]; Amee L. Seitz, DPT, PhD[3,7]

[1]Biomedical Engineering, Northwestern University, Evanston IL 60208, USA
[2]Shirley Ryan AbilityLab, Chicago IL 60611, USA
[3]Feinberg School of Medicine, Northwestern University, Chicago IL 60611, USA
[4]Epidemiology, Graduate School of Public Health, University of Pittsburgh, Pittsburgh PA 15260, USA
[5]Orthopaedic Surgery, Northwestern University, Chicago IL 60611, USA
[6]Physical Medicine & Rehabilitation, Northwestern University, Chicago IL 60611, USA
[7]Physical Therapy & Human Movement Sciences, Northwestern University, Chicago IL 60611, USA

This study was funded by the National Institutes of Arthritis and Musculoskeletal and Skin Diseases (NIAMS F31AR077426), the American Society of Biomechanics, the Department of Physical Therapy and Human Movement Sciences at Northwestern University, and the Department of Orthopaedic Surgery at Northwestern University. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We thank Timothy M. Haswell, MS, for his technical assistance during experimental setup design and data collection and Constantine P. Nicolozakes, PhD, for his assistance with study design.

This chapter has been accepted for publication by *Clinical Orthopaedics and Related Research*.

Abstract

Background When nonoperative measures do not alleviate the symptoms of glenohumeral osteoarthritis (OA), patients with advanced OA primarily are treated with anatomic total shoulder arthroplasty (TSA). It is unknown why TSAs performed in patients with eccentric (asymmetric glenoid wear) compared with concentric (symmetric glenoid wear) deformities exhibit higher failure rates, despite surgical advances. Persistent disruption of the posterior-to-anterior rotator cuff (RC) force couple resulting from posterior RC intramuscular degeneration in patients with eccentric deformities could impair external rotation strength and may contribute to eventual TSA failure. Pain and intramuscular fat within the RC muscles may impact external rotation strength measures and are important to consider.

Questions/purposes (1) Is there relative shoulder external rotation weakness in patients with eccentric compared with concentric deformities? (2) Is there higher resting or torque-dependent pain in patients with eccentric compared with concentric deformities? (3) Do patients with eccentric deformities have higher posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities?

Methods From February 2020 to November 2021, 65% (52 of 80) of patients with OA met study eligibility criteria. Of these, 63% (33 of 52) of patients enrolled and completed informed consent. From a convenience sample of 21 older adults with no history of shoulder pain, 20 met eligibility criteria as control participants. Of the convenience sample, 18 patients enrolled and completed informed consent. In total for this prospective, cross-sectional study, across patients with OA and control participants, 50% (51 of 101) of participants were enrolled and allocated into the eccentric (n = 16), concentric (n = 17), and control groups (n = 18). A 3°-of-freedom load cell was used to

sensitively quantify strength in all three dimensions (3D) surrounding the shoulder. Participants performed maximal isometric contractions in 26 1°-, 2°- and 3°-of-freedom direction combinations involving adduction/abduction, internal/external rotation, and/or flexion/extension. To test for relative external rotation weakness, we quantified relative strength in opposing directions (3D strength balance) along the X (+adduction/-abduction), Y (+internal/-external rotation), and Z (+flexion/-extension) axes and compared across the three groups. Patients with OA rated their shoulder pain (numerical rating 0-10) before testing at rest (resting pain; response to "How bad is your pain today?") and with each maximal contraction (torque-dependent pain; numerical rating 0-10). Resting and torque-dependent pain were compared between patients with eccentric and concentric deformities to determine if pain was higher in the eccentric group. The RC cross-sectional areas and intramuscular fat percentages were quantified on Dixon-sequence MRIs by a single observer who performed manual segmentation using previously validated methods. Ratios of posterior-to-anterior RC fat percent (infraspinatus + teres minor fat percent/subscapularis fat percent) were computed and compared between the OA groups.

Results There was no relative external rotation weakness in patients with eccentric deformities (Y component of 3D strength balance, mean ± SD: -4.7% ± 5.1%) compared with patients with concentric deformities (-0.05% ± 4.5%, mean difference -4.7% [95% CI -7.5% to -1.9%]; p = 0.05). However, there was more variability in 3D strength balance in the eccentric group (95% CI volume, $\%^3$: 893) compared with the concentric group (95% CI volume, $\%^3$: 579). In patients with eccentric compared with concentric deformities, there was no difference in median (interquartile range) resting pain (1.0 [3.0] versus 2.0 [2.3], mean rank difference 4.5 [95% CI -6.6 to 16]; p = 0.61) or torque-dependent pain (0.70 [3.0] versus 0.58 [1.5]; mean rank difference 2.6 [95% CI -8.8

to 14]; p = 0.86). In the subset of 18 of 33 patients with OA who underwent MRI, patients with eccentric deformities (n = 7) demonstrated a higher posterior-to-anterior RC fat percent ratio than patients (n = 11) with concentric deformities (1.2 [0.83] versus 0.70 [0.30], mean rank difference 6.4 [95% CI 1.4 to 11]; p = 0.01).

Conclusion Patients with eccentric deformities demonstrated higher variability in strength compared with patients with concentric deformities. This increased variability suggests patients with potential subtypes of eccentric wear patterns (posterior-superior, posterior-central, and posterior-inferior) may compensate differently for underlying anatomic changes by adopting unique kinematic or muscle activation patterns.

Clinical Relevance Our findings highlight the importance of careful clinical evaluation of patients presenting with eccentric deformities as some may exhibit potentially detrimental strength deficits. Recognition of such strength deficits may allow for targeted rehabilitation. Future work should explore the relationship between strength in patients with specific subtypes of eccentric wear patterns and potential forms of kinematic or muscular compensation to determine whether these factors play a role in TSA failures in patients with eccentric deformities.

Introduction

Glenohumeral osteoarthritis (OA) is associated with pain, weakness, and functional limitations in older adults. Glenoid erosion with OA can result in a concentric (Walch Type A1 and A2) or eccentric deformity (Walch Type B1, B2, and B3) (Bercik et al., 2016). The failure rate of anatomic total shoulder arthroplasty (TSA) in patients with eccentric deformities is substantially higher than in patients with concentric deformities, despite advances in surgical techniques (Denard & Walch, 2013; Kiet et al., 2015; Luedke et al., 2018; Sears et al., 2012; Sperling et al., 2008; Walch et al., 2012). A potential cause of persistent TSA failure in patients with eccentric deformities is disruption of the force couple between the posterior (infraspinatus and teres minor) and anterior (subscapularis) rotator cuff (RC) muscles (Domos et al., 2018; Donohue et al., 2018). Increased posterior RC intramuscular fat, which impairs external rotation strength (Nakamura et al., 2017; Yoon et al., 2018), has been identified preoperatively in patients with eccentric deformities (Donohue et al., 2018). External rotation weakness that persists postoperatively could result in asymmetric glenoid loading (Parsons et al., 2002; Walch et al., 1999) and contribute to subsequent glenoid implant failure (Collins et al., 1992; Farron et al., 2006; Mansat et al., 2007).

Factors including pain and RC muscle size may impact measures of external rotation strength. Prior evidence suggests relative external-to-internal rotation strength is similar between patients with OA (across all glenoid deformity types) (Sperling et al., 2008) and healthy adults (Andrews et al., 1996), but the influence of pain has not, to our knowledge, been considered. A patient may demonstrate apparent weakness in a certain direction if their effort was limited by pain. Although increased intramuscular fat has been identified in the posterior RC in patients with eccentric compared with concentric deformities (Donohue et al., 2018), ratios comparing the relative amount of remaining muscle (fat-adjusted) have not been reported. Lastly, strength assessments in patients with OA have been performed in a single dimension using hand-held dynamometers. Such devices only measure the component of a generated torque aligned with the measurement direction, thus allowing patients to maximize torque in the measurement direction by generating off-axis torques in other directions (such as, abduction to enhance external rotation) (Pan et al., 2005). Assessing strength in three dimensions (3D; along flexion/extension, internal/external rotation, and adduction/abduction simultaneously) overcomes these limitations by minimizing off-axis torque generation. Thus, 3D measures may be more sensitive to detect weakness in the direction of interest. Considering these factors, it is unknown if patients with eccentric deformities demonstrate relative external rotation weakness. Rehabilitation after TSA that does not detect or correct pre-existing external rotation weakness may contribute to higher failure rates in patients with eccentric deformities. Identification of external rotation weakness in patients with eccentric deformities may elucidate mechanisms contributing to bony deformity development and TSA failure, allowing for modification of postoperative rehabilitation with targeted strengthening.

Therefore, we asked: (1) Is there relative shoulder external rotation weakness in patients with eccentric compared with concentric deformities? (2) Is there higher resting or torque-dependent pain in patients with eccentric compared with concentric deformities? (3) Do patients with eccentric deformities have higher posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities?

Patients and Methods

Study Design and Setting

For this prospective, cross-sectional study, participants were recruited over a 17-month period from February 2020 to November 2021, when the clinic was open for elective consultations during the COVID-19 pandemic.

Participants

Patients with a diagnosis of primary glenohumeral OA evaluated by a fellowship-trained orthopaedic surgeon (GM) were recruited. Primary glenohumeral OA with an intact RC was diagnosed based on an examination and imaging findings. The surgeon (GM) classified glenoid deformities according to the Walsh classification (Bercik et al., 2016) for group allocation (eccentric or concentric). Patients with prior shoulder fracture, surgery, infection, or shoulder pain greater than a 6 of 10 at rest were excluded. Age-matched older adults without shoulder pain (< 1 of 10) were recruited as control participants from the surrounding local community and excluded if they previously sought care for shoulder pain. Potential participants with neurologic disease, systemic inflammatory conditions, shoulder pain with cervical spine motion, prior breast cancer treatment, and active cancer were excluded. Sixty-five percent (52 of 80) of patients with OA screened for eligiblity met study criteria. Of these, 63% (33 of 52) of patients with OA enrolled and completed informed consent. From a convenience sample of 21 older adults with no history of shoulder pain, 20 met eligibility criteria as control participants. Of the convenience sample, eighteen control participants enrolled and completed informed consent. Of the 50% (51 of 101) of patients with OA and control participants enrolled, 100% (51 of 51) completed strength testing, and based on eligiblity a subset of patients with OA, 18 of 33 underwent an MRI for the study.

Descriptive Data

In total, 51 participants were enrolled and allocated into the eccentric (n = 16), concentric (n = 17), and control groups (n = 18) (Table 3.1). All participants completed the Penn shoulder score (Leggin et al., 2006) and provided demographic information. There were no differences between groups on the basis of age, gender, BMI, or dominance of the side tested. Patients with eccentric (median 1.0 [IQR 3.0]) and concentric (2.0 [2.3]) deformities had higher resting pain than control participants (0.0 [0.0]; $p < 0.001$). Patients with eccentric (62 [23]) and concentric (67 [26]) deformities had lower total Penn shoulder scores than control participants (100 [4.2]; $p < 0.001$). The minimum clinically important difference for improvement for the Penn shoulder score is 11 points (Leggin et al., 2006), although after TSA, patients have demonstrated, on average, a 50-point improvement from pre- to postoperatively (Matsen et al., 2019).

Table 3.1. Participant demographics, pain, and disability

Characteristic	Concentric	Eccentric	Control	p value
Number of patients	17	16	18	
Age in years, median [IQR] [a]	70 [7.3]	69 [15]	68 [21]	0.81
Gender, n (% men)[b]	9.0 (53)	12 (75)	11 (61)	0.42
Hand dominance, n (% right)[b]	15 (88)	13 (81)	18 (100)	0.18
Side tested, n (% dominant)[b]	6.0 (35)	7.0 (44)	8.0 (44)	0.83
BMI in kg/m^2, median [IQR] [a]	27 [5.0]	31 [9.2]	26 [4.9]	0.11
Resting pain, median [IQR] [a]	2.0 [2.3]	1.0 [3.0]	0.0 [0.0]	< 0.001 Ecc v Conc: 0.86 Ecc v Cont: < 0.001 Conc v Cont: < 0.001
Total Penn shoulder score, median [IQR] [a]	67 [26]	62 [23]	100 [4.2]	< 0.001 Ecc v Conc: 0.71 Ecc v Cont: < 0.001 Conc v Cont: < 0.001
Pain subscore (0-30), median [IQR] [a]	24 [10]	22 [9.5]	30 [0]	< 0.001 Ecc v Conc: 0.66 Ecc v Cont: < 0.001 Conc v Cont: < 0.001
Satisfaction subscore (0-10), median [IQR][a]	3.0 [4.8]	3.0 [5.5]	10 [1.0]	< 0.001 Ecc v Conc: 0.85 Ecc v Cont: < 0.001 Conc v Cont: < 0.001
Function subscore (0-60), median [IQR][a]	43 [16]	39 [15]	60 [2]	< 0.001 Ecc v Conc: 0.73 Ecc v Cont: < 0.001 Conc v Cont: < 0.001

All comparisons were made across shoulders. [a]p values were calculated using a Kruskal-Wallis test between groups. [b]p values were calculated using a chi-squared test between groups. Ecc = eccentric. Conc = concentric. Cont = control. IQR = interquartile range.

Data Measurement

Strength

The tested arm was fitted with a fiberglass cast extending from the upper arm to the wrist in 90º of elbow flexion. The casted arm was attached to a 6°-of-freedom load cell (45E15A4, JR3) in 45º of shoulder elevation, 30º anterior to the coronal plane, and neutral rotation (Fig. 3.1). Force and torque measurements were made at the load cell and transformed to a glenohumeral coordinate system (Wu et al., 2005).

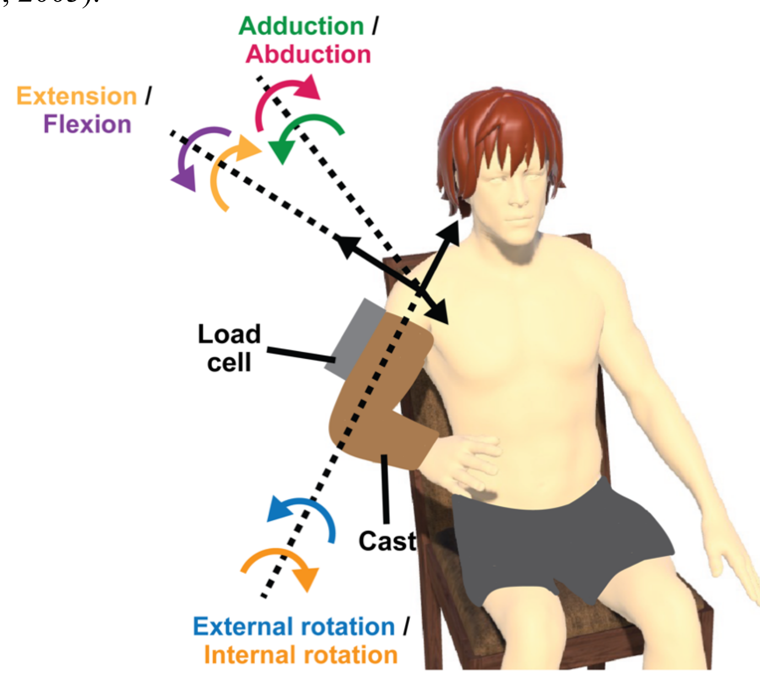

Figure 3.1. Experimental Setup
Participants performed maximal isometric contractions while their arm was attached to a 6°-of-freedom load cell via a premade fiberglass cast. Straps were used to secure the trunk, and scapular motion was not fixed. After submaximal practice trials, participants performed 3-second maximal isometric contractions in 26 equally spaced, randomly ordered directions with 30-second breaks between trials. Participants were guided by 3D visual feedback of the target torque direction, preventing off-axis torque generation. Target directions included 1°-of-freedom targets (flexion, adduction, or internal rotation independently), and combined 2°-of-freedom or 3°-of-freedom targets (extension, abduction, and external rotation simultaneously).

After submaximal practice trials, participants performed 3-second maximal isometric contractions in 26 equally spaced, randomly ordered directions with 30-second breaks between trials. Participants were guided by 3D visual feedback of the target torque direction, preventing off-axis torque generation. Target directions included 1°-of-freedom targets (flexion, adduction, or internal rotation independently), and combined 2°-of-freedom or 3°-of-freedom targets (extension, abduction, and external rotation simultaneously).

