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Dynamic acromiohumeral interval changes during scapular plane arm motions

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DYNAMIC ACROMIOHUMERAL INTERVAL CHANGES DURING SCAPULAR PLANE ARM MOTIONS

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ABSTRACT

This purpose of this dissertation is to explore changes in the acromiohumeral interval during dynamic motion in the scapular plane. All of the experiments were completed in the Football Operations Athletic Training Room at Louisiana State University. The first experiment which investigated dynamic acromiohumeral interval changes in baseball players during a loaded and unloaded scaption exercise from 0°-75°, has been accepted for publication by the Journal of Shoulder and Elbow Surgery (in press, 2010). The mean acromiohumeral interval (AHI) for unloaded and loaded scaption decreased significantly ($p<.001$) from the arm at the side until 45° and loaded scaption narrowed AHI at 60° ($p=.005$) and 75° ($p=.003$). The second experiment investigates AHI and scapular upward rotation (SUR) changes in baseball and softball players during scaption exercises from 0°-75°. Significant load related narrowing of the AHI at 45°($p=.005$), 60°($p=.001$), and 75°($p<.001$) and a significant load-position interaction ($p=.001$) at 0° and 75°was observed for all subjects. No gender differences in SUR or AHI were found. AHI and SUR displayed moderate positive correlations at 30° for both the unloaded scaption ($r=.648$, $p=.001$) and the loaded scaption ($r=.445$, $p=.038$) however, no significant relationships were present at 0°, 45°, 60° or 75°. The third experiment compared dynamic acromiohumeral interval and scapulohumeral rhythm changes in trained and untrained females during scaption exercises from 0°-90°. In general, AHI was maximal with the arm at the side and declined significantly ($p<.001$) during arm elevation until 60°, but increased significantly ($p<.001$) between 60° and 90°. Significant load related narrowing of the AHI at all positions ($p<.05$), a more negative SUR at 0° ($p<.001$) and a more positive SUR at 90° ($p=.009$) was observed for all subjects. Female athletes had significantly stronger external rotators ($p<.001$), larger overall AHI ($p=.003$) and

more SUR ($p=.008$) than untrained females. Significant positive correlations ($p<.05$) between AHI and SUR were observed at 0°, 30°, and 60° during both loaded and unloaded scaption.

CHAPTER 1
INTRODUCTION

Subacromial impingement syndrome (SIS), involves compression of the anatomical structures within the subacromial space, especially the tendons of the rotator cuff. As the humerus moves into flexion or abduction, decreases in subacromial space may result in "impingement" of the rotator cuff tendons and subacromial bursa between the humeral head and the acromion. Static analysis of the interval between the inferior surface of the acromion and the humeral head, the acromiohumeral interval (AHI), has led to the conclusion that a space less than 7 mm, at rest, is indicative of rotator cuff injury.[18,32,102] A normal range for AHI with the shoulder at rest may be a helpful diagnostic tool, but gives clinicians little knowledge about changes in the AHI in more functional and dynamic arm positions.

Neer, [75] who was one of the first to define SIS, divided this progressive disorder into three stages. Stage 1 is related to overuse in the overhead arm position and causes inflammation, including edema in the subacromial bursa and the supraspinatus tendon. Neer [75] postulates that most stage 1 patients are typically twenty-five years old or less. Patients who ignore stage one and continue to use the arm in the overhead position may develop stage 2, characterized by thickening of the bursa and fibrosis and damage to the supraspinatus and infraspinatus tendons. Stage 2 patients are typically twenty-five to forty years old. Further use may lead to stage 3, which is often seen in patients above the age of forty and results in tearing or fraying of the supraspinatus and infraspinatus tendons, possible rupture of the long head of the biceps tendon and alterations on the surface of the humeral head. As SIS progresses the patient loses functionality of the shoulder and suffers from increased pain.[7,57,58,68] While SIS may affect a variety of patient populations, increased incidence of SIS has been noted in athletes who participate in repetitive overhead sports, such as tennis, baseball, and swimming.[7,13]

Mechanisms behind the development of SIS are still widely debated.[7,63,71,98] Possible mechanisms can be globally divided into two categories, structural and functional. Structural mechanisms are believed to cause degenerative changes to the rotator cuff as a result of overuse or trauma to the rotator cuff tendons. Subsequent to damage of the rotator cuff, kinematic differences, muscle imbalances, osteophytes and other factors leading to impingement then occur. Alternatively, the functional theory follows that damage to the rotator cuff tendons is due to narrowing of the osseous AHI due to abnormal function of the shoulder/arm. Potential functional mechanisms include, posture, altered scapular kinematics, superior glenohumeral translations, range of motion abnormalities and capsular instabilities/tightness. Often patients suffering from SIS do not seek immediate care, thus making it difficult for clinicians to determine the stage of impingement progression and the factors initially present.

There is a general consensus that subacromial space is maximal at 0° and narrows during arm elevation, however, considerable debate still exists on which point in the range of motion it is the smallest and how this may affect the treatment of patients with SIS. Analysis of cadaver shoulders during passive motion[11,14] has identified 60° of elevation in both the sagittal and scapular plane as critical zones, where the rotator cuff is directly under, or in contact with, the acromion. However, *in-vivo* analysis of the AHI at 60 degrees in healthy subjects has led to a wide range of values between 4.7 mm and 9.94 mm.[3,20,33,35] This variability is partially due to the variety of scapular and glenohumeral kinematic factors that can impact the osseous AHI, large subject variability,[36] and differences in study designs. While the functional range of impingement symptoms is believed to occur between 60° and 120° of arm elevation,[7,28,71,105] previous research has failed to provide a suitable description of the dynamic AHI changes within this range of arm motion.

The following three experiments in this dissertation explore changes in dynamic acromiohumeral intervals during functional scaption exercises, which are commonly prescribed for strengthening of the rotator cuff musculature[27,73] in the prevention and rehabilitation of SIS. The purpose of experiment 1 was to test the hypothesis that a gradual narrowing of the AHI occurs during arm elevation in a scaption exercise regardless of the application of a normalized external load in baseball players. The purpose of experiment 2 was to test the hypothesis that an increase in scapular upward rotation would correlate to a larger AHI at higher arm positions, with both baseball and softball players demonstrating similar trends in dynamic AHI changes during the scaption exercises. The purpose of experiment 3 was to build on the findings of first two experiments and determine if untrained females demonstrate different dynamic AHI patterns than trained female athletes during loaded and unloaded scaption exercises.