To evaluate for external rotation weakness, we quantified relative strength in opposing directions (strength balance). First, the maximum torque (Nm) achieved in each target direction was determined as described (Fig. 3.2A-B) (Baillargeon et al., 2022). Using a principal components analysis of the 26 maximal torques, we determined the magnitude (Nm) and direction of the three principal axes spanning the space of achieved 3D torques. The overall strength magnitude was computed as the Euclidian norm of the three principal axis magnitudes (Nm) (Fig. 3.2C), normalized by weight (Nm/kg). Strength balance was derived by computing the 3D center of the torque space as the vector mean of the 26 measures, normalized by strength magnitude (Fig. 3.2D). A strength balance (% of strength magnitude) at the origin suggests equivalent strength between internal and external rotation. A strength balance that shifts towards internal rotation (+ Y), adduction (+ X), or flexion (+ Z) suggests relative weakness in external rotation (- Y), abduction (- X), or extension (- Z).

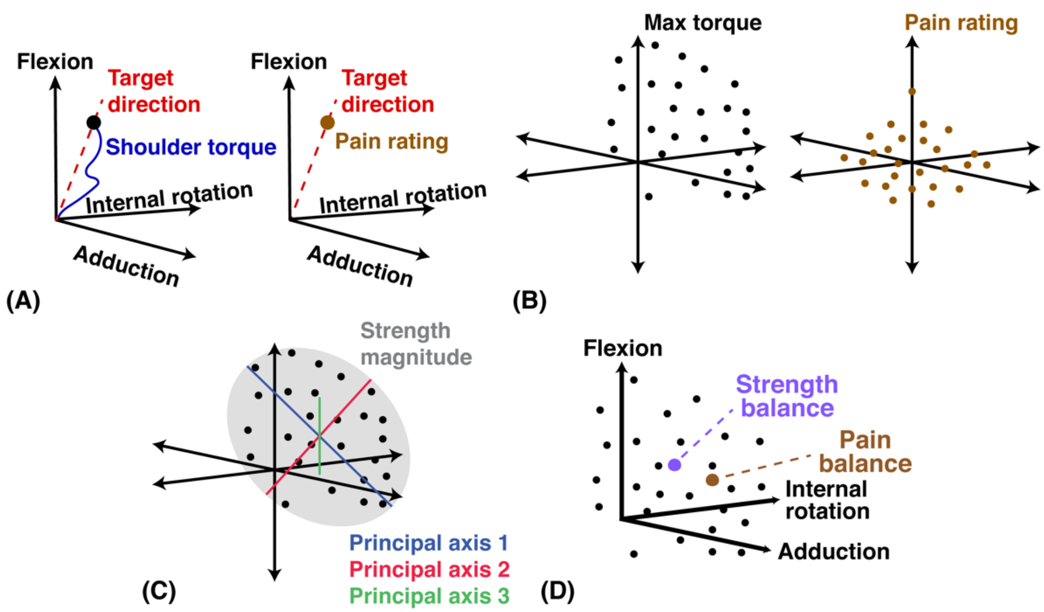

Figure 3.2. Derivation of strength balance

These graphs show the derivation of strength balance, including (A) torque trajectory from a single trial, demonstrating maximum torque achieved (black dot) along the target direction (red dotted line), along with the associated pain rating during torque generation (brown dot). (B) Illustrates the maximum torques achieved in all 26 directions and associated 3D pain ratings. (C) The overall strength magnitude was computed by performing a principal components analysis on the 26 maximal torques and taking the Euclidian norm of the three principal axis magnitudes normalized to weight. (D) Strength balance was computed by taking the vector mean of the 26 3D maximal torque vectors, then normalizing them by strength magnitude. Pain balance was computed by summing 3D pain ratings across all 26 directions.

Effects of Pain and Percentage of Fat

Patients with OA rated their resting pain before testing ("How bad is your pain today?") and during each strength trial using a verbal numeric scale 0 to 10. Pain ratings were plotted along the associated target direction to visualize pain throughout the 3D space (Fig. 3.2B). The mean of all 26 pain rating magnitudes was computed to determine the torque-dependent pain. Resting and torque-dependent pain elucidate if the eccentric group experiences more pain at baseline or when performing isometric contractions. Since pain can limit strength and could thus affect our results, we also examined its influence in two other ways. First, we evaluated if there was more or less pain in specific directions in the eccentric group. To do this, each patient's 3D pain ratings across all 26 directions were summed to determine pain balance (Fig. 3.2D). Pain balance at the origin indicates equal pain in all directions, whereas a shift towards external over internal rotation suggests greater pain with external rotation. If a patient rated their pain as a 10 of 10 for all 1°-, 2°-, and 3°-of-freedom targets involving a direction (such as internal rotation) and 0 of 10 for all targets involving the opposing direction (such as external rotation), the maximum possible pain balance value along the associated axis (such as Y) would be 61. Second, we tested if pain limited torque generation in some but not others on a patient-by-patient basis. To do this, we determined the overall average torque (normalized to strength magnitude) generated in each direction across patients with OA. The overall average torque was subtracted from the torque generated in each direction to determine the patient-specific relative torque in the 26 directions tested.

To characterize RC muscle degeneration, eligible patients with OA with concentric deformities (n = 11) and with eccentric deformities (n = 7) underwent MRI for the study. Patients with MRI-incompatible implants, claustrophobia, or body size prohibiting closed MRI were excluded. Sagittal oblique images were acquired with a 3D two-point Dixon fat-water imaging sequence to quantify intramuscular fat (Elliott et al., 2013; Fischer et al., 2014; Smith et al., 2014) using a 3T Siemens (Prisma, Siemens) MR scanner and a 16-channel phased array shoulder coil.

The cross-sectional area and intramuscular fat percentage (fat%) were quantified using Analyze software (Analyze 14.0, Analyze Direct). Manual segmentation was performed inside the anterior and posterior RC fascial borders at the characteristic Y-view (Lehtinen et al., 2003) after reorientation to the scapular plane (Chalmers et al., 2017). The infraspinatus and teres minor muscles were combined, representing the posterior RC (Tingart et al., 2003). Quantification of cross-sectional area and fat% at the Y-view has been validated with muscle volume (Lehtinen et al., 2003), regional distribution of RC intramuscular fat (Hansen et al., 2021), and clinical assessments of intramuscular fat (Fuchs et al., 1999; Goutallier et al., 1994; Miller et al., 2014). The fat% for each muscle was computed by dividing the fat signal intensity by the fat plus water signal intensities and multiplying by 100. Muscle cross-sectional areas were corrected for fat% (fat-adjusted muscle cross-sectional area) by subtracting the fat% cross-sectional area (original muscle cross-sectional area*fat%). The posterior-to-anterior RC fat% ratio was computed by dividing the fat% of the infraspinatus and teres minor by that of the subscapularis. Additionally, the fat-adjusted cross-sectional area ratio was computed by dividing the fat-adjusted cross-sectional area of the infraspinatus and teres minor by that of the subscapularis.

Study Size

Based on pilot data, an a-priori power analysis revealed 12 participants would be required per group to detect differences in 3D strength between groups, with an anticipated effect size of 0.97 and 80% power.

Bias

We strove to recruit equal numbers of age-matched men and women in each group, as evidenced by the lack of a difference between groups on the basis of gender or age. Our analyses of strength incorporated gender, age, and dominance of the side tested as confounding factors, thus removing additional variability resulting from these parameters. Ratios were used when evaluating RC muscle cross-sectional area and fat percentages, allowing for comparison across men and women.

Primary and Secondary Study Outcomes

Our primary study goal was to determine if patients with eccentric compared with concentric deformities demonstrate relative external rotation weakness. To achieve this, we measured relative shoulder strength in opposing directions (strength balance) as participants performed maximal isometric contractions in 26 distinct directions.

Our secondary study goals were to determine if patients with eccentric deformities exhibit higher resting pain, torque-dependent pain, or posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities. To achieve this, patients rated their shoulder resting pain and pain during each isometric contraction (torque-dependent pain). Additionally, we quantified the posterior-to anterior RC fat percent ratios from MR images.

Ethical Approval

This study was approved by our institutional review board. Participants gave written informed consent for participation.

Statistical Analysis

To test our primary hypothesis that patients with eccentric deformities demonstrate relative external rotation weakness compared to patients with concentric deformities, we used a multivariable regression. We modeled 3D strength balance as dependent on group and confounding demographic effects of age, gender, and dominance of the side tested. We used a Hotelling t-square statistic to test for group differences. Although not our primary study goal, we additionally tested for between-group (independent variable) differences in strength magnitude (dependent variable) using a univariate linear model. Independent factors included age, gender, and dominance of the side tested.

Secondarily, we evaluated for the effects of pain and fat% on strength results. To determine if patients with eccentric deformities exhibited more pain, we compared the resting and torque-dependent pain ratings between groups using Kruskal-Wallis tests. To determine if patients with eccentric deformities had higher posterior-to anterior RC fat percent ratios, we compared these ratios between patients with eccentric and concentric deformities using Kruskal-Wallis tests.

Although not our secondary study goals, we performed additional analyses on pain and RC cross-sectional areas. To determine if there were direction-specific differences in pain between groups, we tested for differences in the X, Y, and Z components of pain balance one at a time using three separate Kruskal-Wallis tests. We used a linear mixed-effects model to determine whether the patient-specific relative torque (dependent variable) was related to the patient's pain rating in all directions (independent variable). Finally, Kruskal-Wallis tests were used to determine whether there were differences in the fat-adjusted cross-sectional area ratios between patients with eccentric deformities and those with concentric deformities.

For all tests, a significance level of $\alpha = 0.05$ was used. Bonferroni corrections were used to account for multiple comparisons.

Results

Differences in External Rotation Strength Between Eccentric and Concentric Deformities

There was no relative external rotation weakness in patients with eccentric deformities (Y component of 3D strength balance, mean ± SD: -4.7% ± 5.1%) compared with patients with concentric deformities (-0.05% ± 4.5%, mean difference -4.7% [95% confidence interval -7.5% to -1.9%]; p = 0.05) (Fig. 3.3). However, patients with eccentric and concentric deformities demonstrated relative strength in external rotation compared with control participants (Table 3.2).

Table 3.2. Three-dimensional strength balance

	Control (n = 18)		Concentric (n = 17)				Eccentric (n = 16)			
	Mean ± SD	95% CI volume, $\%^3$	Mean ± SD	95% CI volume, $\%^3$	Mean difference from control (95% CI)	p value	Mean ± SD	95% CI volume, $\%^3$	Mean difference from control (95% CI)	p value
X (Add-Abd)	-0.50% ± 2.4%		-3.5% ± 4.6%		-3.0 (-5.1 to -0.90)		-1.8% ± 7.1%		-1.3 (-4.4 to 1.8)	
Y (IR-ER)	2.9% ± 4.0%	129	-0.05% ± 4.5%	579	-2.9 (-5.3 to -0.45)	0.005	-4.7% ± 5.1%	893	-7.6 (-10 to -5.0)	<0.001
Z (Flex-Ext)	3.0% ± 3.2%		1.9% ± 6.3%		-1.1 (-4.0 to 1.8)		3.5% ± 4.6%		0.54 (-1.7 to 2.8)	

All values are reported as the mean ± standard deviation (SD). All p values were calculated using the Hotelling's t-square statistic.

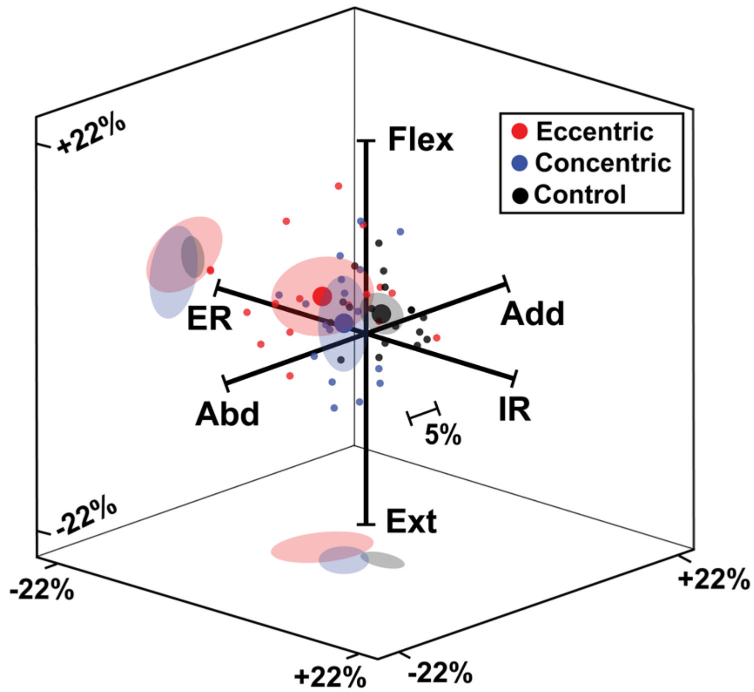

Figure 3.3. Strength balance across groups
This graph shows a 3D view of strength balance for all participants (smaller dots) as well as group means (larger dots), with shaded ellipses representing 95% CIs for the group means. Two-dimensional projections (XY and XZ) of 95% CIs are included. Add/Abd = adduction/abduction; IR/ER = internal/external rotation; Flex/Ext = flexion/extension.

There was more variability in 3D strength balance in the eccentric group (95% CI volume, $\%^3$: 893) than in the concentric group (95% CI volume, $\%^3$: 579) and control group (95% CI volume, $\%^3$: 129). Weight-normalized strength magnitude, a measure of overall strength, was no different between patients with eccentric (0.22 ± 0.11 Nm/kg) and concentric deformities (0.25 ± 0.10 Nm/kg, mean difference -0.04 [95% CI -0.10 to 0.02]; p = 0.32) (Fig. 3.4). Strength magnitude was 35% (0.12 of 0.33) lower in patients with eccentric deformities (0.22 ± 0.11 Nm/kg) compared with control participants (0.33 ± 0.10 Nm/kg, mean difference -0.12 [95% CI -0.18 to -0.06]; p = 0.002). Strength magnitude was no different between patients with concentric deformities (0.25 ± 0.10 Nm/kg) and control participants (0.33 ± 0.10 Nm/kg, mean difference -0.08 [95% CI -0.14 to -0.02]; p = 0.03).

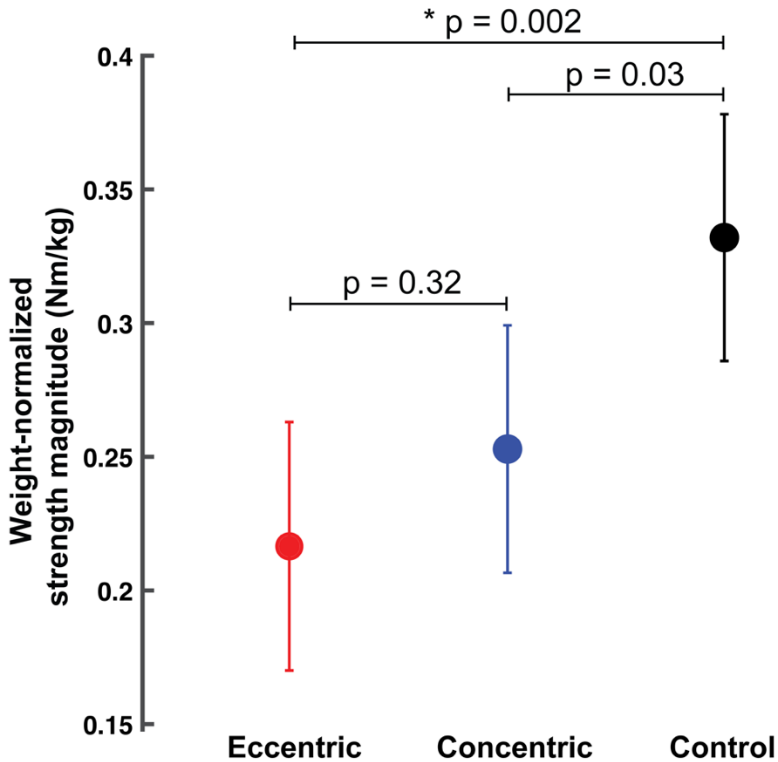

Figure 3.4. Strength magnitude across groups
This graph shows the mean (95% CI) weight-normalized strength magnitude by group.

Resting and Torque-dependent Pain

There was no difference between the eccentric and concentric deformity groups in median (interquartile range) resting pain (1.0 [3.0] versus 2.0 [2.3], mean rank difference 4.5 [95% CI -6.6 to 16]; p = 0.61) or torque-dependent pain (0.70 [3.0] versus 0.58 [1.5], mean rank difference 2.6 [95% CI -8.8 to 14]; p = 0.86). The X, Y, and Z components of pain balance also did not differ between deformity groups (X: -1.4 [4.0] versus -0.15 [2.6], mean rank difference -1.6 [95% CI -8.1 to 5.0]; p = 0.64; Y: 0.0 [1.9] versus 0.0 [1.7], mean rank difference 3.2 [95% CI -3.4 to 9.7]; p = 0.35; Z: 0.0 [2.3] versus 0.0 [1.4], mean rank difference -0.06 [95% CI -6.6 to 6.4]; p = 0.99) (Fig. 3.5), suggesting no direction-specific pain differences. Finally, there was no relationship between pain rating and patient-specific relative torque ($r^2 = 0.001$; $p = 0.29$) in patients with OA who experienced pain with testing (79%; 26 of 33 patients).

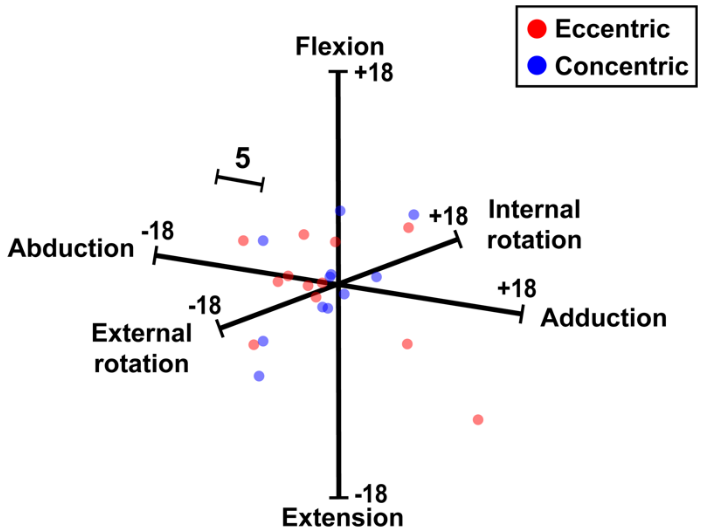

Figure 3.5. Pain balance in patients with OA
This graph shows pain balance in each patient with OA.

Shoulder Bony Morphology and Posterior-to-anterior RC Fat Ratios

In the subgroup of patients with MRI, the seven patients with eccentric deformities demonstrated a higher posterior-to-anterior RC fat% ratio than the 11 patients with concentric deformities (1.2 [0.8] versus 0.7 [0.3], mean rank difference 6.4 [95% CI 1.4 to 11]; p = 0.01) (Table 3.3). There was no difference in the fat-adjusted posterior-to-anterior RC cross-sectional area ratio between eccentric and concentric deformity groups (0.7 [0.4] versus 0.8 [0.1], mean rank difference -0.82 [95% CI -5.9 to 4.2]; p = 0.75). A subgroup of patients with eccentric deformities (57% [4 of 7] of patients) demonstrated a fat-adjusted posterior-to-anterior RC cross-sectional area ratio at least 20% lower than the median in patients with concentric deformities.

Table 3.3. Posterior-to-anterior rotator cuff intramuscular fat percentage and cross-sectional area ratios

	Concentric			Eccentric			Difference in mean rank (95% CI)	p value
	IFTM	SC	Ratio	IFTM	SC	Ratio	Ratio	Ratio
Percentage of fat	4.83 (2.97)	7.00 (5.3)	0.70 (0.30)	10.2 (11.3)	7.82 (3.46)	1.22 (0.83)	6.43 (1.37 to 11.5)	0.01
NFA cross-sectional area in mm^2	1520 (655)	1870 (713)	0.80 (0.11)	1660 (510)	1900 (713)	0.75 (0.38)	0.12 (-4.94 to 5.18)	0.96
FA cross-sectional area in mm^2	1330 (630)	1670 (739)	0.82 (0.09)	1430 (455)	1750 (729)	0.65 (0.38)	-0.82 (-5.88 to 4.24)	0.75

All values are reported as the median (IQR); all p values were calculated between groups using a Kruskal-Wallis test; IFTM = infraspinatus and teres minor; SC = subscapularis; NFA = nonfat-adjusted; FA = fat-adjusted.

Discussion

It is unknown what leads to eccentric deformity development and why anatomic TSAs in these patients exhibit higher failure rates (Denard & Walch, 2013; Kiet et al., 2015; Walch et al., 2012), despite surgical advances (Luedke et al., 2018; Sears et al., 2012). Clinical theory suggests persistent disruption of the posterior-to-anterior RC force couple that results from posterior RC intramuscular degeneration (Domos et al., 2018; Donohue et al., 2018), which impairs external rotation strength (Nakamura et al., 2017; Yoon et al., 2018), may contribute to eventual TSA failure. Rehabilitation after TSA that does not correct preexisting external rotation weakness will be of minimal benefit as persistent weakness may promote failure. Identification of external rotation weakness in patients with eccentric deformities may elucidate mechanisms contributing to bony deformity development and TSA failure, allowing for treatment modification with targeted strengthening. Interestingly, we found no weakness in external rotation relative to internal rotation in patients with eccentric deformities compared with patients with concentric deformities. However, patients with eccentric deformities demonstrated higher strength variability, which suggests there may be potential subtypes of eccentric wear patterns (posterior-superior, posterior-central, and posterior-inferior) and patients with these subtypes may compensate differently for underlying anatomic changes by adopting unique kinematic or muscle activation patterns. These findings highlight the importance of careful clinical evaluation in patients presenting with eccentric deformities as some may exhibit potentially detrimental strength deficits. Recognition of such deficits may allow for targeted rehabilitation.

Limitations

Our study has limitations. Our study was based on theorized force couple disruption between the anterior and posterior RC muscles (Donohue et al., 2018); however, consistent with other studies (Andrews et al., 1996; Lapner et al., 2015; Sperling et al., 2008), larger primary shoulder movers and compensatory scapulothoracic motion may contribute to strength, given the lack of scapular stabilization. Strength as measured in the current study is consistent with clinical measures of external and internal rotation strength, as patients use both RC muscles and primary shoulder movers; however, results may differ if 3D strength is assessed in positions targeting specific RC muscles (Kelly et al., 1996). Additionally, we were only able to assess strength in a single posture in the current study. As muscle moment arms change with posture (Ackland et al., 2008), the current findings, which provide useful information about strength in the posture selected, cannot be generalized to other postures. However, the posture selected is one all patients with OA could achieve and is used with common daily activities.

More variability than anticipated was observed in patients with OA. A post-hoc power analysis revealed we were underpowered (required n = 22) given this variability, which may contribute to our finding of no relative external rotation weakness in patients with eccentric deformities. Despite our finding of no difference, these results are the first to characterize strength in 3D in patients with OA with eccentric and concentric deformities and address an unanswered question regarding potential force couple disruption in patients with eccentric deformities. Additionally, our results identify an important difference between deformity groups: the amount of variability in 3D strength. The observed variability was unexpected but may be explained by the existence of distinct eccentric deformity subtypes, which was beyond the scope of the current study. Although not one of our study purposes, it will be important in the future to examine how 3D strength may differ across eccentric deformity subtypes in a larger group of patients.

Our focus was characterizing strength in patients with primary glenohumeral OA, and thus our results are not generalizable to patients with glenohumeral OA secondary to rheumatologic disorders. It will be important to explore how strength compares between patients with eccentric deformities and patients with concentric deformities because these diagnoses are risk factors for postoperative complications (Aibinder et al., 2021). The current study examined maximal isometric strength in 26 distinct directions to evaluate for relative external rotation weakness. Future work to determine if endurance or fatigue are factors related to potential force couple disruption may be beneficial.

With regard to our secondary study goals, MRIs were only collected in a subset of patients, limiting the information we have on RC fat infiltration to this subset. Despite the small sample size, the differences observed between deformity groups in the amount of fat in the posterior relative to the anterior RC agree with existing evidence (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). Additionally, we examined all primary and secondary study outcome metrics in the subsets of patients with and without MRIs in each deformity group and confirmed the subsets were representative samples. As it was not possible to obtain advanced imaging in all participants, we were not able to reliably classify deformity severity within the eccentric and concentric groups and thus could not specifically evaluate how deformity severity (such as the degree of retroversion) may influence our measures. Our results are still representative of these overall populations and are the first to evaluate the influence of pain on observed strength in patients with OA; however, further work evaluating how strength may vary with deformity severity would be beneficial.

Differences in External Rotation Strength Between Eccentric and Concentric Deformities

Our findings suggest that there is no relative external rotation weakness in patients with eccentric deformities compared with patients with concentric deformities. In our study, strength balance may not have differed between deformity groups because there was unexpectedly higher variability in the eccentric group than in the concentric group. Greater variation in strength balance in patients with eccentric deformities may be owing to alterations in joint kinematic (Bruttel et al., 2020; Fayad et al., 2008) or muscle activation patterns adopted to compensate for underlying anatomic changes in the setting of a deformity. Higher variability in strength balance may also be attributed to patients with existing subtypes of eccentric glenoid wear patterns (posterior-superior, posterior-central, and posterior-inferior (Otto et al., 2021)) compensating differently and may potentially explain why TSA failure rates are technique-dependent (Luedke et al., 2018). Further, the increased variability suggests the utility of a more individualized approach to surgical and postoperative management in patients with eccentric deformities. In addition to greater variability, we found greater strength in external relative to internal rotation in both OA groups, contrary to a prior study demonstrating greater strength in internal relative to external rotation in patients with OA (Sperling et al., 2008). Our findings may differ because our 3D methods prevent off-axis torque generation. In contrast, the prior study used a one-dimensional (1D) hand-held dynamometer, which allows participants to maximize torque in the measurement direction by generating off-axis torques (Pan et al., 2005). Measurements from a 1D method could be less sensitive than those from a 3D method to detect weakness in the direction of interest (Baillargeon et al., 2022). Devising accurate and efficient methods to quantify strength in 3D for clinical use may be of great benefit.

Resting and Torque-dependent Pain

Our findings suggest there was no difference in the pain experienced by patients with eccentric deformities and the pain experienced by those with concentric deformities, and that pain did not influence measures of strength balance. Given these findings, it is unlikely that pain concealed underlying strength differences between the groups. Analysis of this confounder is important as pain has been shown to decrease RC muscle force production and voluntary muscle activation (Stackhouse et al., 2013). Although the pain experienced did not differ between deformity groups, future work exploring the implications of pain on muscle activation in both deformity groups is warranted as differences in muscle activation may influence measured strength.

Shoulder Bony Morphology and Posterior-to-anterior RC Fat Ratios

Our results show the posterior-to-anterior RC fat% ratio was higher in patients with eccentric deformities than in patients with concentric deformities, in agreement with prior studies showing greater posterior RC intramuscular fat in patients with eccentric deformities (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). Our quantitative methods show that the median fat% in the posterior RC in patients with eccentric deformities (10.2%) fell within the range identified for Goutallier Grade 2 fatty degeneration (6.44% to 14.86%), whereas that in patients with concentric deformities (4.83%) fell within the range for

Goutallier Grade 1 (1.1% to 9.70%) (Nardo et al., 2014). Our results also agree with prior work showing no difference in the volume ratio (nonfat-adjusted) of the posterior-to-anterior RC between patients with eccentric deformities and those with concentric deformities (Arenas-Miquelez et al., 2021). Although not previously reported, we found that the relative remaining muscle, represented by the posterior-to-anterior RC fat-adjusted cross-sectional area ratio, did not differ between groups.

The lack of a between-group difference in the posterior-to-anterior RC fat-adjusted cross-sectional area ratio may be attributed to high variability in the eccentric group. In the subgroup of patients with eccentric deformities demonstrating a posterior-to-anterior RC fat-adjusted cross-sectional area ratio at least 20% lower than the median in patients with concentric deformities, posterior RC weakness may exist. This weakness may be compensated by the surrounding shoulder musculature through scapulothoracic motion and the remaining posterior RC muscle. Such compensation may have prevented our robust 3D methods from detecting a difference in strength balance. Any underlying RC strength imbalance that is offset through compensation by larger surrounding shoulder muscles may be a concern for TSA failure.

Conclusion

Patients with eccentric deformities demonstrated no relative external to internal rotation weakness compared with patients with concentric deformities, but they exhibited greater variability in strength measured with 3D methods. More intramuscular fat was found in the posterior RC in patients with eccentric compared with concentric deformities, as reported previously (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). The size of the posterior relative to the anterior RC, after adjusting for intramuscular fat, did not differ between deformity groups. The increased variability in patients with eccentric deformities suggests patients with potential subtypes of eccentric wear patterns may compensate differently for underlying bony changes. Overall, this variability highlights the potential importance of a more individualized approach to surgical and postoperative management in these patients. Future work should use motion tracking and electromyography to explore increased variability in patients with eccentric deformities and potential forms of kinematic or muscular compensation to determine whether these factors play a role in TSA failure. Although we did not observe differences preoperatively, it will be important to evaluate whether strength differences exist between patients with eccentric deformities and those with concentric deformities who have undergone TSA.

Chapter 4: External rotation strength is not diminished despite reduced infraspinatus activity in eccentric glenohumeral osteoarthritis

Margaret S. Coats-Thomas[1-3]; Daniel Ludvig, PhD[1,2]; Guido Marra, MD[4]; Ankur Garg, MD[5]; Eric J. Perreault, PhD[1,2,6]; Amee L. Seitz, DPT, PhD[3,7]

[1]Biomedical Engineering, Northwestern University, Evanston IL 60208, USA
[2]Shirley Ryan AbilityLab, Chicago IL 60611, USA
[3]Feinberg School of Medicine, Northwestern University, Chicago IL 60611, USA
[4]Orthopaedic Surgery, Northwestern University, Chicago IL 60611, USA
[5]Radiology, Northwestern University, Chicago IL 60611, USA
[6]Physical Medicine & Rehabilitation, Northwestern University, Chicago IL 60611, USA
[7]Physical Therapy & Human Movement Sciences, Northwestern University, Chicago IL 60611, USA

This work was supported by the National Institutes of Arthritis and Musculoskeletal and Skin Diseases (NIAMS, F31AR077426), the American Society of Biomechanics, the Department of Physical Therapy and Human Movement Sciences at Northwestern University, and the Department of Orthopaedic Surgery at Northwestern University. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We would like to acknowledge Matthew Saltzman, MD, for his assistance with patient recruitment, Constantine P. Nicolozakes, PhD, for his assistance with study design, and Timothy Haswell, MS, for his technical assistance during data collection.

Abstract

Background

Anatomic total shoulder arthroplasty (TSA) is a treatment option for patients with persistent end-stage glenohumeral osteoarthritis (OA) symptoms despite conservative management. Higher TSA revision rates have been observed in patients with eccentric (asymmetric glenoid erosion) compared to concentric (symmetric erosion) deformities. Posterior relative to anterior rotator cuff (RC) deficiency, which would manifest as relative external rotation weakness (as compared to internal rotation), is theorized to contribute to TSA failures in the eccentric group. However, strength has not been compared between deformity groups after TSA and the potential impact of dysfunctional muscle activity on strength has not been considered. Our goal was to determine if patients with eccentric compared to concentric deformities exhibit relative external rotation weakness or changes in muscle activity of shoulder rotators.

Methods

This cross-sectional, prospective study was conducted on patients with primary glenohumeral OA with eccentric and concentric deformities at least 1 year after TSA. To get sensitive strength measures, participants generated maximal isometric contractions in 26 directions within the three-dimensional space surrounding the shoulder. Strength in opposing directions (strength balance) was computed to compare relative external to internal rotation strength between deformity groups. During maximal contractions, electromyography were recorded from the anterior and posterior deltoids, pectoralis major, latissimus dorsi, teres major, and infraspinatus. Muscle activity of internal and external rotators was compared across direction combinations

involving internal and external rotation, respectively, to determine if activity differed in the eccentric group.

Results

Patients with eccentric deformities (internal(+)/external(-) rotation component of strength balance, mean±SD: -7.6±7.4%) did not demonstrate relative external to internal rotation weakness compared to patients with concentric deformities (-10±6.8%, mean difference 2.7% [95% CI -1.3% to 6.7%] ; p = 0.59). Muscle activity of the infraspinatus was reduced in patients with eccentric (44±22%MVC) compared to concentric (51±19%MVC) deformities (-7.4%MVC [-12%MVC to -2.7%MVC] ; p = 0.002).

Conclusions

Relative external rotation strength does not differ by deformity type despite reduced activity of a primary external rotator in patients with eccentric deformities. Reduced infraspinatus muscle activity in the eccentric group may suggest a muscle activity-based posterior RC deficiency.

Clinical Relevance

Our findings may be used to inform post-operative rehabilitation for patients following TSA. Biofeedback training to increase infraspinatus muscle activity in patients with eccentric deformities may help correct underlying muscle activity deficits and ultimately prevent TSA failure. Further, our results suggest preserved external rotation strength is possible in patients with eccentric deformities, but the exact mechanism by which this occurs remains to be seen.