CHAPTER 2
EXPERIMENT 1: DYNAMIC ACROMIOHUMERAL INTERVAL CHANGES IN BASEBALL PLAYERS DURING SCAPTION EXERCISES

While the mechanisms behind the development of subacromial impingement syndrome (SIS) are debated, the functional theory proposes that narrowing of the subacromial space may be injurious to the supraspinatus as it passes thru the coracoacromial arch and inserts on the greater tuberosity of the humerus.[7,14,63,71] Development of SIS has been related to overuse in the overhead arm position[75] with increased incidence in overhead athletes[13,59] and those who participate in frequent overhead work related tasks, such as construction workers.[10] Based on cadaver analysis[14,28] and in-vivo magnetic resonance (MR) studies,[33,35] as the humerus moves into flexion or abduction, decreases in subacromial space may result in "impingement" of the rotator cuff tendons and subacromial bursa between the humeral head and the acromion. Previous research has established the acromiohumeral interval or distance (AHI) as a quantitative method for evaluating the size of the subacromial space.[18,20,32-35,37,41,81] Narrowing of the AHI has been observed during arm elevation in healthy subjects[20,37,41] with even greater narrowing observed in SIS subjects during muscle activity.[35] Both scapular retraction[88] and adduction muscle activity[34] have been shown to widen the space, and Desmueles et al[20] reported a strong positive relationship between the reduction of AHI narrowing and functional improvement in SIS patients. Alterations in AHI appear to be related to SIS and may be important in the therapeutic treatment and prevention of this disease, yet little is known about the changes in AHI during dynamic arm motions.

Previous investigations have reported that isometric activity of the abductor muscles appears to decrease AHI approximately 53%,[37,43] but it is unknown if the AHI is affected differently by static (isometric) or dynamic muscle activity. Based on Neer's[75] description of

SIS as an "overuse condition" and the increased incidence of SIS in overhead athletes[13,59] who are engaged in repetitive dynamic arm movements, it seems necessary to study AHI changes during similar types of functional muscle activity. Baseball athletes have demonstrated larger passive AHI values than matched controls at 90° of abduction (frontal plane)[99]; however, as these results were conducted with passive arm positions it is difficult to determine how muscle dynamic muscle activity may affect this at-risk population. The only dynamic, *in-vivo* study of AHI was performed on the contralateral shoulder of rotator cuff repair patients.[5] Using bi-plane radiographs and re-constructed computed tomography (CT) images, the subacromial space ranged from 1.2 mm to 7.1 mm during loaded, active arm elevation in the frontal plane between 0° and 120°. An AHI of 1.2 mm at approximately 120° represents the smallest reported AHI. However, most AHI analysis has been performed in the more functional scapular plane.

Recent advances in the image quality of digital fluoroscopic video (DFV) have made it an attractive imaging modality for the shoulder joint during static and dynamic motion. DFVs have been used to study subacromial spurs,[66] scapulohumeral rhythm,[67] subtle glenohumeral joint instabilities,[79] and superior migration of the humeral head.[91] Teyhen et al[91] demonstrated excellent reliability when using DFV during dynamic arm elevation in the scapular plane. DFV expose the subject to significantly less radiation than conventional radiographs without reduction in diagnostic accuracy.[45] In addition to the enhanced safety for subjects, DFV allows for dynamic analysis during functional and upright positions and may provide a more viable method for capturing *in-vivo* AHI.

Clinicians also have limited knowledge of the direct effect of rehabilitation exercises on AHI. Scaption is a commonly prescribed shoulder exercise that has been used for assessment of scapular dysfunction[48] and for strengthening of the rotator cuff musculature.[27,73] The scaption

exercise is often performed as part of a shoulder strengthening/maintenance program in overhead athletes, yet little is known about the affect of this exercise on the AHI in this population. Scaption involves raising the arm from the resting position to approximately 90° in the plane of the scapula, which is 30°-40° anterior to the frontal plane. The addition of external loads during the scaption exercise is commonly prescribed for strengthening purposes, but appears to increase scapular protraction,[80] which has been linked to decreases in AHI.[88] However, loaded scaption increases the activity of the rotator cuff muscles,[1] which should lead to increased stability of the humeral head on the glenoid during abduction and thus better maintenance of subacromial space. Since clinicians often prescribe this exercise for healthy and pathological patients, it is important to understand how AHI is directly affected during loaded and unloaded conditions. Therefore, the purpose of this study is to examine changes to AHI during an unloaded and loaded scaption exercise in healthy, baseball athletes using digital fluoroscopy. We hypothesize a gradual decrease in the AHI during arm elevation, and we expect 60° to be the smallest AHI value. We do not believe that the addition of the load will result in any significant changes in AHI in baseball players.

MATERIALS AND METHODS

We recruited 16 healthy, NCAA division I, baseball players from a Southeastern University. Participant inclusion was based on no history of shoulder disorders and no current shoulder, arm, neck or back pathology. To ensure that study participants were currently without pathology we administered a screening questionnaire and consulted with the team's Certified Athletic Trainer. We also screened all participants for hooked acromion morphology according to Bigliani's criteria[6] using a standard outlet fluoroscopic radiograph.[76] All participants had either a flat (type 1) or slightly curved (type 2) acromion; none of the participants exhibited hooked (type 3) acromions or bony osteophytes within the subacromial region. All participants

were right hand dominant. One participant was excluded because he was unable to fit within the Mini C-Arm, and two participants were excluded based on improper image recording, resulting in data from 13 participants. Each participant signed an informed consent form approved by the University's Internal Review Board, IRB# 2778.

Instrumentation

We obtained all DFV sequences with an Orthoscan HD Mini C-Arm (Orthoscan, Scottsdale, AZ) that had a resolution of 1000 X 1000 pixels per image. The images were collected at 30 Hz and recorded using a digital video recorder. Videos were transferred to a laptop computer and analyzed using OsiriX imaging software (version 3.6.1; open source software for MacOS X). The Osirix imaging software converted all DFVs into sequences of still frames. Pixel width calibration was determined during pilot testing using a radiopaque calibration device on the image intensifier of the C-arm. Based on data from pilot testing, a consistent pixel width calibration value was obtained and used for all subsequent data.

Imaging Protocol

The DFVs were obtained in a manner similar to that described by Poppen and Walker[82] and Teyhen et al.[91] Due to limitations in positioning of the C-arm, participants were seated with the elbow fully extended, palm facing forward and the thumb towards the ceiling. The C-arm was rotated 30 degrees from the frontal plane, such that the X-ray beam was perpendicular with the plane of the scapula and adjusted for each subject until a single glenoid rim was present on the image. The posterior shoulder was placed in direct contact with the image intensifier to minimize image distortion. The height of the C-arm was adjusted for each participant so that the acromion and humeral shaft were adequately visible. A board was placed in the participant's scapular plane to ensure that the participants moved in a consistent scapular plane during all trials. A device was placed on the board to prevent scaption past 90° during each trial. The

participants were instructed to remain in the same comfortable, upright posture during the trials. One researcher monitored arm elevation during the trials, as well as any compensatory trunk or shoulder/arm movements.

FIGURE 1. Setup and participant positioning during data collection.