Introduction

Anatomic total shoulder arthroplasty (TSA) is a viable treatment option when pain and functional limitations persist despite conservative management in patients with end-stage glenohumeral osteoarthritis (OA). TSA outcomes vary based on the type of glenoid deformity. Patients with concentric deformities (Walch Type A1/A2) exhibit symmetric bony wear about the glenoid center, as described by Walch, while patients with eccentric deformities demonstrate asymmetric wear (Walch Type B1/B2/B3) (Bercik et al., 2016). In patients with eccentric deformities, TSAs require revision at higher rates than overall TSAs (Kiet et al., 2015; Walch et al., 2012). Disruption of the transverse force couple with weakness in the posterior (infraspinatus & teres minor) relative to the anterior (subscapularis) rotator cuff (RC) muscles is theorized to contribute to eccentric deformity development and surgical outcomes (Domos et al., 2018; Donohue et al., 2018). This theory is supported by studies demonstrating greater posterior RC intramuscular fat in patients with eccentric deformities (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018), which would impair external rotation strength (Nakamura et al., 2017; Yoon et al., 2018). Persistent weakness in external relative to internal rotation may alter load transmission across the glenoid (Parsons et al., 2002) and ultimately lead to glenoid component loosening and TSA failure (Collins et al., 1992; Walch et al., 1999).

Despite the importance of understanding relative external rotation strength (as compared to internal rotation) following TSA, the evidence on this topic is currently limited. Existing studies in patients who have undergone TSA have focused on strength recovery of the subscapularis muscle, an internal rotator. In patients who had a TSA with unknown deformity types, subscapularis strength improved post-operatively but remained inferior to the contralateral shoulder (Baumgarten et al., 2018; Lapner et al., 2015). Similarly, post-operative subscapularis strength was found to improve compared to pre-operative levels but did not reach normative values (Sperling et al., 2008).

While these studies have advanced our knowledge of strength recovery after TSA, there are a few important limitations. First, one-dimensional (1D) hand-held dynamometers (Baumgarten et al., 2018; Lapner et al., 2015; Sperling et al., 2008) have been used to evaluate shoulder rotational strength following TSA; however, these tools may overestimate strength as they allow patients to maximize torque in the direction of interest (e.g. internal rotation) by generating off-axis torques (e.g. adduction) (Pan et al., 2005). Further, 1D dynamometers cannot parse out the specific contribution of internal or external rotation to functional, combined motions, such as abduction with external rotation. Additionally, while existing studies have not measured muscle activity, it is crucial to consider the possible impact of muscle dysfunction on strength as chronic RC de-and reinnervation changes have been reported in patients after TSA (Armstrong et al., 2016). Most importantly, existing studies have yet to compare strength between deformity types; thus, it remains unknown whether patients with eccentric compared to concentric deformities exhibit relative external rotation weakness following TSA.

Therefore, the primary goal of this study was to determine whether patients with eccentric compared to concentric deformities demonstrate relative external rotation weakness. Additionally, we evaluated whether patients with eccentric compared to concentric deformities exhibit changes in muscle activity of internal or external rotators after TSA. To overcome prior study limitations, we used three-dimensional (3D) strength measurement methods that limit off-axis torque generation and, thus, may be more sensitive to detect external rotation weakness than 1D methods

(Baillargeon et al., 2022). Additionally, we recorded muscle activity during strength testing so we could elucidate whether dysfunctional muscle activity contributes to strength deficits. If relative external rotation weakness is a factor contributing to TSA failure, greater emphasis of post-operative rehabilitation on strengthening deficient muscles or use of biofeedback training may be necessary.

Materials and Methods

Patient Recruitment

The Northwestern University institutional review board approved this study. Prior to completion of any study procedures, participants provided written informed consent. For this prospective, cross-sectional study, participants were recruited over a 4-month period from November 2021 to March 2022. Patients with primary glenohumeral OA at least one year status post anatomic TSA by one of two fellowship-trained orthopaedic surgeons were recruited. Patient pre-operative glenoid deformities were classified by the treating surgeon based on the Walch classification (Walch et al., 1999) for group assignment (eccentric or concentric). Equal numbers of patients in each deformity group were recruited from each surgeon. Exclusion criteria for patients following TSA included additional shoulder surgery before or after the TSA, prior shoulder fracture/infection, or shoulder pain at rest >6/10. A group of control participants consisting of age-matched older adults without shoulder pain (<1/10) was recruited from the community. Control participants were excluded if they previously sought care for shoulder pain. Additional exclusion criteria applied to all groups included neurological disease, systemic inflammatory conditions, shoulder pain with cervical spine motion, prior breast cancer treatment, or active cancer. All enrolled participants underwent ultrasound screening and those with complete full-thickness subscapularis or supraspinatus tendon tears were excluded. A musculoskeletal radiologist read all ultrasound images. Forty-seven out of 105 patients treated with TSA screened for eligibility met study criteria. Thirty-six enrolled and completed informed consent. Twenty out of 21 older adults without shoulder pain screened for eligibility met study criteria. Eighteen agreed to participate and gave informed consent.

Patient Characteristics

A total of 54 participants were enrolled and assigned to the eccentric (n = 18), concentric (n = 18), and control (n = 18) groups (Table 4.1). Participants answered demographic questions and completed the Penn shoulder score (Leggin et al., 2006). Groups did not differ on the basis of age, gender, dominance of the side tested, or length of follow-up in patients following TSA. BMI was higher in the concentric group compared to control participants (Table 4.1). The Penn satisfaction subscore did not differ between groups, though the pain and function subscores and total scores were lower in patients following TSA compared to control participants (Table 4.1). There were no differences in any components of the Penn score between the eccentric and concentric groups. Additionally, the differences between patients following TSA and control participants did not exceed the minimum clinically important difference for improvement for the Penn shoulder score (11 points) (Leggin et al., 2006).

Table 4.1. Participant demographics, pain, and disability

Characteristic	Concentric	Eccentric	Control	Chi-square statistic[a] or Mean difference (95% CI)[b]	p value
Number of participants/ patients	18	18	18		
Age in years, mean [SD][b]	68 [6.9]	70 [8.1]	64 [14]	Ecc v Conc: 2.4 (-5.7, 10) Ecc v Cont: 6.2 (-1.9, 14) Conc v Cont: 3.7 (-4.3, 12)	0.19
Gender, n (% men)[a]	10 (56)	11 (61)	12 (67)	0.47	0.79
Hand dominance, n (% right)[a]	16 (89)	16 (89)	18 (100)	2.2	0.34
Side tested, n (% dominant)[a]	12 (67)	7.0 (39)	8.0 (44)	3.1	0.21
Follow-up in months, mean [SD][b]	36 [25]	48 [32]	NA	Ecc v Conc: -12 (-32, 7.0)	0.20
BMI in kg/m^2, mean [SD][b]	31 [4.5]	30 [6.3]	26 [5.2]	Ecc v Conc: -1.8 (-6.1, 2.6) Ecc v Cont: 3.2 (-1.1, 7.6) Conc v Cont: 5.0 (0.67, 9.3)	0.02 Ecc v Conc: 0.58 Ecc v Cont: 0.18 Conc v Cont: 0.02
Total Penn shoulder score, mean [SD][b]	89 [13]	89 [9.1]	98 [2.4]	Ecc v Conc: 0.60 (-6.7, 7.9) Ecc v Cont: -8.8 (-16, -1.4) Conc v Cont: -9.4 (-17, -2.0)	<0.01 Ecc v Conc: 0.98 Ecc v Cont: 0.02 Conc v Cont: 0.01
Pain subscore (0-30), mean [SD][b]	28 [2.3]	28 [2.3]	30 [0.84]	Ecc v Conc: -0.06 (-1.6, 1.5) Ecc v Cont: -1.7 (-3.2, -0.10) Conc v Cont: -1.6 (-3.2, -0.05)	0.02 Ecc v Conc: 0.99 Ecc v Cont: 0.03 Conc v Cont: 0.04
Satisfaction subscore (0-10), mean [SD][b]	8.9 [1.6]	8.9 [1.7]	9.4 [0.92]	Ecc v Conc: 0.03 (-1.2, 1.2) Ecc v Cont: -0.44 (-1.6, 0.74) Conc v Cont: -0.47 (-1.7, 0.71)	0.56
Function subscore (0-60), mean [SD][b]	52 [9.3]	52 [5.8]	59 [2.3]	Ecc v Conc: 0.63 (-4.5, 5.8) Ecc v Cont: -6.7 (-12, -1.5) Conc v Cont: -7.3 (-12, -2.1)	<0.01 Ecc v Conc: 0.95 Ecc v Cont: 0.01 Conc v Cont: <0.01

All comparisons were made across shoulders. [a]p values were calculated using a chi-squared test between groups. [b]p values were calculated using a one-way analysis of variance between groups. Ecc = eccentric. Conc = concentric. Cont = control. SD = standard deviation.

Data Measurement

Three-Dimensional Strength

To complete strength testing, each participant's arm was first fit with a pre-made fiberglass cast running from the upper arm to the wrist, with the elbow in 90º flexion. Via the cast, the arm was fixed to a six degree-of-freedom load cell (45E15A4, JR3, Woodland, CA, USA). The arm was positioned at 45º of scapular plane elevation and neutral rotation (Fig. 4.1). Torque and force measurements made within the load cell's local coordinate system were transformed to a glenohumeral joint coordinate system (Wu et al., 2005) to determine torque specifically in shoulder adduction/abduction, internal/external rotation, and flexion/extension.

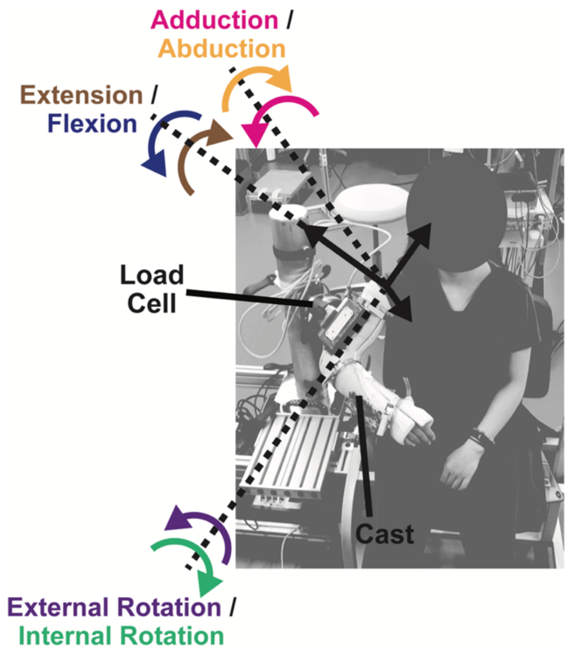

Figure 4.1. Experimental setup
Participants were seated with their trunk secured by straps while they performed maximal isometric contractions. The arm was fixed to a six degree-of-freedom load cell via a pre-made fiberglass cast.

All participants first performed submaximal practice trials to gain familiarity with the visual feedback provided, which prevented participants from generating off-axis torques. After practicing, participants performed 3-second maximal isometric contractions across 26 equally spaced directions spanning the 3D space surrounding the shoulder. The direction order was randomized for each participant, and rest breaks lasting at least 30 seconds were provided between trials. The directions tested encompassed 1D targets (e.g. external rotation individually), as well as combined 2D or 3D targets (e.g. flexion, adduction, and internal rotation concurrently). Strength measurements in all 26 directions were needed for normalization to each patient's overall strength and to compute relative strength in opposing directions.

To evaluate for relative external rotation weakness, we quantified relative strength in opposing directions (strength balance) across all 26 directions tested. Prior to further analysis, a 1-second moving average filter was applied to the torque data. For each of the 26 target directions tested, the maximum torque achieved in the prescribed target direction was identified (Fig. 4.2A-B) (Baillargeon et al., 2022). A principal components analysis of the 26 maxima yielded the three principal axes defining the 3D space of achievable torques. The Euclidian norm of the three principal axis magnitudes represented the overall strength magnitude, which was then normalized to weight (Nm/kg) (Fig. 4.2C). To derive strength balance, we determined the 3D center of the torque space by calculating the vector mean of the 26 maximal torques normalized by strength magnitude (% of unnormalized strength magnitude, % SM) (Fig. 4.2D). Strength balance located at the origin represents equal strength in all opposing directions. Strength balance favoring abduction (-X), external rotation (-Y), or extension (-Z) suggests relative weakness in adduction (+X), internal rotation (+Y), or flexion (+Z), respectively. If strength balance does not significantly differ between groups, this suggests no relative weakness along the adduction/abduction, internal/external rotation, or flexion/extension axis.

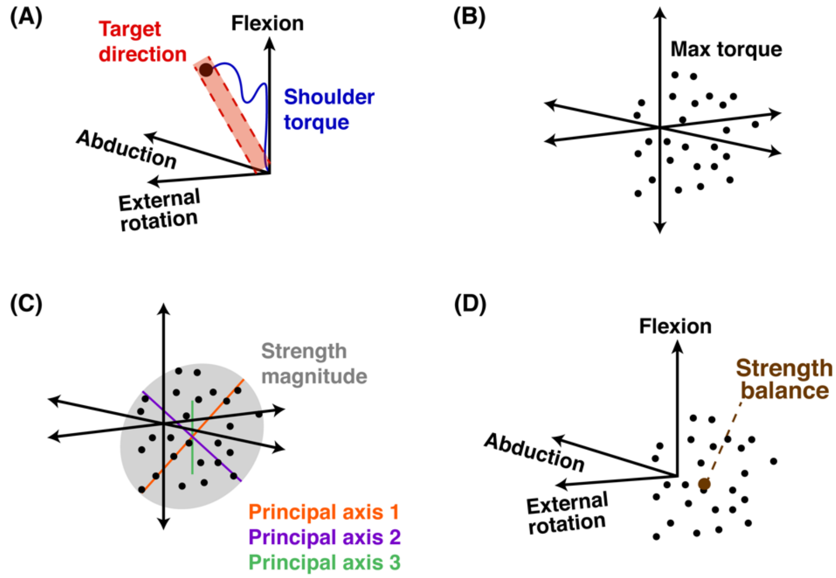

Figure 4.2. Quantification of 3-dimensional (3D) strength balance as a measure of relative external rotation weakness
(A) Sample trajectory of the torque generated during a trial involving combined flexion and abduction, demonstrating the maximum torque (black dot) that was achieved in the target direction (red shaded channel). (B) Each point represents the maximal torque achieved in all 26 directions that were tested. (C) Our measure of overall 3D strength, strength magnitude, was computed by performing a principal components analysis on the 26 maxima and then taking the Euclidian norm of the three principal axis magnitudes and normalizing to weight. (D) Our measure of relative strength in opposing directions, strength balance, was computed as the vector mean of the 26 maximal torques normalized to strength magnitude. The Y component of strength balance represented relative strength along the external-internal rotation axis, which was the axis of interest.

Muscle Activity

In addition to strength, muscle activity was recorded in patients following TSA to test for changes in the activity of external or internal rotators between patients with eccentric and concentric deformities. To record the muscle activity of 6 shoulder muscles during maximal isometric contractions, we used surface EMG (Table 4.2). The muscles included were selected because they are primary contributors to torque production specifically in internal or external rotation. Muscles recorded that contribute to external rotation include the infraspinatus and posterior deltoid (Kang et al., 2014). Muscles recorded that contribute to internal rotation include the pectoralis major, teres major, latissimus dorsi, and anterior deltoid (Mansfield & Neumann, 2019). Before placing surface electrodes (Trigno Avanti, Delsys Incorporated, Natick, MA, USA), skin preparation was performed as follows: shave, clean with alcohol, and apply abrasive electrode gel (NuPrep). All EMG signals were recorded using the Delsys Trigno system (Delsys Incorporated, Natick, MA, USA) and bandpass filtered by the EMG system at 20-450 Hz. Sensors have dimensions of 27 x 37 x 13 mm, an interelectrode distance of 10 mm, and a dual on-board stabilizing reference. Surface EMG data were sampled at 2148.1 Hz (Delsys Trigno system, Delsys Incorporated, Natick, MA, USA).

Table 4.2. Surface electromyography electrode placement and orientation

Muscle	Placement and Orientation
Anterior Deltoid	One finger width distal and anterior to the acromion oriented along the line between the acromion and the thumb.[1]
Posterior Deltoid	Two finger widths behind the angle of the acromion oriented along the line between the acromion and the little finger.[1]
Pectoralis Major	Two finger widths below the midpoint of the clavicle along the line between the sternoclavicular joint and the anterior axillary fold.[2]
Latissimus Dorsi	Three finger widths distal to and along the posterior axillary fold along the line between the posterior axillary fold and L3.[2]
Teres Major	Three finger widths above the inferior angle of the scapula along the lateral border along the line between the posterior axillary fold and inferior angle.[2]
Infraspinatus	Two to three finger widths below the scapular spine at the midpoint between the posterior acromion and the trigonum spinae parallel to the scapular spine.[2]

[1]Hermens HJ. SENIAM : European recommendations for surface electromyography : results of the SENIAM project. [Pays-Bas]: Roessingh Research and Development; 1999.
[2]Perotto A, Delagi EF. Anatomical Guide for the Electromyographer: The Limbs and Trunk: Charles C Thomas; 2005.

Surface EMG data were digitally bandpass filtered between 20 and 500Hz and then rectified. EMG data for each muscle were normalized to the maximum activity achieved by that muscle across all 26 directions tested (% MVC). After filtering, rectifying, and normalizing, the EMG data were further processed following the same procedure used for the torque data to ensure the torque and EMG data were aligned. A 1-second moving average filter was applied and the EMG activity was determined at the time of maximal torque production for each muscle for each target direction. This yielded a mean EMG activity across 1 second, as % MVC, for each subject for each muscle in each of the 26 directions tested. Of the 26 directions tested, 9 involved an internal rotation component and 9 involved an external rotation component: 1D rotation along with 2D and 3D combinations of rotation, flexion/extension, and/or adduction/abduction. To evaluate for changes in muscle activity of internal rotators in patients with eccentric deformities, muscle activity across the 9 directions involving internal rotation was compared between groups. Similarly, to evaluate for changes in muscle activity of external rotators, muscle activity across the 9 directions involving external rotation was compared between groups. EMGs from two patients (1 eccentric and 1 concentric) were not included in the analysis due to uncommon and excessive noise observed in the signals.

Statistical Analysis

To test our hypothesis that patients with eccentric compared to concentric deformities exhibit relative external rotation weakness, we applied a multivariate regression. Strength balance was modeled to be dependent on group and the confounding effects of age, gender, and dominance of the side tested. To test for group differences in 3D strength balance, we used the Hotelling's t-squared statistic. Although not our primary hypothesis, we also tested for differences in strength magnitude (dependent variable) between groups (independent variable) by applying a univariate linear model. Confounders including age, gender, and dominance of the side tested were again included as independent factors in the model.

To test our hypothesis that patients with eccentric compared to concentric deformities demonstrate changes in muscle activity, we used t-tests. Specifically, we tested for differences in internal rotator muscle activity across direction combinations involving internal rotation between patients with eccentric and concentric deformities using a separate t-test for each muscle. We used the same method to test for differences in external rotator muscle activity across direction combinations involving external rotation between deformity groups.

Based on pilot data, an *a priori* power analysis revealed 18 subjects would be required per group to detect between-group differences in strength balance along the internal/external rotation axis with an anticipated effect size of 0.97 and 80% power. For all tests, we used a significance level of $\alpha = 0.05$ with Bonferroni corrections as needed to adjust for multiple comparisons.

Source of Funding

This study was supported by the National Institutes of Arthritis and Musculoskeletal and Skin Diseases (NIAMS, F31AR077426), the American Society of Biomechanics, the Department of Physical Therapy and Human Movement Sciences at Northwestern University, and the Department of Orthopaedic Surgery at Northwestern University.

Results

Effects of glenoid deformity type on 3D strength

Patients with eccentric deformities (internal/external rotation component of strength balance, mean±SD: -7.6±7.4% of unnormalized strength magnitude, %SM) did not demonstrate relative external rotation weakness compared to patients with concentric deformities (-10±6.8%SM, mean difference 2.7%SM [95% CI -1.3%SM to 6.7%SM] ; p = 0.59) (Fig. 4.3). However, both patient groups were weaker in relative internal rotation when compared to control participants (3.3±4.3%SM ; *Eccentric vs. Control* -11%SM [-14%SM to -7.5%SM] ; $p < 0.01$; *Concentric vs. Control* -14%SM [-17%SM to -10%SM] ; $p < 0.01$). All components of strength balance (adduction/abduction, internal/external rotation, and flexion/extension) are reported for each group in Table 4.3. As shown in Figure 4.3, there was greater variability in strength balance in patients with eccentric deformities (95% CI volume, $\%SM^3$, 740) compared to patients with concentric deformities (95% CI volume, $\%SM^3$, 345) and control participants (95% CI volume, $\%SM^3$, 152). As might be expected, the overall strength, as measured by the weight-normalized strength magnitude, did not differ between deformity groups (both groups 0.26±0.07 Nm/kg, mean difference 0.01 Nm/kg [95% CI -0.04 Nm/kg to 0.05 Nm/kg] ; $p = 0.83$) (Fig. 4.4). However, there were strength magnitude differences between patients following TSA and control participants. Strength magnitude was reduced by 19% (0.06/0.32) in patients with concentric deformities compared to control participants (0.32±0.07 Nm/kg, -0.06 Nm/kg [-0.10 Nm/kg to -0.02 Nm/kg] ; $p = 0.015$). While not reaching statistical significance when adjusting for multiple comparisons, strength magnitude was reduced by 17% in patients with eccentric deformities compared to control participants (-0.05 Nm/kg [-0.10 Nm/kg to -0.01 Nm/kg] ; $p = 0.03$).

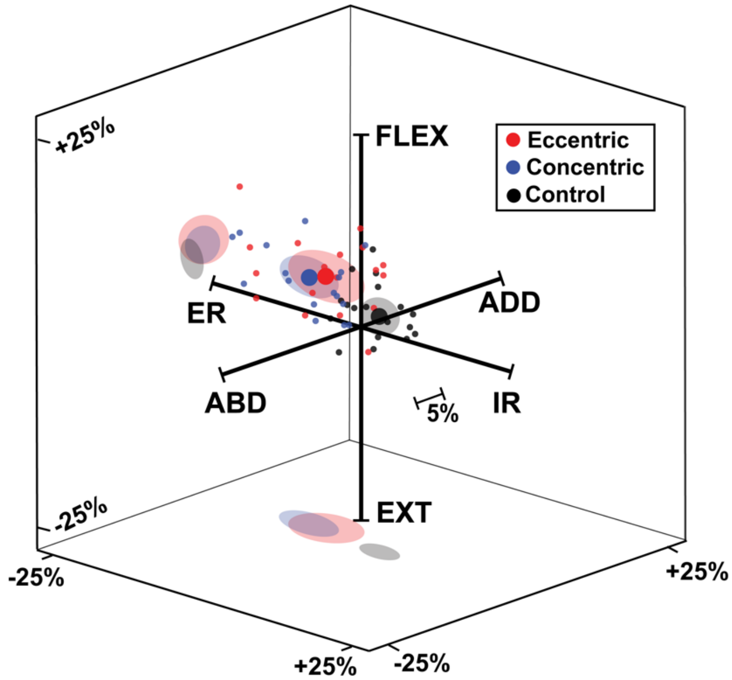

Figure 4.3. Three-dimensional strength balance results
Results showing three-dimensional strength balance for all participants (smaller dots) and group means (larger dots), which did not differ between eccentric and concentric groups. Both OA groups demonstrated weakness in internal relative to external rotation compared to control participants. Shaded ellipses represent the 95% confidence intervals of the group means and two-dimensional projections (XY and XZ) of these intervals are shown. ADD/ABD = adduction/abduction; IR/ER = internal/external rotation; FLEX/EXT = flexion/extension.

Table 4.3. Three-dimensional strength balance

	Control (n = 18)		Concentric (n = 18)				Eccentric (n = 18)					
	Mean ± SD	95% CI volume $\%^3$	Mean ± SD	95% CI volume $\%^3$	Mean difference from control (95% CI)	p value	Mean ± SD	95% CI volume $\%^3$	Mean difference from control (95% CI)	p value	Mean difference from concentric (95% CI)	p value
X (Add-Abd)	-0.3 ± 2.6%		1.6% ± 4.0%		1.9 (0.0, 3.8)		1.8% ± 5.8%		2.1 (-0.4, 4.6)		0.2 (-2.6, 3.0)	
Y (IR-ER)	3.3 ± 4.3%	152	-10.3% ± 6.8%	345	-13.6 (-15.5, -11.7)	<0.01	-7.6% ± 7.4%	740	-10.9 (-13.4, -8.4)	<0.01	-2.7 (-0.1, 5.5)	0.59
Z (Flex-Ext)	2.3 ± 3.5%		3.8% ± 3.1%		1.4 (-0.5, 3.3)		4.4% ± 4.1%		2.1 (-0.4, 4.6)		0.6 (-2.1, 3.4)	

All values are reported as the mean ± standard deviation (SD). The unit is percent of unnormalized strength magnitude. All p values were calculated using the Hotelling's t-square statistic.

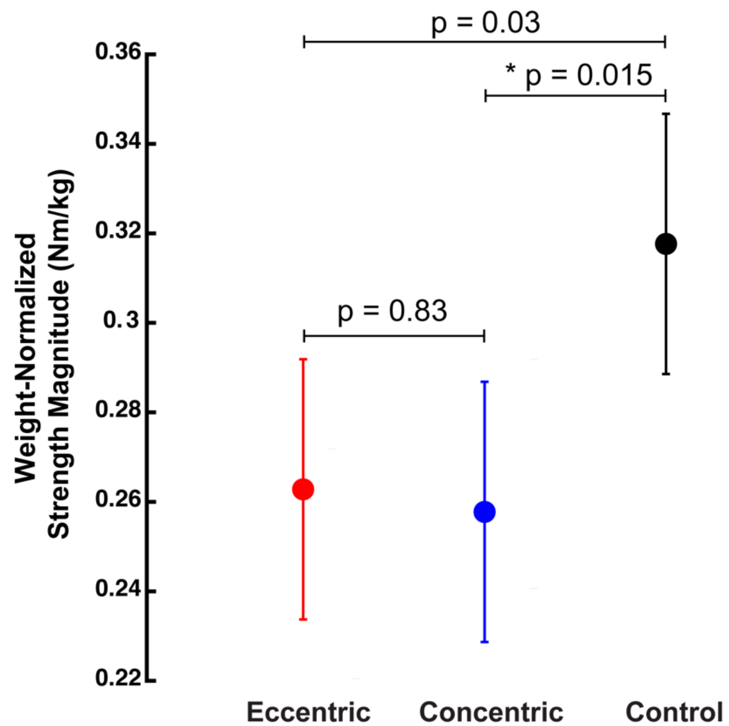

Figure 4.4. Weight-normalized strength magnitude results
Mean weight-normalized strength magnitude for each group shown with 95% confidence intervals. There was no difference in weight-normalized strength magnitude between the eccentric and concentric groups, though the magnitude was reduced by at least 17% in patients after TSA compared to control participants.

Effects of glenoid deformity type on muscle activity

Muscle activity of each internal rotator (pectoralis major, anterior deltoid, teres major, and latissimus dorsi) was not significantly different between patients with eccentric and concentric deformities across the 9 target directions involving internal rotation (Table 4.4) (Fig. 4.5A,C), suggesting no changes in internal rotator muscle activity in the eccentric group. While activity of the posterior deltoid did not differ between deformity groups across target directions involving external rotation (Table 4.4), activity of the infraspinatus was reduced in the eccentric (44±22 %MVC) compared to the concentric (51±19 %MVC) group (mean difference -7.4 %MVC [95% CI -12 %MVC to -2.7 %MVC] ; p = 0.002) (Fig. 4.5B,D). This suggests a potential muscle activity-based deficiency of the posterior RC in the eccentric group.

Table 4.4. Muscle activity across 9 targets involving internal or external rotation

		Concentric (n = 17)	**Eccentric** (n = 17)		
Muscle	**Muscle Action**	Mean ± SD, %MVC	Mean ± SD, %MVC	Mean difference (95% CI), %MVC	p-value
Anterior Deltoid	IR	16 ± 16	16 ± 15	-0.40 [-3.8, 3.0]	0.82
Teres Major	IR	21 ± 16	23 ± 16	1.7 [-1.9, 5.3]	0.36
Latissimus Dorsi	IR	21 ± 14	21 ± 14	0.33 [-2.8, 3.4]	0.83
Pectoralis Major	IR	23 ± 16	23 ± 19	0.29 [-3.6, 4.2]	0.88
Posterior Deltoid	ER	27 ± 21	24 ± 22	-2.4 [-7.3, 2.5]	0.33
Infraspinatus	ER	51 ± 19	44 ± 22	-7.4 [-12, -2.7]	0.002

Mean muscle activity was computed across directions involving internal or external rotation if the muscle was an internal (purple shading) or external (orange shading) rotator, respectively. Muscle action, and thus directions across which mean muscle activity was computed, is designated in the table. All p values were calculated using t-tests. The adjusted p-value designating significance was p < 0.008 (0.05/6). IR = internal rotation. ER = external rotation.

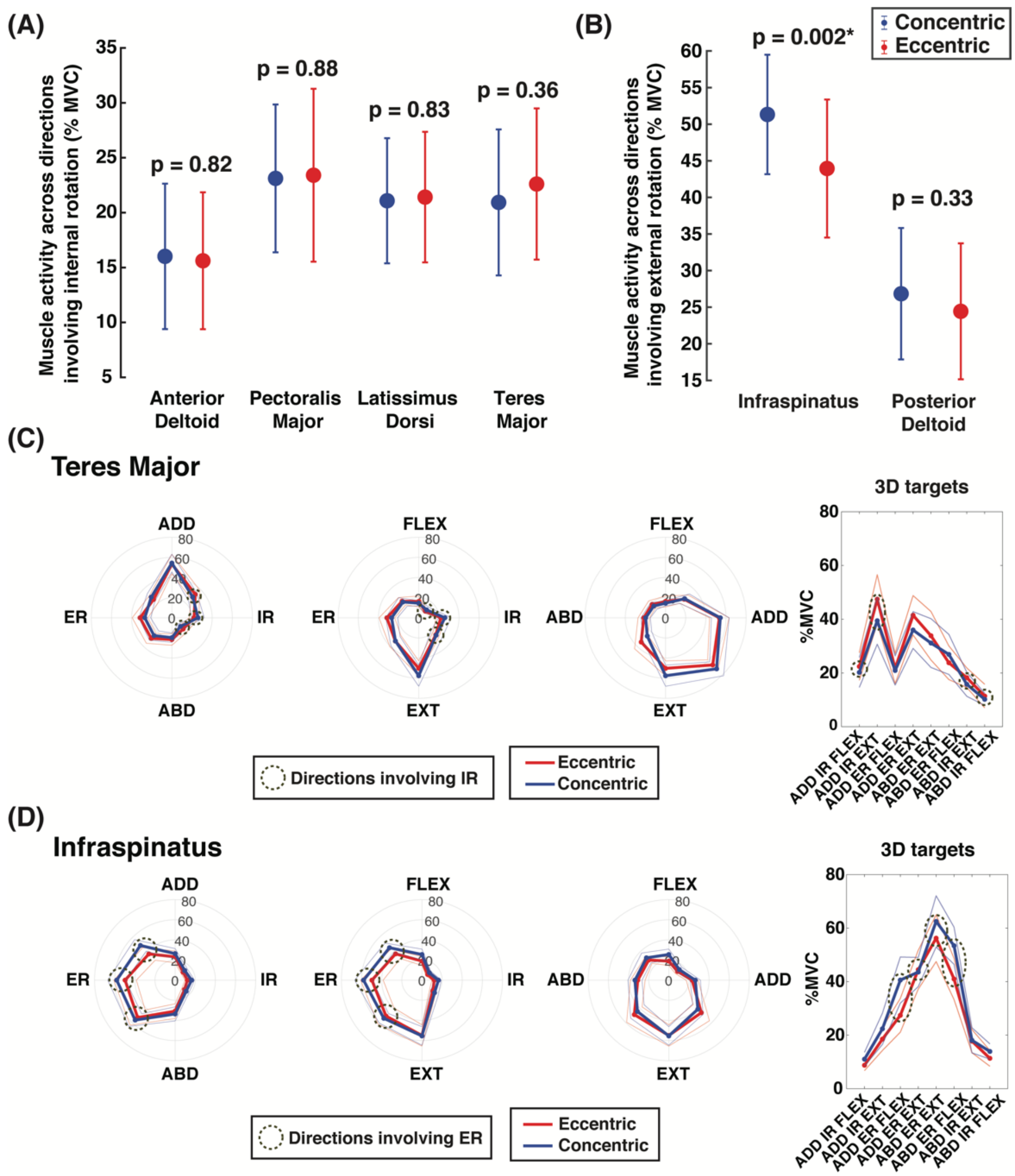

Figure 4.5. Muscle activity of internal and external rotators
Group results for muscle activity (mean and 95% CI) of (A) internal and (B) external rotators demonstrating significantly lower muscle activity in the infraspinatus in the eccentric group. Group results are also shown for muscle activity of (C) the teres major, an internal rotator, and (D) the infraspinatus, an external rotator, across all 26 directions tested. For (C) and (D), three 2D slices demonstrate direction combinations involving 1 or 2 directions. At the far right, combinations involving 3 directions are shown. For the teres major, directions involving internal rotation are designated by the dashed circles. For the infraspinatus, directions involving external rotation are designated by the dashed circles. Muscle activity was compared between groups across all 9 directions involving internal rotation for the teres major, and across all 9 involving external rotation for the infraspinatus.