Participants performed dynamic arm elevations in the scapular plane from the arm positioned at the side until 90° with and without resistance. The hand remained in neutral position, with the palm facing forward and thumb towards the ceiling. The amount of resistance was adjusted for each participant based on limb anthropometrics,[52,56] that was calculated using bodyweight, height, and arm length. The formula used to determine resistance was modified from that previously used in research with upper[52] and lower[56] extremity muscles. This formula ensured a comparable level of effort across the participants on the loaded trials. Average resistance used was 3.6 kg with a range of 2.6 – 4.4 kg. The participants were instructed to perform three consecutive trials of unloaded and loaded scaption, with approximately three minutes between the unloaded and loaded conditions. Each arm elevation trial, from the arm at the side up to 90°, was performed at a speed of 3 seconds and was controlled using visual and

auditory cues. DFVs were only captured on the last two trials of each condition in order to minimize radiation exposure to the participants.

Radiographic Analysis

The best sequence of images out of two captured trials for each condition was used to calculate acromiohumeral interval (AHI) and humeral angle. AHI was calculated in a method similar to Petersson and Redlund-Johnell [81] which was defined as the smallest vertical distance between the dense cortical line of the acromion and the most superior aspect of the humerus.

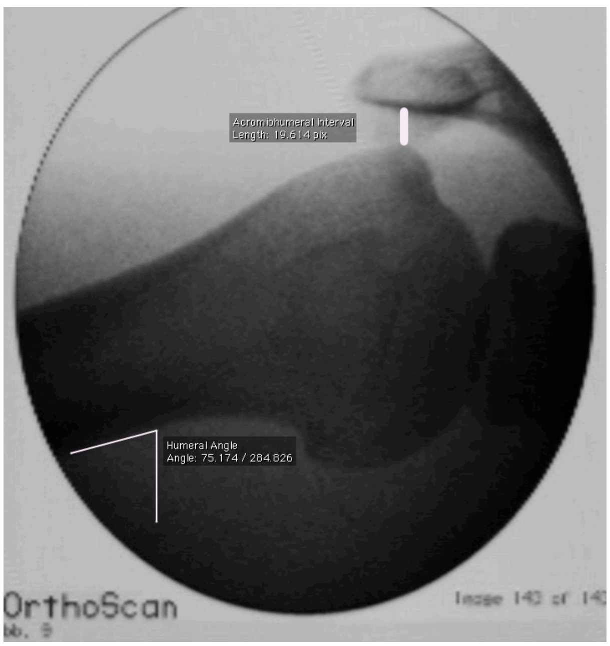

FIGURE 2. Sample data analysis image at 75°.

Humeral angle was defined as the angle between a line drawn on the shaft of the humerus and a line drawn vertically, representing the axis of the body. One researcher (MT), who was blinded, reviewed all frames and performed all measurements. A musculoskeletal radiologist, who reviewed images for 4 out of 13 randomly selected participants verified measurement accuracy. AHI was only measured on the image frames that corresponded to the following humeral angles: arm at side (as close to 0 degree as possible for each participant), 30°, 45°, 60°, and 75°. A relatively small (15.24 cm) viewing window on the C-arm did not allow for adequate view of the

acromion past a 75° humeral angle; therefore, although elevation was continued to 90°, data could be reliably captured only to 75°. Humeral angle values were selected to allow comparisons with the results from previous studies.[35,37]

STATISTICAL ANALYSIS

During pilot testing, an intra-class correlation coefficient (ICC) model (2,1) was used to measure the test-retest reliability, and the standard error of the measurement (SEM) was calculated to determine variability due to random error.[103] Short-term test-retest reliability was established during pilot testing of 5 healthy, college males by comparing AHI within participants with the arm at the side (ICC = .98, SEM = .01 mm) and at 30° (ICC = .96, SEM = .02 mm), 45° (ICC= .99, SEM= .02 mm), 60° (ICC = .97, SEM = .01 mm), and 75° (ICC = .75, SEM = .03 mm) of elevation from 2 unloaded trials captured approximately five minutes apart. Long-term test-retest reliability was determined by retesting the loaded trials of 5 healthy baseball players with 9 months between trials (Rest ICC = .96, SEM= .08 mm; 30° ICC = .30, SEM= .24 mm; 45° ICC = .43, SEM= .12 mm; 60° ICC = .82, SEM= .12 mm; 75° ICC = .98, SEM= .06 mm).

The effect of resistance on AHI during scaption was tested with a 2 x 5 repeated measures analysis of variance (ANOVA). The independent variables used were resistance (unloaded and loaded) and arm position (arm at the side, 30°, 45°, 60°, and 75°). Herein, the position of the arm at the side will be referred to as 0°. The dependent variable was the AHI, measured in millimeters. The α level was set at .05. Post hoc analysis, when applicable, was performed using paired t tests with a Bonferroni correction. Data analysis was accomplished with the following software packages: OsiriX (version 3.6.1; open source software for MacOS X), Excel (Professional Edition 2003; Microsoft Corp, Redmond, WA), and SPSS (version 17.0; SPSS inc, Chicago, IL).

RESULTS

Data was collected on 13 healthy, NCAA Division I baseball players. Age, weight and height values were 20.1 ± 1.1 years, 85.3 ± 6.7 kg, 179.3 ± 6.8 cm respectively.

The mean AHI for both unloaded and loaded scaption decreased significantly ($p < .001$) from the arm at the side (12.7 mm) until 45° (4.9 mm), further changes in the mean AHI between 45°, 60°, and 75° were not significantly different (main effect for arm position, $F = 87.3$, $p<.001$).

TABLE 1. Descriptive statistics for acromiohumeral intervals (AHI) at selected humeral angles. (N =13)

	Unloaded AHI (Mean ± Std)	**Unloaded SEM**	**Loaded AHI (Mean ± Std)**	**Loaded SEM**
0°	12.8 ± 2.1 mm	.575 mm	12.5 ± 2.3 mm	.632 mm
30°	6.9 ± 2.7 mm	.743 mm	7.0 ± 2.5 mm	.696 mm
45°	5.2 ± 2.1 mm	.591 mm	4.7 ± 1.4 mm	.387 mm
60°	5.3 ± 2.1 mm	.594 mm	4.1 ± 1.7 mm	.483 mm
75°	6.1 ± 3.3 mm	.911 mm	4.6 ± 2.5 mm	.692 mm

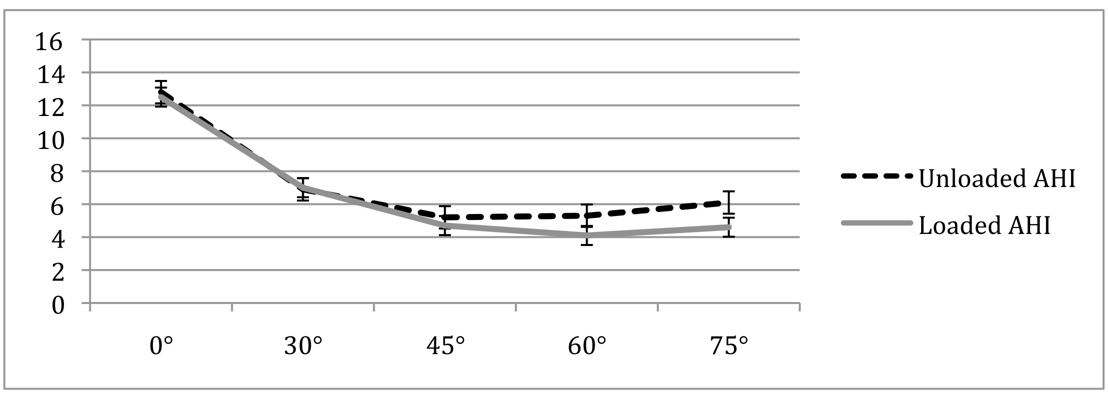

FIGURE 3. Graph of mean acromiohumeral interval (AHI) in millimeters for unloaded and loaded scaption at each humeral angle. Error bars represent average SEM values across unloaded and loaded scaption, respectively. (N = 13)