Discussion

Relative posterior to anterior RC deficiency has been theorized to contribute to TSA failures in patients with eccentric (asymmetric glenoid erosion) compared to concentric (symmetric erosion) deformities. Therefore, we used 3D strength assessments and EMG recordings to compare both relative external to internal rotation strength and muscle activity of shoulder rotators between deformity types in patients following TSA. We found no difference in strength balance, and thus no relative external rotation weakness, in patients with eccentric compared to concentric deformities. Furthermore, patients with eccentric and concentric deformities exhibited comparable overall strength. While strength was not impaired in the eccentric compared to the concentric group, infraspinatus activity was reduced, potentially suggesting a muscle activity-based posterior RC deficiency.

Effects of glenoid deformity type on 3D strength

Current study findings agree with existing clinical work measuring strength following TSA. Prior works have examined internal and external rotation strength in positions isolating the subscapularis and infraspinatus, respectively, to gauge post-operative recovery of these muscles across all glenoid types. In the belly-press position, internal rotation strength in the operative shoulder improved by 12% from before surgery to one year after surgery (Lapner et al., 2015). However, internal rotation strength in the operative shoulder pre- and 1 year post-operatively was 48% and 47% of that in the contralateral shoulder, respectively (Lapner et al., 2015). In the liftoff and bear-hug positions or with the arm at the side in the neutral position, internal and external rotation strength, respectively, improved significantly from pre- to 1 year post-operatively but did not reach the level of the contralateral shoulder (Baumgarten et al., 2018). While post-operative internal and external rotation strength improvements are observed, strength does not reach normative levels. In agreement with these studies demonstrating inferior strength after TSA, we observed a 17-19% reduction in overall strength magnitude in patients following TSA compared to control participants. Of importance when considering our results compared to the existing literature is the different methodological approaches. Given the cross-sectional design of the current study, we cannot compare our results to existing longitudinal findings. Furthermore, the aforementioned studies either measured only internal rotation strength or measured external and internal rotation strength in distinct positions. Thus, comparison of their isolated measurements of rotational strength to our measurements of relative external to internal rotation strength is not possible. Despite these differences, our consistent finding that strength remains inferior following TSA highlights the utility of overall post-operative strengthening regardless of glenoid deformity type.

One existing study measured external and internal rotation strength in the same position, allowing for consideration of relative external to internal rotation strength. Internal and external rotation strength improved from 43% and 44% of normal pre-operatively to 71% and 73% of normal at 1 year post-operative, respectively, with the arm positioned in 45° shoulder abduction and 90° elbow flexion (Sperling et al., 2008). Furthermore, the authors found that internal rotation strength exceeded external rotation strength by 11% across patients with all glenoid deformity types at 1 year after TSA (Sperling et al., 2008). In contrast, the current study found that patients after TSA were 11-14% weaker in relative internal rotation than control participants. This difference may be due to the distinct measurement methods. Sperling et al. tested internal and external rotation strength with the patient supine and the arm at 45° abduction, whereas the current study tested strength with the patient seated and the arm positioned at 45° elevation in the scapular plane. As moment arms for shoulder muscles change with position (Ackland et al., 2008), the unique arm positions used in these studies may have contributed to differences in the results. Furthermore, different measures were used to represent strength: force readings from a 1D hand-held dynamometer in the prior work and joint torques derived from 3D methods in the current study. In contrast to 1D methods, 3D methods allow for measurement of torque contributions along all three axes during contractions in isolated rotation as well as in combinations of 2 or 3 directions including rotation. Additionally, visual feedback provided with 3D methods prevents off-axis torque generation, whereas 1D methods rely on verbal feedback from the clinician to minimize off-axis torques if they are observed. Thus, 3D measurements of strength in internal and external rotation may be more sensitive to detect weakness than 1D measurements. These differences highlight the importance of careful consideration of the position and method used when interpreting and comparing strength measurements.

Effects of glenoid deformity type on muscle activity

Activity of the infraspinatus, a posterior RC muscle, was reduced in patients with eccentric compared to concentric deformities when performing maximal isometric contractions in direction combinations involving external rotation. To our knowledge, one existing study has used EMG to examine RC muscle activity in patients who underwent anatomic TSA; however, the authors' outcome metrics were different from those in the current study (Armstrong et al., 2016). Using needle EMG examination, insertional muscle activity, muscle recruitment patterns, and motor unit morphology were measured to check for abnormalities. Insertional muscle activity was measured to look for evidence of fibrillation potentials, positive sharp waves, or fasciculations, all of which are hallmarks of abnormal spontaneous muscle activity, and thus denervation (Breiner, 2014). A reduced muscle recruitment pattern, whereby increasing voluntary effort results in overly rapid firing of a reduced number of motor unit potentials, would be further indicative of denervation (Breiner, 2014). Finally, motor unit morphology changes including prolonged duration, increased amplitude, and a polyphasic configuration are signs of reinnervation (Breiner, 2014). Considering these metrics, abnormal EMG results with evidence of chronic de- and reinnervation changes were observed in the infraspinatus in the operative compared to the contralateral shoulder in 27% of patients at least 1 year following TSA (Armstrong et al., 2016). The authors theorized the observed changes may be due to factors related to the surgery, such as soft tissue releases, retraction, or use of regional anesthesia. As the existing work did not separate by glenoid deformity type, it is unknown how many of the patients demonstrating chronic de- and reinnervation changes had concentric versus eccentric glenoid deformities. However, as denervation may cause dysfunction, these findings elucidate a possible mechanism explaining the current study findings demonstrating reduced activity of the infraspinatus in the eccentric group.

One consequence of muscle denervation is intramuscular fat infiltration (Gerber et al., 2017; Liu et al., 2012), which has been observed to a greater extent in the posterior RC in pre-operative patients with eccentric compared to concentric deformities (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). Fat infiltration may be irreversible (Kuzel et al., 2013) and thus, if present pre-operatively, could remain post-operatively. Increased intramuscular fat has been associated with decreasing contractile force in the shoulder (Gerber et al., 2007), decreasing central activation in the knee (Yoshida et al., 2012), and reduced neuromuscular activation in the hip (Lanza et al., 2020). Therefore, these findings suggest that intramuscular fat infiltration may lead to altered motor control with changes in the extent to which the nervous system activates the affected muscles. We did not examine RC muscle quality in the current study; however, if patients with eccentric deformities exhibited increased intramuscular fat in the posterior RC, infraspinatus activity may have been reduced as a result of associated motor control alterations. Identifying muscles under altered motor control is crucial for management of patients following TSA, as biofeedback training may be implemented to enhance neuromuscular control of affected muscles (Larsen et al., 2014).

Relative external rotation strength is not diminished despite reduced infraspinatus activity

Despite the observed reduction in infraspinatus muscle activity, external rotation strength was not diminished in patients with eccentric compared to concentric deformities. External rotation strength may not have been compromised due to compensatory hypertrophy of the teres minor, another external rotator, which has been demonstrated in response to infraspinatus muscle atrophy in the setting of tendon tears (Kikukawa et al., 2014; Oh et al., 2022). Teres minor hypertrophy has been identified in patients undergoing reverse TSA (Hung et al., 2021; Jang et al., 2020) and associated with significantly lower 2-year postoperative functional outcome (ASES) scores relative to patients with a normal teres minor (Hung et al., 2021). We did not have imaging or EMG data to evaluate for hypertrophy of the teres minor in the current study; therefore, whether teres minor hypertrophy offset the effects of reduced infraspinatus activity in our sample remains unknown. Furthermore, to our knowledge, whether teres minor hypertrophy contributes to inferior outcomes following anatomic TSA has yet to be determined.

Relative internal rotation weakness and subscapularis surgical management

Our finding that patients after TSA were 11-14% weaker in relative internal rotation compared to control participants brings to light an important factor to consider: varying surgical approaches to subscapularis tendon management during TSA. As the subscapularis is a primary internal rotator, this finding is of interest given extensive work has been done to identify the optimal technique for management of the subscapularis during TSA. To our knowledge, few studies have directly compared subscapularis strength between the two surgical methods used to manage the subscapularis in the current study, the peel and the tenotomy. Lapner et al. conducted a randomized controlled trial comparing strength measured using a 1D handheld dynamometer between patients treated with a peel or a tenotomy (Lapner et al., 2020). The authors found internal rotation strength was 10% greater in the peel group, though this small difference was not statistically significant (Lapner et al., 2020). Consistent with this work, we found that the 18 patients managed with a peel (internal(+)/external(-) rotation component of strength balance, -6.8±6.9 %SM) were slightly stronger (3.8%) in relative internal rotation compared to the 18 patients managed with a tenotomy (-11±7.3 %SM). For a patient with average weight (90 kg) and strength magnitude (24 Nm), this 3.8% would amount to a difference of approximately 82 Nm. Additionally, overall 3D strength was 19% greater in the peel compared to the tenotomy group. While the current study was not designed to answer this question, these results provide compelling preliminary evidence for technique-dependent differences in post-operative strength after TSA. Further, these findings may directly impact surgical management and post-operative rehabilitation. Specifically, particular attention to strengthening in patients managed with a tenotomy to ensure adequate strength recovery after TSA way be warranted.

Strengths and Limitations

One of the major strengths of the current study was the robust 3D method (Baillargeon et al., 2022) used to measure shoulder rotational strength in patients following TSA, which overcomes limitations of existing work using 1D hand-held dynamometry. These methods enabled us to evaluate relative external rotation strength, which is pertinent since the theorized source of TSA failures in patients with eccentric deformities is deficiency of the posterior relative to the anterior RC. Additionally, we demonstrated the importance of evaluating both strength and muscle activity: while no differences were observed in strength, our results suggest there is a muscle activity-based posterior RC deficiency in the eccentric group. Finally, by accounting for confounders including age, sex, and dominance of the side tested in our strength analyses, we were able to specifically test for differences due to deformity type.

There were also study limitations. First, strength was tested only in the selected position: 45° scapular plane elevation and neutral rotation. As muscle moment arms change with arm position (Ackland et al., 2008), these results may not be generalizable to other positions. Second, we do not have EMG recorded from the subscapularis, an internal rotator, or from the teres minor, an external rotator. Recording from these muscles requires more invasive intramuscular EMG technique that carries additional risks including infection and cannot be performed in patients with elevated bleeding risk. The six muscles included encompass the other major contributors to internal and external rotation, thus allowing us to answer the questions posed. In addition, all measurements were made statically. Results may differ when measurements are made during movement; however, our methods match standard clinical methods for assessing strength, which are also conducted in static positions. The focus of the current study was the contributions of muscle activity to strength. Therefore, we did not acquire pre- or post-operative advanced imaging to assess RC muscle size and intramuscular fat as a potential explanation for the study results. Finally, the current study included only patients following TSA for primary glenohumeral OA; therefore, these results may not be generalized to patients after a TSA for secondary glenohumeral OA.

Conclusion

In conclusion, relative external rotation strength following TSA does not appear to differ based on pre-operative glenoid deformity type (eccentric vs. concentric). However, reduced infraspinatus muscle activity in patients with eccentric deformities may suggest a muscle activity-based posterior RC deficiency. Patients following TSA, regardless of pre-operative deformity, demonstrate weakness in relative internal rotation compared to participants without shoulder pain or pathology. Furthermore, overall strength magnitude following TSA, as measured across multidimensional direction combinations, remains inferior to that in healthy participants. These findings highlight the potential need for strengthening following TSA regardless of glenoid deformity type. Furthermore, biofeedback training targeted at increasing infraspinatus muscle activity in patients with eccentric deformities may help correct underlying muscle activity deficits in efforts to ultimately prevent TSA failure.

Chapter 5: Discussion

This dissertation quantified the effects of measurement technique and glenoid deformity type on shoulder strength in patients with glenohumeral osteoarthritis (OA). The primary motivation for this work was the observation that outcomes vary following surgical treatment for OA with total shoulder arthroplasty (TSA) depending on the type of glenoid deformity. Specifically, additional, revision surgery is more often required in patients with eccentric deformities (asymmetric bony erosion about the glenoid center) than patients with concentric deformities (symmetric bony erosion). A recent theory suggests that imbalances between the rotator cuff muscles, which would manifest as strength imbalances, contribute to higher revision rates in the setting of eccentric deformities. While this has been proposed, shoulder strength has yet to be compared between patients with eccentric and concentric deformities either pre- or post-operatively. This work takes a first step toward improving TSA outcomes by elucidating techniques that may be more sensitive to detect muscular imbalances, using these techniques to evaluate for strength differences between patients with eccentric and concentric deformities cross-sectionally before and after surgery, and exploring mechanisms contributing to strength. We completed three studies to accomplish these goals. In this chapter, I summarize the major contributions and results of each of these studies, discuss their clinical implications, and highlight questions that remain unanswered.

One-dimensional hand-held dynamometry overestimates external and internal rotation strength

A main focus of this dissertation is evaluating implications of a potential disruption of the posterior to anterior rotator cuff force couple in patients after TSA. Disruption of this force couple in patients following TSA may lead to muscular imbalances, which may cause asymmetric loading of the prosthetic glenoid component (Collins et al., 1992). Asymmetric loading may ultimately cause glenoid loosening and TSA failure (Matsen et al., 2008; Papadonikolakis et al., 2013). Thus, measuring internal and external rotation strength after TSA is essential to tailor rehabilitation, maintain integrity of the rotator cuff force couple, and detect imbalances if they arise. However, methods for measuring isolated internal and external rotation strength, and thus detecting imbalances, may be limited. Therefore, in chapter 2 we measured internal and external rotation strength using one- (1D) and three-dimensional (3D) methods while also measuring muscle activity in patients following TSA to determine if 3D measurements may overcome potential limitations of 1D measurements. A main, important difference between 3D and 1D methods is the feedback provided. During 3D testing patients are continuously provided with feedback showing the torque being generated, which helps ensure that they only generate the prescribed torque and no off-axis torques. In contrast, 1D methods rely on feedback from the clinician and may be affected by off-axis torques. As expected, we found that 1D measurements overestimated strength in internal and external rotation, and that patients enlisted unique patterns of muscle activity between 1D and 3D rotational strength testing. Furthermore, predictions derived from a model relating EMG to torque suggest that greater off-axis torques are generated in the 1D compared to the 3D case. These findings are clinically important as most clinical knowledge of shoulder strength after TSA is based on measurements obtained using 1D hand-held dynamometers. The current study results provide important context within which to consider the existing work, as 1D measurements may suggest falsely greater internal and external rotation strength. In contrast, 3D measurements effectively limited off-axis contributions and provide novel insight into shoulder strength in isolated rotation. Given these results, 3D methods were used to test for muscular imbalances in patients with OA. Future work exploring translation of 3D methods efficiently into the clinic to complement 1D methods is warranted as these methods may provide distinct clinical information regarding rotational strength in patients following TSA. Use of both methods may be crucial to ensure imbalances are detected and to allow for implementation of appropriate post-operative strengthening to avoid TSA failure.

No strength differences despite greater posterior rotator cuff intramuscular fat in patients with eccentric glenohumeral osteoarthritis before TSA

In chapter 3, we quantified 3D shoulder strength and pain, as well as rotator cuff muscle size, in patients with eccentric and concentric deformities before TSA. By using 3D measurement methods and concurrently measuring pain and rotator cuff muscle size, we overcame several limitations of existing studies examining strength in patients with OA prior to surgery. In contrast to the proposed theory suggesting posterior rotator cuff deficiencies exist in patients with eccentric deformities (Domos et al., 2018; Donohue et al., 2018), we found that relative external to internal rotation strength did not differ between patients with eccentric and concentric deformities. Corroborating this finding, the relative amount of remaining posterior to anterior rotator cuff muscle was comparable between the eccentric and concentric groups. As reported previously (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018), greater intramuscular fat was observed in the posterior relative to the anterior rotator cuff in the eccentric group. However, since the amount of remaining muscle was comparable between groups, potentially due to compensatory hypertrophy of the teres minor, this had no functional implication on strength. Higher variability in strength in the eccentric compared to the concentric group may suggest that patients with potential subtypes of eccentric deformities (posterior-superior, posterior-central, and posterior-inferior (Otto et al., 2021)) adopt unique kinematic or muscle activation patterns to compensate for anatomic changes. Overall, this work highlights the importance of careful clinical evaluation of patients with eccentric deformities as, given the observed variability in these patients, some may exhibit potentially detrimental strength deficits that may be targeted with rehabilitation. Future work should explore strength and muscle activity in patients with different subtypes of eccentric glenoid wear patterns to determine whether unique compensation patterns are adopted and whether these factors play a role in higher TSA failure rates in patients with pre-operative eccentric deformities. Additionally, as the current work has revealed that differences in strength do not exist between patients with eccentric and concentric deformities before surgery, an important remaining question is whether this remains the case in patients following TSA.

External rotation strength is not diminished despite reduced infraspinatus activity in eccentric glenohumeral osteoarthritis following TSA

Contrary to a hypothesized deficiency of the posterior relative to the anterior rotator cuff, relative external to internal rotation strength was comparable between patients with eccentric and concentric deformities before TSA. However, greater variability in the eccentric group suggested muscular compensation may be occurring. Therefore, our next question was whether strength and muscle activity differ between patients with eccentric and concentric deformities following TSA. In chapter 4, we simultaneously quantified 3D shoulder strength and muscle activity of shoulder muscles contributing to internal and external rotation in patients after TSA. Despite observing reduced muscle activity of the infraspinatus, an external rotator, in the eccentric group, relative external to internal rotation strength was comparable between patients with eccentric and concentric deformities after TSA. Thus, while posterior rotator cuff weakness was not observed, our findings do suggest presence of a muscle activity-based posterior rotator cuff deficiency in patients with eccentric deformities.

The finding that external rotation strength was not diminished despite a reduction in muscle activity of a primary external rotator was surprising, but has a possible explanation. Chronic de- and reinnervation changes have been demonstrated in the posterior rotator cuff in patients treated with TSA (Armstrong et al., 2016). Furthermore, increased intramuscular fat exists in the posterior rotator cuff in patients with eccentric compared to concentric deformities before surgical intervention (Arenas-Miquelez et al., 2021; Donohue et al., 2018; Hartwell et al., 2021; Walker et al., 2018). While this has not specifically been shown post-operatively, fat infiltration is believed to be irreversible (Kuzel et al., 2013) and thus, if present pre-operatively, could remain post-operatively. Intramuscular fat has been associated with decreasing contractile force (Gerber et al., 2007), central activation (Yoshida et al., 2012), and neuromuscular activation (Lanza et al., 2020). Therefore, if the posterior rotator cuff in the eccentric group had greater intramuscular fat infiltration, it is possible that this resulted in motor control changes leading to reduced activation of the affected muscles. Strength may have been preserved via compensatory hypertrophy of the remaining external rotator, as infraspinatus deficiency has been associated with teres minor hypertrophy (Kikukawa et al., 2014; Oh et al., 2022). In the current study we could not test whether the teres minor was compensating and helping to bolster external rotation strength in patients with eccentric deformities after TSA. Therefore, future work focused on determining whether teres minor compensation occurs in patients with eccentric deformities is warranted. This is especially pertinent as teres minor hypertrophy has been associated with inferior clinical outcomes in patients following reverse TSA (Hung et al., 2021). Thus, future research should also explore how teres minor hypertrophy affects anatomic TSA outcomes in patients with eccentric and concentric deformities to see if this may be a factor contributing to surgical failure.

Implications of this work

This work has drawn attention to an important factor to consider when measuring strength, which is the measurement technique. While handheld dynamometry is commonly accepted in the clinic, our findings reveal that this methodology may not accurately isolate internal and external rotation strength. The continuous feedback provided with 3D measurement methods effectively eliminates torques generated in adduction/abduction or flexion/extension, thereby successfully isolating internal and external rotation strength. The main limitation of 3D methods, however, is that they are time-consuming and require more equipment, and thus cannot be used as easily in clinical settings. Thus, future efforts should focus on exploring ways to practically conduct 3D strength measurements alongside 1D measurements in the clinic to further elucidate the additional clinical information that 3D methods may provide for patients following TSA. This is an important finding not only for helping to reduce TSA failures, but also for management of patients with other shoulder pathologies for which accurate measurement of shoulder strength is essential.

Using 3D methods, this research explored a clinical theory suggesting relative deficiency of the posterior to anterior rotator cuff contributes to eccentric deformity development and TSA failure. Importantly, the findings demonstrate that strength and relative posterior to anterior rotator cuff muscle size are not diminished in patients with eccentric compared to concentric deformities, though a muscle activity-based posterior rotator cuff deficiency was observed in the eccentric group following TSA. These results are clinically informative as much of the work comparing patients with eccentric and concentric deformities has focused on rotator cuff muscle degeneration and the extent of intramuscular fat infiltration. While this is an important factor to consider, our results suggest that efforts should be directed at exploring other mechanisms that may contribute to differences between patients with eccentric and concentric deformities. Specifically, our findings emphasize the potential benefit of comparing muscle activity and kinematic patterns between patients with eccentric and concentric deformities, as underlying differences may result from alterations in motor control.

Remaining questions and future directions

This work has quantified 3D strength and its core determinants for the first time in patients with glenohumeral OA and has made direct comparisons between patients with eccentric and concentric deformities. First, we elucidated that 3D strength measurements may provide complementary, clinically-pertinent information particularly regarding isolated internal and external rotation strength. Use of both 1D and 3D methods may provide a more comprehensive and accurate assessment of strength in patients following TSA, which is crucial for detection of muscular imbalances and thus implementation of appropriate rehabilitation to help prevent surgical failure. Importantly, our findings have revealed that, contrary to an existing clinical hypothesis for increased TSA revision rates in patients with eccentric compared to concentric deformities, 3D strength and rotator cuff muscle size were similar between deformity groups. However, reduced activity of the infraspinatus was observed in the eccentric group following TSA. Although these studies have taken important first steps toward improving outcomes for patients following TSA, the current work has also inspired several follow-up questions and worthwhile future pursuits.

> Hand-held dynamometry was found to overestimate measurements of internal and external rotation strength compared to 3D methods in patients following TSA; is the same trend observed when measuring strength using these methods in control participants or patients with other shoulder pathologies? How can 3D strength measurements be applied more feasibly in clinical settings? Do patients with different subtypes of eccentric wear patterns demonstrate differences in strength, muscle activity, or rotator cuff muscle size compared to one another and compared to patients with concentric deformities? If so, do these differences contribute to TSA failure in these patients? Does teres minor hypertrophy occur in patients with OA exhibiting increased intramuscular fat infiltration in the infraspinatus? If so, how does this influence outcomes of TSA in affected patients compared to patients with a normal teres minor muscle? Can longitudinal studies elucidate whether posterior rotator cuff fat infiltration is a cause or effect of eccentric deformity development?

Clearly, there are numerous newly-inspired questions to explore to further advance our knowledge and identify feasible interventions to ultimately reduce TSA failures. However, this work successfully answered the questions that we set out to address and enhanced our understanding of how strength and its core determinants are affected in the setting of glenohumeral OA. The findings may inform clinical management of patients with OA. Specifically, the results highlight the importance of obtaining accurate strength measurements and assessing for potentially detrimental alterations in motor control before and after TSA to direct rehabilitation, all in efforts to reduce TSA failures.

References

Ackland, D. C., Pak, P., Richardson, M., & Pandy, M. G. (2008). Moment arms of the muscles crossing the anatomical shoulder. *J Anat, 213*(4), 383-390. https://doi.org/10.1111/j.1469-7580.2008.00965.x

Aibinder, W., Schoch, B., Parsons, M., Watling, J., Ko, J. K., Gobbato, B., Throckmorton, T., Routman, H., Fan, W., Simmons, C., & Roche, C. (2021). Risk factors for complications and revision surgery after anatomic and reverse total shoulder arthroplasty. *J Shoulder Elbow Surg, 30*(11), e689-e701. https://doi.org/10.1016/j.jse.2021.04.029

Aleem, A. W., Chalmers, P. N., Bechtold, D., Khan, A. Z., Tashjian, R. Z., & Keener, J. D. (2019). Association Between Rotator Cuff Muscle Size and Glenoid Deformity in Primary Glenohumeral Osteoarthritis. *J Bone Joint Surg Am, 101*(21), 1912-1920. https://doi.org/10.2106/JBJS.19.00086

Andrews, A. W., Thomas, M. W., & Bohannon, R. W. (1996). Normative values for isometric muscle force measurements obtained with hand-held dynamometers. *Phys Ther, 76*, 248-259.

Arenas-Miquelez, A., Liu, V. K., Cavanagh, J., Graham, P. L., Ferreira, L. M., Bokor, D. J., Athwal, G. S., & Raniga, S. (2021). Does the Walch Type B shoulder have a transverse force couple imbalance? A volumetric analysis of segmented rotator cuff muscles in osteoarthritic shoulders. *J Shoulder Elbow Surg, 30*, 2344-2354. https://doi.org/10.1016/j.jse.2021.02.005

Armstrong, A. D., Southam, J. D., Horne, A. H., Hollenbeak, C. S., Flemming, D. J., & Kothari, M. J. (2016). Subscapularis function after total shoulder arthroplasty: electromyography, ultrasound, and clinical correlation. *J Shoulder Elbow Surg, 25*(10), 1674-1680. https://doi.org/10.1016/j.jse.2016.02.018

Ashford, S., & Williard, J. (2014). Osteoarthritis: A review. *Nurse Pract, 39*(5), 1-8. https://doi.org/10.1097/01.NPR.0000445886.71205.c4

Baillargeon, E. M., Ludvig, D., Sohn, M. H., Nicolozakes, C. P., Seitz, A. L., & Perreault, E. J. (2022). Experimentally quantifying the feasible torque space of the human shoulder. *J Electromyogr Kinesiol, 62*, 1-10, Article 102313. https://doi.org/10.1016/j.jelekin.2019.05.014

Baumgarten, K. M., Osborn, R., Schweinle, W. E., & Zens, M. J. (2018). The influence of anatomic total shoulder arthroplasty using a subscapularis tenotomy on shoulder strength. *Journal of Shoulder and Elbow Surgery, 27*(1), 82-89. https://doi.org/10.1016/j.jse.2017.06.043

Bercik, M. J., Kruse, K., 2nd, Yalizis, M., Gauci, M. O., Chaoui, J., & Walch, G. (2016). A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. *J Shoulder Elbow Surg, 25*(10), 1601-1606. https://doi.org/10.1016/j.jse.2016.03.010

Bohsali, K. I., Bois, A. J., & Wirth, M. A. (2017). Complications of Shoulder Arthroplasty. *J Bone Joint Surg Am, 99*(3), 256-269. https://doi.org/10.2106/JBJS.16.00935

Breiner, A. (2014). Denervation. In M. J. Aminoff & R. B. Daroff (Eds.), *Encyclopedia of the Neurological Sciences (Second Edition)* (pp. 971-972). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-385157-4.00655-2

Bruttel, H., Spranz, D. M., Wolf, S. I., & Maier, M. W. (2020). Scapulohumeral rhythm in patients after total shoulder arthroplasty compared to age-matched healthy individuals [Article]. *Gait & Posture, 82*, 38-44. https://doi.org/10.1016/j.gaitpost.2020.08.111

Cancienne, J. M., Brockmeier, S. F., Gulotta, L. V., Dines, D. M., & Werner, B. C. (2017). Ambulatory Total Shoulder Arthroplasty: A Comprehensive Analysis of Current Trends, Complications, Readmissions, and Costs. *J Bone Joint Surg Am, 99*(8), 629-637. https://doi.org/10.2106/JBJS.16.00287

Chalmers, P. N., Salazar, D., Chamberlain, A., & Keener, J. D. (2017). Radiographic characterization of the B2 glenoid: is inclusion of the entirety of the scapula necessary? *J Shoulder Elbow Surg, 26*(5), 855-860. https://doi.org/10.1016/j.jse.2016.10.027

Collins, D., Tencer, A., Sidles, J., & Matsen, F., 3rd. (1992). Edge displacement and deformation of glenoid components in response to eccentric loading. The effect of preparation of the glenoid bone. *J Bone Joint Surg Am, 74*(4), 501-507.

Denard, P. J., & Walch, G. (2013). Current concepts in the surgical management of primary glenohumeral arthritis with a biconcave glenoid. *J Shoulder Elbow Surg, 22*(11), 1589-1598. https://doi.org/10.1016/j.jse.2013.06.017

Deshmukh, A. V., Koris, M., Zurakowski, D., & Thornhill, T. S. (2005). Total shoulder arthroplasty: long-term survivorship, functional outcome, and quality of life. *J Shoulder Elbow Surg, 14*(5), 471-479. https://doi.org/10.1016/j.jse.2005.02.009

Domos, P., Checchia, C. S., & Walch, G. (2018). Walch B0 glenoid: pre-osteoarthritic posterior subluxation of the humeral head. *J Shoulder Elbow Surg, 27*(1), 181-188. https://doi.org/10.1016/j.jse.2017.08.014

Donohue, K. W., Ricchetti, E. T., Ho, J. C., & Iannotti, J. P. (2018). The association between rotator cuff muscle fatty infiltration and glenoid morphology in glenohumeral osteoarthritis. *J Bone Joint Surg Am, 100*(5), 381-387. https://doi.org/10.2106/JBJS.17.00232

Elliott, J. M., Walton, D. M., Rademaker, A., & Parrish, T. B. (2013). Quantification of cervical spine muscle fat: a comparison between T1-weighted and multi-echo gradient echo imaging using a variable projection algorithm (VARPRO). *BMC Med Imaging, 13*, 1-8.

Farron, A., Terrier, A., & Büchler, P. (2006). Risks of loosening of a prosthetic glenoid implanted in retroversion. *J Shoulder Elbow Surg, 15*(4), 521-526. https://doi.org/10.1016/j.jse.2005.10.003

Fayad, F., Roby-Brami, A., Yazbeck, C., Hanneton, S., Lefevre-Colau, M. M., Gautheron, V., Poiraudeau, S., & Revel, M. (2008). Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder. *J Biomech, 41*(2), 326-332. https://doi.org/10.1016/j.jbiomech.2007.09.004

Fischer, M. A., Pfirrmann, C. W., Espinosa, N., Raptis, D. A., & Buck, F. M. (2014). Dixon-based MRI for assessment of muscle-fat content in phantoms, healthy volunteers and patients with achillodynia: comparison to visual assessment of calf muscle quality. *Eur Radiol, 24*(6), 1366-1375. https://doi.org/10.1007/s00330-014-3121-1

Fuchs, B., Weishaupt, D., Zanetti, M., Hodler, J., & Gerber, C. (1999). Fatty degeneration of the muscles of the rotator cuff: assessment by computed tomography versus magnetic resonance imaging. *J Shoulder Elbow Surg, 8*, 599-605.

Gerber, C., Meyer, D. C., Fluck, M., Valdivieso, P., von Rechenberg, B., Benn, M. C., & Wieser, K. (2017). Muscle Degeneration Associated With Rotator Cuff Tendon Release and/or Denervation in Sheep. *Am J Sports Med, 45*(3), 651-658. https://doi.org/10.1177/0363546516677254

Gerber, C., Schneeberger, A. G., Hoppeler, H., & Meyer, D. C. (2007). Correlation of atrophy and fatty infiltration on strength and integrity of rotator cuff repairs: a study in thirteen patients. *J Shoulder Elbow Surg, 16*(6), 691-696. https://doi.org/10.1016/j.jse.2007.02.122

Goutallier, D., Postel, J., Bernageau, J., Lavau, L., & Voisin, M. (1994). Fatty muscle degeneration in cuff ruptures: pre- and postoperative evaluation by CT scan. *Clin Orthop Relat Res*(304), 78-83.

Hannah, D. C., Scibek, J. S., & Carcia, C. R. (2017). Strength profiles in healthy indviiduals with and without scapular dyskinesis. *Int J Sports Phys Ther, 12*(3), 390-401.