Generally, loaded scaption resulted in smaller AHI values at 45°, 60°, and 75° (main effect for resistance, $F= 6.7$, $p = .024$), however only the differences at 60° ($p = .005$) and 75° ($p = .003$) were significant). The difference between unloaded and loaded at 45°was not significant ($p = .247$); however, based on a small effect size (.297) for the resistance and position interaction we did not have enough subjects to detect whether a true difference exists at this arm position.

Mean AHI for both the unloaded and loaded scaption exercises at each humeral angle are presented in Table 1 and Figure 3.

DISCUSSION

Results from the analysis of dynamic AHI during scaption indicate decreases in AHI from the resting position thru 60°, and are similar to previous passive and static AHI analyses. Arm elevation from 0° - 30° has typically been described as the scapular setting phase,[44,78] in which the scapula contributes little to total arm elevation. Our findings of large reductions in the AHI between the arm at rest and 30° support the concept that initial humeral elevation with little or no scapular upward rotation results in significant narrowing of the AHI during early arm elevation. Although we observed further narrowing of the AHI until 60°, we suspect that increases in scapular upward rotation in this range contributed to relatively less narrowing of the AHI as compared to the 0° – 30° range. Our unloaded scaption findings with the arm at the side (12.8 ± 2.1 mm) are larger than those reported by Wang et al (7.8 ± 3.6 mm),[99] and Desmueles et al (9.9 ± 1.5mm),[20] however we captured AHI with the arm at the side during transition from eccentric lowering of the arm to concentric raising of the arm, not at rest. Capturing AHI during uninterrupted dynamic motion represents functional arm motion and likely results in a different neuromuscular and kinematic pattern as compared to static positioning. In addition, variability in humeral position with the arm at the side, due to anatomical and body type variations, also may contribute to the differences between the studies.

It is possible that differences in AHI exist based on patient positioning (supine, seated, or standing) however we found similar results between our seated scaption and the supine positioning used in MR imaging studies with isometric muscle activity[35,43] at both 30° and 60°. While the standing position may contribute slightly to scapular stabilization through kinetic

chain mechanisms, further research is needed to determine if the seated or standing positions contribute to neuromuscular-related changes in AHI. Only one other study has examined AHI at 45°,[20] and our findings are much smaller, but significant differences in methodology exist between the two studies, such as plane of movement, ultrasound versus DFV, and static versus dynamic motion. Although not significantly different from the AHI at 60°, a trend towards a widening of the AHI at 75° does occur. Based on observations during data analysis, at a humeral angle of 75° most of the subject's greater tubercles appeared to have passed thru the subacromial space and was no longer directly under the lateral edge of the acromion, leading to a wider AHI interval. Although no measurements were taken, the passage of the greater tubercle thru the subacromial space appeared to occur between 60° and 75° for most subjects, which is similar to previous analysis using cadaveric specimens.[11,14] Slight differences between humeral angle calculations from radiographs and clinical/goniometric measurements have been previously reported[82] to be 6°. Given possible examiner error in goniometric measurements, the humeral angles we report are likely similar, but not identical, to the arm angles observed by clinicians. Differences in reporting AHI based on calculation of arm range of motion and planes of motion make it difficult to compare our results to the only other dynamic analysis of AHI by Bey et al;[5] however, the trend in a decreasing AHI from rest through abduction appears to be similar to their results. Our ability to analyze dynamic AHI from the arm at the side until only 75° represents a limitation in our results, as previous investigators have indicated further narrowing of the AHI at 90 degrees.[34,35,99]

No previous research has studied the effect of loaded versus unloaded on AHI during dynamic shoulder elevation. We found that adding a load to a scaption exercise results in a significantly smaller AHI at 60°and 75° in healthy, baseball athletes. The size of the AHI at 75°

during un-loaded scaption represented 48% of the AHI present with the arm at the side, whereas the size of the AHI during loaded scaption at 75° represents only 37% of the AHI present with the arm at the side. While loaded scaption appears to result in an additional narrowing of 11% during scaption at 75°, no subjects reported pain during the exercise, indicating that the additional reduction caused by the weight did not result in acute impingement in these subjects.

Although we did not directly measure any scapular positions or motions, it is possible that narrowing of the AHI during loaded scaption may be related to differences in shoulder kinematics caused by the addition of the load. Similar loading of the arm during elevation has been shown to decrease scapular upward rotation[50,70] and increase scapular protraction.[80] Protraction of the scapula may result in a more anterior acromial position and is known to cause narrowing of the subacromial space at rest.[39,88] Failure of the scapula to upwardly rotation during humeral elevation increases the scapulohumeral rhythm and is believed to result in a more inferiorly positioned acromion.[30,48,60,64,89,95] During humeral elevation the encroachment of the greater tuberosity to the acromion has been found to occur between 48° and 90°,[28] thus a more anterior or inferior acromion due to scapular kinematic alterations are likely to result in significant narrowing of the AHI in this range.

It is important to note that differences in the resting scapular posture between dominant and non-dominant arms[77,93] and baseball athletes and controls[74] have been noted, thus our results may not correspond outside of the baseball population. Wang et al[99] were the only others to present AHI values specific to baseball players, although they used static ultrasound images to measure the AHI. They demonstrated relatively larger passive AHI values at 0° and 90° in the frontal plane for healthy athletes compared to anthropometrically matched controls, yet not in the scapular plane. More dynamic AHI analysis between athletes and non-athletes is warranted.

The addition of the load did not affect the AHI between the arm at the side and 45°. Alpert et al[1] reported peak muscle activity for the rotator cuff muscles between 30° and 60°, and noted the largest increases in muscle activity with additional loads during this range. Between 0° and 60° the deltoid produces a significant upward shear force on the humerus, which may result in superior humeral head migration and narrowing of the AHI. The rotator cuff muscles counteract this upward shear force and keep the humeral head centered on the glenoid, while the scapular stabilizer muscles impact the relative position of the acromion. Thus, increased rotator cuff or scapular stabilizer muscle activity in the lower arm elevation positions may assist in maintaining AHI in the ranges of 0 - 45°. Further research is necessary to determine the relationship of these two muscle groups in regards to maintenance of AHI during dynamic arm motions.

Supine MRI examinations of 3 patients with rotator cuff tears reported a 3 mm reduction of AHI at 30°, while only a 1 mm reduction at 90°,[35] which provides further support for the influence of the rotator cuff on AHI in lower arm elevation positions. The strength of the rotator cuff muscles, specifically external rotation, has been shown to result in decreased subacromial pressures, measured in-vivo with pressure transducers implanted in the subacromial space.[104] We presume that our healthy, baseball players who regularly participate in rotator cuff strengthening exercises had strong and functional rotator cuff muscles that were successful in maintaining AHI, despite the added load, during these lower arm elevations. Although we did not measure shoulder strength, all subjects were currently engaged in a similar shoulder strength training programs. Fatigue of the rotator cuff muscles has been shown to increase upward migration of the humeral head in healthy subjects;[15,91] however, since our subjects only performed 3 repetitions of scaption and rested between loaded and unloaded trials, it is unlikely that fatigue

would be a factor in these differences. Further dynamic AHI examinations are necessary to determine exactly how those with untrained or dysfunctional rotator cuff muscles may respond to loaded scaption exercises in the 0 – 60° range of arm elevation.

We examined changes in AHI during a loaded and unloaded scaption exercise using DFV, providing the first study to directly record dynamic AHI using DFV to our knowledge. Previous studies have used DFV only to capture humeral head migration[91] during dynamic arm movements. DFVs cannot capture of all the kinematic factors involved in defining AHI, but they do allow for dynamic analysis using methods of radiographic image acquisition and measurement frequently used to diagnose rotator cuff injury.[18,32,81] Although our AHI findings were similar to previous MR studies with muscle activity,[33,35,43] limitations due to two-dimensional viewing and lack of ability to visualize soft tissue structures, such as articular cartilage and the supraspinatus tendon do exist in this method of AHI analysis. Despite the limitations, the use of DFV adds an important dynamic component to the understanding of subacromial space changes during arm abduction. Short-term test-retest reliability analysis done during pilot testing indicated excellent reliability between testing sessions performed on the same day. Long-term test-retest reliability revealed that some variability exists in the early phases of arm elevation (0° – 45°); however, good to excellent reliability occurred during the later phases of arm elevation. The lack of a significant F value during ICC analysis and low SEM values indicate that systematic error was not a factor in the poor reliability during the early phases of arm elevation. High intra-subject variability for scapular positioning and shoulder kinematics during the scapular setting phase (0° – 30°) of arm elevation is well accepted in the literature,[44,67,78,85] and may significantly contribute to the variability seen only in the low ranges of arm elevation. Furthermore, the good to excellent reliability observed at humeral angles of

60° and 75° supports the concept of differences in reliability based on range of motion. Based on the test-retest results we believe that DFVs provide can provide very reliable intra-subject analysis of dynamic AHI during scapular plane elevation (0° – 75°), however caution should be exercised when comparing results in the lower ranges of elevation when significant time exists between sessions.

CONCLUSION

In conclusion, we found significant reductions in AHI during dynamic scaption exercises with even greater reductions in AHI noted at 60°and 75° during loaded scaption in healthy, baseball athletes. Because of the approximately 11% further reduction in AHI with the load, we urge clinicians to be cautious in their use of loaded scaption exercises, especially in cases where AHI may already be narrow or in cases of current subacromial inflammation. We recommend that more research be done during functional arm activities to determine which activities are safe for athletes and patients with SIS. The differences between loaded and unloaded AHI seem to suggest that scapular position may be a key factor in AHI at this position, however more investigation into the direct relationship of scapular position, rotator cuff muscle activity, and AHI are necessary before any firm conclusions can be made.

CHAPTER 3
EXPERIMENT 2: DYNAMIC ACROMIOHUMERAL INTERVAL AND SCAPULAR UPWARD ROTATION CHANGES IN BASEBALL AND SOFTBALL PLAYERS

Subacromial impingement syndrome, involves compression of the anatomical structures within the subacromial space, especially the tendons of the supraspinatus and infraspinatus of the rotator cuff muscle group. As the humerus moves into flexion or abduction, decreases in subacromial space may result in "impingement" of the rotator cuff tendons and subacromial bursa between the humeral head and the acromion. Static analysis of the space in which the supraspinatus tendon passes, the acromiohumeral interval (AHI), has been extensively studied with the arm at rest, leading physicians to use narrowing of the AHI less than 7 millimeters (mm) as a diagnostic tool for rotator cuff injury.[18,32,102] Recently, more attention has focused on measuring the AHI beyond the resting position since the functional range of impingement symptoms is believed to occur between 60° and 120° of arm elevation.[7,28,71,105]

In-vivo analysis of the AHI at 60° in healthy subjects has lead to a wide range of values between 4.7 mm and 9.94 mm.[3,20,33,35] This variability is partially due to the variety of scapular and glenohumeral kinematic factors that can impact the osseous AHI, large subject variability,[36] and differences in study designs. Findings from these studies describe narrowing of the AHI during static arm elevation positions beyond 0°,[3,20,33-35,37,41,99] but do not provide a suitable description of AHI during dynamic arm movements. Furthermore, significant reductions in AHI have been noted with isometric abduction activity at 60°[35] and 90°;[34] however, the influence of dynamic muscle activity on AHI is relatively unknown.

Recent advances in the image quality of digital fluoroscopic video (DFV) have made it an attractive imaging modality for the shoulder joint during static and dynamic motion.[66,67,79,91]. Experiment 1 demonstrated excellent reliability when using DFV during dynamic arm elevation

in the scapular plane. In addition to the reduction in radiation exposure compared to conventional radiographs,[45] DFV allows for dynamic analysis during functional and upright positions and may provide a viable method for capturing *in-vivo* AHI. The dynamic AHI measurements taken with DFV in the scapular plane during experiment 1 indicate that the AHI is the most narrow in baseball players at 45° and 60° (5.2 ± 2.1 mm), with approximately 11% further reduction in AHI during the addition of a load during the exercise at 60° and 75°.

The possibility of a gender effect on AHI, especially at rest and lower arm elevation positions has been noted, but no dynamic AHI analysis with separate gender effects has been performed. Petersson and Redlund-Johnell[81] reviewed 175 radiographs with the shoulder at rest and noted that on average, females had an AHI 1.0 mm smaller than males. Graichen et al[34] reports that females on average had a 1.2 mm smaller AHI than males at 30 degrees, however this difference was not present at 90 degrees with and without isometric muscle activity. Gender differences at lower arm elevation positions may be the result of a relationship between anthropometric variables and AHI at rest, however muscle activity, especially during higher arm elevation positions, may negate these differences.[38] Interestingly, no research related to AHI has been reported on trained female athletes.