Hansen, L. M., Garg, A., Khanna, R., Thayer, M., Saltzman, M. D., Marra, G., & Seitz, A. L. (2021). Clinical Y-view versus 3-dimensional assessments of intramuscular fat in patients with full-thickness rotator cuff tears. *Clin Imaging, 77*, 13-16. https://doi.org/10.1016/j.clinimag.2021.01.038

Hartwell, M. J., Harold, R. E., Sweeney, P. T., Seitz, A. L., Marra, G., & Saltzman, M. D. (2021). Imbalance in axial-plane rotator cuff fatty infiltration in posteriorly worn glenoids in primary glenohumeral osteoarthritis: an MRI-based study. *Clin Orthop Relat Res, 479*, 2471-2479. https://doi.org/10.1097/CORR.0000000000001798

Hayes, K., Walton, J. R., Szomor, Z. L., & Murrell, G. A. (2002). Reliability of 3 methods for assessing shoulder strength. *J Shoulder Elbow Surg, 11*(1), 33-39. https://doi.org/10.1067/mse.2002.119852

Holzbaur, K. R., Delp, S. L., Gold, G. E., & Murray, W. M. (2007). Moment-generating capacity of upper limb muscles in healthy adults. *J Biomech, 40*(11), 2442-2449. https://doi.org/10.1016/j.jbiomech.2006.11.013

Hung, L. W., Wu, S., Lee, A., Zhang, A. L., Feeley, B. T., Xiao, W., Ma, C. B., & Lansdown, D. A. (2021). Teres minor muscle hypertrophy is a negative predictor of outcomes after reverse total shoulder arthroplasty: an evaluation of preoperative magnetic resonance imaging and postoperative implant position. *J Shoulder Elbow Surg, 30*(10), e636-e645. https://doi.org/10.1016/j.jse.2020.12.020

Hussey, M. M., Steen, B. M., Cusick, M. C., Cox, J. L., Marberry, S. T., Simon, P., Cottrell, B. J., Santoni, B. G., & Frankle, M. A. (2015). The effects of glenoid wear patterns on patients with osteoarthritis in total shoulder arthroplasty: an assessment of outcomes and value. *J Shoulder Elbow Surg, 24*(5), 682-690. https://doi.org/10.1016/j.jse.2014.09.043

Jang, Y. H., Kim, D. O., & Kim, S. H. (2020). Effect of preoperative teres minor hypertrophy on reverse total shoulder arthroplasty. *J Shoulder Elbow Surg, 29*(6), 1136-1144. https://doi.org/10.1016/j.jse.2019.10.014

Jobe, C. M., Phipatanakul, W. P., & Petkovic, D. (2022). Gross anatomy of the shoulder. In *Rockwood and Matsen's The Shoulder* (Sixth ed.).

Kang, M. H., Oh, J. S., & Jang, J. H. (2014). Differences in muscle activities of the infraspinatus and posterior deltoid during shoulder external rotation in open kinetic chain and closed kinetic chain exercises. *J Phys Ther Sci, 26*, 895-897.

Kasten, P., Pape, G., Raiss, P., Bruckner, T., Rickert, M., Zeifang, F., & Loew, M. (2010). Mid-term survivorship analysis of a shoulder replacement with a keeled glenoid and a modern cementing technique. *J Bone Joint Surg Br, 92*(3), 387-392. https://doi.org/10.1302/0301-620X.92B3.23073

Kelly, B. T., Kadrmas, W. R., & Speer, K. P. (1996). The manual muscle examination for rotator cuff strength: an electromyographic investigation. *Am J Sports Med, 24*(5), 581-588.

Kerr, R., Resnick, D., Pineda, C., & Haghighi, P. (1985). Osteoarthritis of the glenohumeral joint: a radiologic-pathologic study. *AJR Am J Roentgenol, 144*(5), 967-972. https://doi.org/10.2214/ajr.144.5.967

Kiet, T. K., Feeley, B. T., Naimark, M., Gajiu, T., Hall, S. L., Chung, T. T., & Ma, C. B. (2015). Outcomes after shoulder replacement: comparison between reverse and anatomic total shoulder arthroplasty. *J Shoulder Elbow Surg, 24*(2), 179-185. https://doi.org/10.1016/j.jse.2014.06.039

Kikukawa, K., Ide, J., Kikuchi, K., Morita, M., Mizuta, H., & Ogata, H. (2014). Hypertrophic changes of the teres minor muscle in rotator cuff tears: quantitative evaluation by magnetic resonance imaging. *J Shoulder Elbow Surg, 23*(12), 1800-1805. https://doi.org/10.1016/j.jse.2014.03.014

Kim, S. G., Lim, D. H., & Cho, Y. H. (2016). Analysis of the reliability of the make test in young adults by using a hand-held dynamometer. *J Phys Ther Sci, 28*, 2238-2240.

Kopka, M., Fourman, M., Soni, A., Cordle, A. C., & Lin, A. (2017). Can glenoid wear be accurately assessed using x-ray imaging? Evaluating agreement of x-ray and magnetic resonance imaging (MRI) Walch classification. *J Shoulder Elbow Surg, 26*(9), 1527-1532. https://doi.org/10.1016/j.jse.2017.03.014

Kopke, J. V., Hargrove, L. J., & Ellis, M. D. (2021). Coupling of shoulder joint torques in individuals with chronic stroke mirrors controls, with additional non-load-dependent negative effects in a combined-torque task. *J Neuroeng Rehabil, 18*(1), 134. https://doi.org/10.1186/s12984-021-00924-1

Kuzel, B. R., Grindel, S., Papandrea, R., & Ziegler, D. (2013). Fatty infiltration and rotator cuff atrophy. *J Am Acad Orthop Surg, 21*(10), 613-623. https://doi.org/10.5435/JAAOS-21-10-613

Lanza, M. B., Ryan, A. S., Gray, V., Perez, W. J., & Addison, O. (2020). Intramuscular Fat Influences Neuromuscular Activation of the Gluteus Medius in Older Adults. *Front Physiol, 11*, 614415. https://doi.org/10.3389/fphys.2020.614415

Lapner, P., Pollock, J. W., Zhang, T., Ruggiero, S., Momoli, F., Sheikh, A., & Athwal, G. S. (2020). A randomized controlled trial comparing subscapularis tenotomy with peel in anatomic shoulder arthroplasty. *J Shoulder Elbow Surg, 29*(2), 225-234. https://doi.org/10.1016/j.jse.2019.09.028

Lapner, P. L. C., Wood, K. S., Zhang, T., & Athwal, G. S. (2015). The return of subscapularis strength after shoulder arthroplasty. *J Shoulder Elbow Surg, 24*(2), 223-228. https://doi.org/10.1016/j.jse.2014.06.042

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. *J Electromyogr Kinesiol, 24*(1), 58-64. https://doi.org/10.1016/j.jelekin.2013.09.008

Leggin, B. G., Michener, L. A., Shaffer, M. A., Brenneman, S. K., Iannotti, J. P., & Williams, G. R., Jr. (2006). The Penn shoulder score: reliability and validity. *J Orthop Sports Phys Ther, 36*(3), 138-151. https://doi.org/10.2519/jospt.2006.36.3.138

Lehtinen, J. T., Tingart, M. J., Apreleva, M., Zurakowski, D., Palmer, W., & Warner, J. J. (2003). Practical assessment of rotator cuff muscle volumes using shoulder MRI. *Acta Orthop Scand, 74*(6), 722-729. https://doi.org/10.1080/00016470310018270

Liu, X., Laron, D., Natsuhara, K., Manzano, G., Kim, H. T., & Feeley, B. T. (2012). A Mouse Model of Massive Rotator Cuff Tears. *JBJS, 94*(7), e41. https://doi.org/10.2106/jbjs.K.00620

Luedke, C., Kissenberth, M. J., Tolan, S. J., Hawkins, R. J., & Tokish, J. M. (2018). Outcomes of anatomic total shoulder arthroplasty with B2 glenoids: a systematic review. *JBJS Rev, 6*(4), e7. https://doi.org/10.2106/JBJS.RVW.17.00112

Mansat, P., Briot, J., Mansat, M., & Swider, P. (2007). Evaluation of the glenoid implant survival using a biomechanical finite element analysis: influence of the implant design, bone properties, and loading location. *J Shoulder Elbow Surg, 16*(3 Suppl), S79-83. https://doi.org/10.1016/j.jse.2005.11.010

Mansfield, P. J., & Neumann, D. A. (2019). Structure and Function of the Shoulder Complex. In P. J. Mansfield & D. A. Neumann (Eds.), *Essentials of Kinesiology for the Physical Therapist Assistant (Third Edition)* (pp. 50-90).

Matsen, F. A., 3rd, Clinton, J., Lynch, J., Bertelsen, A., & Richardson, M. L. (2008). Glenoid component failure in total shoulder arthroplasty. *J Bone Joint Surg Am, 90*(4), 885-896. https://doi.org/10.2106/JBJS.G.01263

Matsen, F. A., 3rd, Iannotti, J. P., Churchill, R. S., De Wilde, L., Edwards, T. B., Evans, M. C., Fehringer, E. V., Groh, G. I., Kelly, J. D., 2nd, Kilian, C. M., Merolla, G., Norris, T. R., Porcellini, G., Spencer, E. E., Jr., Vidil, A., Wirth, M. A., Russ, S. M., Neradilek, M., & Somerson, J. S. (2019). One and two-year clinical outcomes for a polyethylene glenoid with a fluted peg: one thousand two hundred seventy individual patients from eleven centers. *Int Orthop, 43*(2), 367-378. https://doi.org/10.1007/s00264-018-4213-3

Miller, C. T., Buck, F. M., Mamisch-Saupe, N., & Gerber, C. (2014). Good correlation of Goutallier rating of supraspinatus fatty changes on axial and reformatted parasagittal computed tomographic images. *J Comput Assist Tomogr, 38*, 340-343.

Nakamura, Y., Yokoya, S., Harada, Y., Shiraishi, K., Adachi, N., & Ochi, M. (2017). The prospective evaluation of changes in fatty infiltration and shoulder strength in nonsurgically treated rotator cuff tears. *J Orthop Sci, 22*(4), 676-681. https://doi.org/10.1016/j.jos.2017.02.008

Nardo, L., Karampinos, D. C., Lansdown, D. A., Carballido-Gamio, J., Lee, S., Maroldi, R., Ma, C. B., Link, T. M., & Krug, R. (2014). Quantitative assessment of fat infiltration in the rotator cuff muscles using water-fat MRI. *J Magn Reson Imaging, 39*(5), 1178-1185. https://doi.org/10.1002/jmri.24278

National Center for Complementary and Integrative Health 2016 Strategic Plan. (2016). Retrieved July 30, 2019 from https://nccih.nih.gov/about/strategic-plans/2016

Norris, T. R., & Iannotti, J. P. (2002). Functional outcome after shoulder arthroplasty for primary osteoarthritis: a multicenter study. *J Shoulder Elbow Surg, 11*(2), 130-135. https://doi.org/10.1067/mse.2002.121146

Novotny, J. E., Nichols, C. E., & Beynnon, B. D. (1998). Normal kinematics of the unconstrained glenohumeral joint under coupled moment loads. *J Shoulder Elbow Surg, 7*, 629-639.

Oh, J. H., Rhee, S. M., Park, J. H., Lee, K. J., Yoon, J. Y., Jeon, Y. D., & Kim, H. S. (2022). Quantitative magnetic resonance imaging assessment of the infraspinatus and teres minor in massive rotator cuff tear and its significance in clinical outcome after rotator cuff repair. *J Shoulder Elbow Surg, 31*(1), 56-62. https://doi.org/10.1016/j.jse.2021.06.001

Otto, A., Scheiderer, B., Murphy, M., Savino, A., Mehl, J., Kia, C., Obopilwe, E., DiVenere, J., Cote, M. P., Denard, P. J., Romeo, A. A., & Mazzocca, A. D. (2021). Biconcave glenoids show 3 differently oriented posterior erosion patterns. *J Shoulder Elbow Surg, 30*(11), 2620-2628. https://doi.org/10.1016/j.jse.2021.04.028

Pan, P., Peshkin, M. A., Colgate, J. E., & Lynch, K. M. (2005). Static single-arm force generation with kinematic constraints. *J Neurophysiol, 93*(5), 2752-2765. https://doi.org/10.1152/jn.00799.2004

Papadonikolakis, A., Neradilek, M. B., & Matsen, F. A., 3rd. (2013). Failure of the glenoid component in anatomic total shoulder arthroplasty: a systematic review of the English-language literature between 2006 and 2012. *J Bone Joint Surg Am, 95*(24), 2205-2212. https://doi.org/10.2106/JBJS.L.00552

Parsons, I. M., Apreleva, M., Fu, F. H., & Woo, S. L. Y. (2002). The effect of rotator cuff tears on reaction forces at the glenohumeral joint. *Journal of Orthopaedic Research, 20*(3), 439-446. https://doi.org/Pii S0736-0266(01)00137-1. Doi 10.1016/S0736-0266(01)00137-1

Petersson, C. J. (1983). Degeneration of the gleno-humeral joint. An anatomical study. *Acta Orthop Scand, 54*(2), 277-283. https://doi.org/10.3109/17453678308996570

Raiss, P., Aldinger, P. R., Kasten, P., Rickert, M., & Loew, M. (2008). Total shoulder replacement in young and middle-aged patients with glenohumeral osteoarthritis. *J Bone Joint Surg Br, 90*(6), 764-769. https://doi.org/10.1302/0301-620X.90B6.20387

Sears, B. W., Johnston, P. S., Ramsey, M. L., & Williams, G. R. (2012). Glenoid bone loss in primary total shoulder arthroplasty: evaluation and management. *J Am Acad Orthop Surg, 20*(9), 604-613. https://doi.org/10.5435/JAAOS-20-09-604

Shields, E., & Wiater, J. M. (2019). Patient Outcomes After Revision of Anatomic Total Shoulder Arthroplasty to Reverse Shoulder Arthroplasty for Rotator Cuff Failure or Component Loosening: A Matched Cohort Study. *J Am Acad Orthop Surg, 27*(4), e193-e198. https://doi.org/10.5435/JAAOS-D-17-00350

Smith, A. C., Parrish, T. B., Abbott, R., Hoggarth, M. A., Mendoza, K., Chen, Y. F., & Elliott, J. M. (2014). Muscle-fat MRI: 1.5 Tesla and 3.0 Tesla versus histology. *Muscle Nerve, 50*(2), 170-176. https://doi.org/10.1002/mus.24255

Somerson, J. S., Hsu, J. E., Gorbaty, J. D., & Gee, A. O. (2016). Classifications in Brief: Goutallier Classification of Fatty Infiltration of the Rotator Cuff Musculature. *Clin Orthop Relat Res, 474*(5), 1328-1332. https://doi.org/10.1007/s11999-015-4630-1

Sperling, J. W., Kaufman, K., Schleck, C., & Cofield, R. H. (2008). A biomechanical analysis of strength and motion following total shoulder arthroplasty. *Int J Shoulder Surg, 2*(1), 1-3.

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. *J Shoulder Elbow Surg, 22*(4), 478-484. https://doi.org/10.1016/j.jse.2012.05.037

Stickley, C. D., Hetzler, R. K., Freemyer, B. G., & Kimura, I. F. (2008). Isokinetic peak torque ratios and shoulder injury history in adolescent female volleyball athletes. *J Athl Train, 43*, 571-577.

Storheim, K., & Zwart, J. A. (2014). Musculoskeletal disorders and the Global Burden of Disease study. *Ann Rheum Dis, 73*(6), 949-950. https://doi.org/10.1136/annrheumdis-2014-205327

Tingart, M. J., Apreleva, M., Lehtinen, J. T., Capell, B., Palmer, W. E., & Warner, J. J. (2003). Magnetic resonance imaging in quantitative analysis of rotator cuff muscle volume. *Clin Orthop Relat Res, 415*(415), 104-110. https://doi.org/10.1097/01.blo.0000092969.12414.e1

US Bone and Joint Initiative: The Burden of Musculoskeletal Diseases in the United States. (2014). Retrieved July 30, 2019, from http://www.boneandjointburden.org

Walch, G., Badet, R., Boulahia, A., & Khoury, A. (1999). Morphologic study of the glenoid in primary glenohumeral osteoarthritis. *J Arthroplasty, 14*(6), 756-760.

Walch, G., Moraga, C., Young, A., & Castellanos-Rosas, J. (2012). Results of anatomic nonconstrained prosthesis in primary osteoarthritis with biconcave glenoid. *J Shoulder Elbow Surg, 21*(11), 1526-1533. https://doi.org/10.1016/j.jse.2011.11.030

Walker, K. E., Simcock, X. C., Jun, B. J., Iannotti, J. P., & Ricchetti, E. T. (2018). Progression of glenoid morphology in glenohumeral osteoarthritis. *J Bone Joint Surg Am, 100*(1), 49-56. https://doi.org/10.2106/JBJS.17.00064

Wilcox, R. B., Arslanian, L. E., & Millett, P. (2005). Rehabilitation following total shoulder arthroplasty. *J Orthop Sports Phys Ther, 35*(12), 821-836. https://doi.org/10.2519/jospt.2005.35.12.821

Wu, G., van der Helm, F. C., Veeger, H. E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., Buchholz, B., & International Society of, 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. *J Biomech, 38*(5), 981-992. https://doi.org/10.1016/j.jbiomech.2004.05.042

Yoon, J. P., Jung, J. W., Lee, C. H., Kim, Y. G., Chung, S. W., Kim, J. Y., Lee, H. J., Yoon, J. W., & Lee, H. (2018). Fatty degeneration of the rotator cuff reflects shoulder strength deficits in patients with rotator cuff tears. *Orthopedics, 41*(1), e15-e21. https://doi.org/doi:10.3928/01477447-20171106-02

Yoshida, Y., Marcus, R. L., & Lastayo, P. C. (2012). Intramuscular adipose tissue and central activation in older adults. *Muscle Nerve, 46*(5), 813-816. https://doi.org/10.1002/mus.23506