Much of the research effort related to the etiology of subacromial impingement has focused on scapular and glenohumeral kinematics and some of the indirect factors (muscle activity, posture) related to altered kinematics.[7,12,48,63,71] The width of the osseous AHI is affected by two independent kinematic factors, the position of the humeral head on the glenoid fossa and the position of the scapula. Scapular position, which directly relates to acromial position, is known to be different in patients with SIS, especially during dynamic arm movements. [57,58,60,64,68] Of particular importance is the relationship between scapular upward

rotation (SUR) and humeral motion during arm elevation, commonly referred to as scapulohumeral rhythm. Failure of the scapula to upwardly rotation during humeral elevation increases the scapulohumeral rhythm and is believed to result in a more inferiorly positioned acromion.[30,47,60,64,89,95] Thus, decreases in SUR may effectively lead to impingement and narrowing of the AHI during arm elevation.[26,60] To date, it appears that Graichen et al[37] is the only study to have evaluated the *in-vivo* relationship between AHI and SUR. They found differences in AHI relative to abducting versus abducting muscle activity, yet no changes in scapular kinematics (including SUR) were noted between the different muscle activities. While they did not directly compare the relationship between AHI and SUR, the use of isometric muscle activity and the supine positioning may partially explain why no difference in scapular kinematics was found.

Knowledge of the direct relationship between SUR and dynamic AHI may affect clinical diagnoses and treatment, especially related to shoulder impingement pathologies in at risk populations, such as overhead athletes. Baseball athletes with shoulder pathologies are known to exhibit scapular dyskinesis, which has been defined by Kibler[48] as alterations in the resting position and kinematics of the scapular during arm movements.[13,47,48] However, healthy baseball athletes appear to have increased SUR,[24,53,74] indicating that they may have adapted to protect the shoulder from impingement during arm elevation by effectively widening the AHI. The results of our previous experiment 1, indicate that baseball players still experience a narrowing of the AHI during loaded arm elevation 60 and 75 degrees, however it is uncertain if and how SUR may be related to these changes in dynamic AHI.

The purpose of this study was to compare the changes in dynamic AHI and SUR and their relationship during a loaded and unloaded scaption exercise in collegiate baseball and softball players using DFV. Based on the results of experiment 1 and previous findings in the

literature, our hypothesis was that an increase in SUR would correlate to a larger AHI. Furthermore, it was expected that baseball and softball athletes would exhibit similar AHI values during the dynamic exercises at all positions.

METHODS

We recruited 12 healthy, NCAA division I, baseball and softball players from a southeastern university. Inclusion criteria were no history of shoulder disorders or current shoulder, arm, neck or back pathology. Pitchers were also excluded from participation. To ensure that study participants were currently without pathology we administered a screening questionnaire and consulted with the team's Certified Athletic Trainer. No participant reported a previous diagnosis of subacromial impingement syndrome or surgery on the dominant arm. All participants were right hand dominant. We also screened all participants for hooked acromion morphology according to Bigliani's criteria[6] using a standard outlet radiograph and administered the clinical tests for subacromial impingement (Neer Impingement test and Hawkins-Kennedy test) and shoulder instability (Apprehension test). All participants had either a flat (type 1) or slightly curved (type 2) acromion, no participants exhibited a hooked (type 3) acromion or bony osteophytes within the subacromial region. Three participants, one baseball and two softball, were excluded based on improper image recording, resulting in data from 21 participants. Each participant signed an informed consent form approved by the university's Internal Review Board.

We obtained all DFV sequences with an Orthoscan HD Mini C-Arm (Orthoscan, Scottsdale, AZ) that had a resolution of 1000 X 1000 pixels per image. The images were collected at 30 Hz and recorded using a digital video recorder. Videos were transferred to a laptop computer and analyzed using Osirix imaging software (version 3.6.1; open source

software for MacOS X). The Osirix imaging software converted all DFVs into sequences of still frames.

Imaging Protocol

The DFVs were obtained in a manner similar to that described by Poppen and Walker[82] and Teyhen et al[91]. Due to limitations in positioning of the C-arm, participants were seated with the elbow fully extended, palm facing forward and the thumb towards the ceiling. The C-arm was rotated 30 degrees from the frontal plane, such that the X-ray beam was perpendicular with the plane of the scapula and adjusted for each subject until a single glenoid rim was present on the image. The posterior shoulder was placed in direct contact with the image intensifier to minimize image distortion. The height of the C-arm was adjusted for each participant so that the acromion and humeral shaft were adequately visible. A board was placed in the participant's scapular plane to ensure that the participants moved in a consistent scapular plane during all trials. A device was placed on the board which did not permit scaption past 90 degrees of elevation during each trial. The participants were instructed to remain in the same comfortable, upright posture during the trials. One researcher monitored arm elevation during the trials, as well as any compensatory trunk or shoulder/arm movements.

Participants performed dynamic arm elevations in the scapular plane from the arm positioned at the side until 90 degrees with and without resistance. The hand remained in neutral position, with the palm facing forward and thumb towards the ceiling. The amount of resistance was adjusted for each participant based on limb anthropometrics,[52,56] which was calculated using bodyweight, height, and arm length. Average load used for baseball athletes was 3.9 kg with a range of 3.2 - 4.5 kg and average load for the softball athletes was 2.5 kg with a range of 1.8 – 3.2 kg. The participants were instructed to perform three consecutive trials of unloaded and loaded scaption, with approximately three minutes between the unloaded and loaded conditions.

Each arm elevation trial, from the arm at the side up to 90 degrees, was performed at a speed of 3 seconds and was controlled using visual and auditory cues. DFVs were only captured on the last two trials of each condition in order to minimize radiation exposure to the participants.

Radiographic Analysis

The best sequence of images out of two captured trials for each condition was used to calculate AHI, SUR and arm angle. AHI was calculated in a method similar to Petersson and Redlund-Johnell[81] and was defined as the smallest vertical distance between the dense cortical line of the acromion and the most superior aspect of the humerus. Arm angle was defined as the angle between a line drawn on the shaft of the humerus and a line drawn vertically. SUR position was defined in a method similar to Poppen and Walker,[82] as the angle between a line drawn from the superior tubercle of the glenoid to the inferior tubercle of the glenoid and a sagittal line. A downward facing glenoid indicated a negative angle, while an upward facing glenoid was a positive angle. One researcher, blind to the experimental conditions, reviewed all frames and performed all measurements. A musculoskeletal radiologist, who reviewed randomly selected images at various times during the analysis, subjectively verified measurement accuracy. AHI and SUR were only measured on the image frames that corresponded to the following arm angles: arm at side (as close to 0° as possible for each participant), 30°, 45°, 60°, and 75°. A relatively small (15.24 cm) viewing window on the C-arm did not allow for adequate view of the acromion past a 75° arm angle; therefore, although elevation was continued to 90°, data could only be reliably captured to 75°. Arm angle values were selected to allow comparisons with the results from previous studies.[3,20,33,35,37]

Data Analysis

During pilot testing in experiment 1, short-term reliability of the same protocol was determined to be excellent. Pixel width calibration was also determined to be highly reliable in experiment 1; therefore a consistent pixel width calibration value was used for all data analysis. The effect of load on AHI during scaption was tested with a 2 x 2 x 5 repeated measures analysis of variance (ANOVA). The within subject independent variables used were load (loaded and unloaded) and arm position (arm at the side, 30°, 45°, 60°, and 75°). The between subject independent variable was gender. The dependent variable was the AHI, measured in millimeters. A separate 2x2x5 repeated measure ANOVA was performed with the same independent variables and the dependent variable was SUR. Pearson bivariate correlation tests were used to analyze the relationship between AHI and SUR at each humeral angle for both the unloaded and loaded conditions. Arm length, height, and weight were tested as covariates for each analysis. The α level was set at .05 for all analyses. Post hoc analysis was performed using paired t tests with a Bonferroni correction. Data analysis was accomplished with the following software packages: OsiriX, Excel (Professional Edition 2003; Microsoft Corp, Redmond, WA), and SPSS (version 17.0; SPSS inc, Chicago, IL).

RESULTS

Dynamic Acromiohumeral Interval

Data was collected from 11 healthy baseball athletes and 10 healthy softball athletes at the division 1 level. Age, weight and height values for the baseball athletes are 19.9 ± 0.9 years, 87.7 ± 6.9 kg, and 1.78 ± .04 m, respectively. Age, weight and height values for the softball athletes are 19.5 ± 0.8 years, 70.5 ± 9.2 kg, and 1.65 ± .04 m, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the effect of position and the interaction of position and load, thus a Greenhouse-Geisser correction was applied to the

degrees of freedom during the ANOVA tests. Table 2 and 3 provide descriptive statistics for the acromiohumeral interval during unloaded and loaded scaption, respectively.

TABLE 2. Descriptive statistics for acromiohumeral intervals (AHI) during unloaded scaption.

	Baseball Unloaded AHI (Mean ± Std) n=11	Softball Unloaded AHI (Mean ± Std) n=10	Overall (Mean ± Std) n=21
0°	12.9 ± 1.9 mm	10.7 ± 1.1 mm	11.8 ± 1.9 mm
30°	7.7 ± 2.8 mm	7.0 ± 2.8 mm	7.4 ± 2.8 mm
45°	5.4 ± 1.8 mm	5.2 ± 1.9 mm	5.3 ± 1.8 mm
60°	4.6 ± 1.6 mm	4.5 ± 1.8 mm	4.6 ± 1.6 mm
75°	5.4 ± 2.0 mm	5.3 ± 1.6 mm	5.4 ± 1.8 mm

TABLE 3. Descriptive statistics for acromiohumeral intervals (AHI) during loaded scaption.

	Baseball Loaded AHI (Mean ± Std) n=11	Softball Loaded AHI (Mean ± Std) n=10	Overall (Mean ± Std) n=21
0°	13.1 ± 2.5 mm	10.9 ± 1.5 mm	12.1 ± 2.4 mm
30°	7.7 ± 2.8 mm	6.7 ± 2.7 mm	7.2 ± 2.5 mm
45°	4.4 ± 0.9 mm	4.5 ± 1.6 mm	4.5 ± 1.3 mm
60°	3.7 ± 1.0 mm	3.8 ± 1.6 mm	3.7 ± 1.3 mm
75°	4.5 ± 1.6 mm	4.3 ± 1.4 mm	4.4 ± 1.4 mm

The main effects for position ($F = 109.8$, $p < .001$) and resistance ($F = 12.9$, $p = .002$) were significantly different and a significant linear interaction of position and resistance ($F = 3.0$, $p = .04$) was found. In general, the mean AHI for both conditions was maximal with the arm at the side (11.9 mm) and declined significantly during arm elevation until 45°(4.9 mm). The smallest mean AHI for both conditions and genders occurred at 60 degrees (4.2 mm); however the AHI at 45°, 60°, and 75°were not significantly different. The addition of the load during the scaption exercise resulted in a significant narrowing of the AHI at 45°($t= 3.1$, $p = .005$), 60°($t=3.9$, $p = .001$), and 75°($t= 5.0$, $p < .001$) for both baseball and softball athletes.

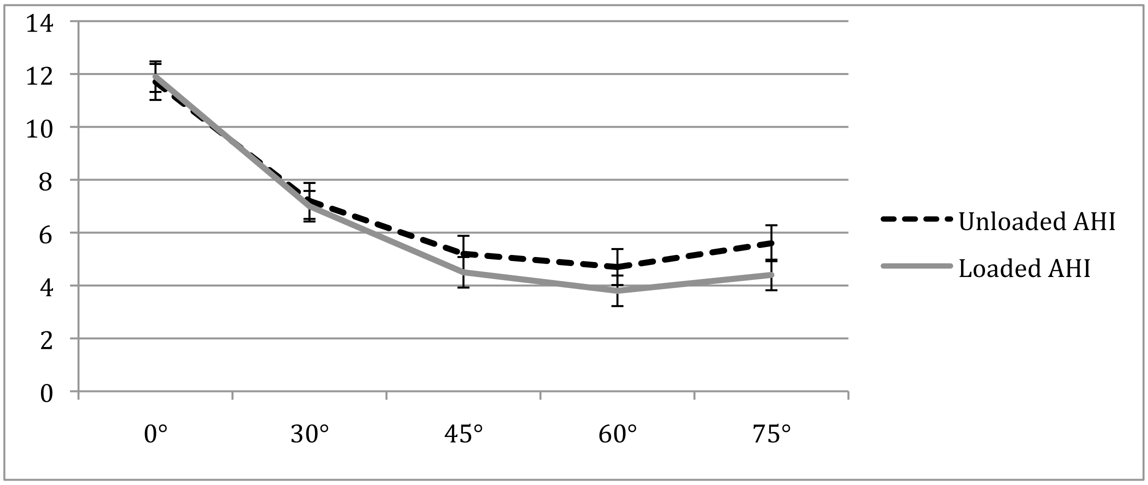

FIGURE 4. Graph of mean acromiohumeral interval (AHI) in millimeters for unloaded and loaded scaption at each humeral angle (n=21). Error bars represent average SEM values.

The main effect for gender was not significant (F = 1.4, p = .247), the interaction between gender and position was not significant (F = 2.4, p = .097) and the interaction of load and gender was not significant (F = .03, p = .876). No change in the F values for any of the variables were found when testing arm length, height, or weight as covariates.

Scapular Upward Rotation Changes

Table 4 provides descriptive statistics for SUR. Mauchly's test indicated that the assumption of sphericity was violated for the effect of position and the interaction of position and load, thus we applied a Greenhouse-Geisser correction to the degrees of freedom on the ANOVA.

TABLE 4. Descriptive statistics for scapular upward rotation (SUR) during unloaded and loaded scaption in baseball and softball athletes.

	Unloaded Scaption (Mean ± Std) n=21	Loaded Scaption (Mean ± Std) n=21
0°	-12.6 ± 6.0°	-15.0 ± 8.1°
30°	-6.2 ± 6.6°	-4.5 ± 5.8°
45°	-2.1 ± 7.5°	-0.2 ± 6.4°
60°	2.9 ± 7.8°	5.8 ± 6.5°
75°	9.0 ± 6.5°	11.8 ± 6.0°

There was a significant main effect for position (F = 291.5, p < .001). The SUR for all subjects increased, or became more positive, from the arm at the side until 75°, with significant differences (p < .01) between each arm angle. The main effect for load was not significant (F = 1.4, p =.245); however, a significant quadratic interaction for position and load (F = 7.1, p = .001) was found. For all subjects, the addition of the load resulted in greater downward tilting of the glenoid with the arm at the side (unloaded = -12.6 ± 6.0°, loaded = -15.0 ± 8.1°) and slightly greater upward tilting of the glenoid at 75° (unloaded = 9.0 ± 6.5°, loaded = 11.8 ± 6.0°); however, paired t test comparisons were not significant (p = .057 and p = .056, respectively). The main effect for gender was not significant (F=0.2, p = .677). Mean total ΔSUR (ΔSUR = SUR at 75° - SUR with arm at the side) during unloaded scaption (21.6 ± 4.84°) was significantly different (p = .004) from the total SUR during loaded scaption (26.8 ± 6.7°). No change in the F values for any of the variables were found when testing arm length, height, or weight as covariates.

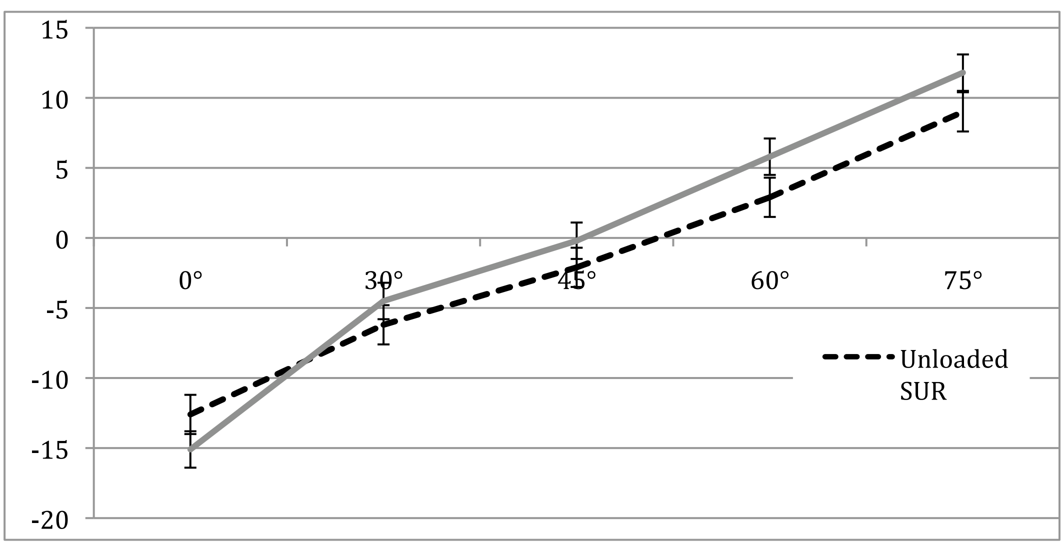

FIGURE 5. Graph of mean scapular upward rotation (SUR) in degrees for unloaded and loaded scaption at each humeral angle (n=21). Error bars represent average SEM values across unloaded and loaded scaption, respectively.

Correlations between AHI and SUR

AHI and SUR displayed moderate positive correlations at 30° for both the unloaded scaption (r=.648, p =.001) and the loaded scaption (r=.445, p=.038). Correlations between AHI and SUR with the arm at the side, 45°, 60°, and 75° were not significant for unloaded or loaded scaption.

TABLE 5. Correlations between AHI and SUR at each arm angle (N = 21).

Arm Angle	Unloaded Scaption	Loaded Scaption
0°	r =-.344 p = .128	r =.098 p = .663
30°	r =.445* p = .038	r = .648* p = .001
45°	r = .382 p = .080	r =.277 p = .212
60°	r =.264 p = .235	r =-.058 p = .798
75°	r =-.205 p = .372	r = -.034 p = .883

* indicates significance p < .05

DISCUSSION

Results from analysis of AHI during dynamic scaption, to 75°, indicate decreases in AHI from the arm at the side thru 60°. These findings are similar to the findings in experiment 1 and previous static AHI analyses.[33-35,41] Based on dynamic AHI measurements between the arm at the side and 75°, it appears that the most significant narrowing of AHI occurs at 60° for both loaded and unloaded scaption (unloaded = 4.6 ± 1.6 mm, loaded = 3.7 ± 1.3 mm). This supports previous cadaver based findings that the insertion of the supraspinatus on the greater tuberosity of the humerus was in closest proximity to the acromion near 60° of arm elevation.[11,14,28]

Our findings indicated a gradual increase in SUR through arm elevation during the loaded and unloaded scaption exercise. Although we only measured range of motion to arm angles of 75°, we found similar patterns of SUR changes as previous investigations that measured scapular kinematics to arm angles of 120°. [37,54] The SUR was negative with the arm at the side, indicating a downward tilting glenoid, and gradually became more positive, with an upward facing glenoid occurring at 60°. Static SUR measurements have previously been reported in baseball athletes[24,54,93] and female overhead athletes,[92] but we are the first to report no significant differences between the dynamic SUR in baseball and softball athletes. Only Myers et al[74] has measured changes in dynamic SUR in baseball athletes using three-dimensional electromagnetic sensors. The overall trends in SUR position are similar; however, the mean SUR values we report at 0°, 30°, and 60° indicate that our subjects started with a more downward facing glenoid. Myers et al[74] used resting scapular position as their initial scapular position and we captured SUR with the arm at the side in-between eccentric and concentric dynamic scaption. We believe that much of these differences are methodological in nature, based on differences between fluoroscopy, electromagnetic sensors, and arm motion. SUR was significantly different at each arm angle we measured, indicating that during dynamic motion the scapula is upwardly rotating throughout arm elevation.

The addition of a normalized load during the scaption exercise resulted in greater narrowing of the AHI at 45°, 60°, and 75° for healthy baseball and softball athletes. These results are similar to the findings in experiment 1. At 60°, the most narrowed AHI we measured, the addition of the load caused an additional narrowing of approximately 10%. No subjects complained of any pain or impingement symptoms during either scaption exercise, thus the further narrowing that occurred did not result in any perceived clinical impingement. However,

if a similar pattern of narrowing occurs in pathological populations, individuals with an already narrow space or those with current inflammation, the loaded scaption exercise may result in further impingement at 45°, 60°, and 75°. The addition of a load during dynamic humeral elevation has been previously shown to decrease SUR,[50] however we found that total SUR significantly increased during loaded, dynamic motion in healthy baseball and softball athletes. With the arm at the side, the load appeared to initially decrease SUR, which may have resulted due to the gravitational effect of the load on the arm in this position. Based on differences between SUR with the arm at the side and 30°, subjects' scapula rotated much more during loaded scaption than during unloaded scaption (loaded ΔSUR = 10.5°, unloaded ΔSUR = 6.4°). This may indicate that healthy, trained shoulders are capable of adapting to scapular positioning by activating the scapular rotator muscles early to increase SUR during arm elevation. Contrary to previous findings, this suggests that although the SUR was increased with the addition of the load at 45°, 60°, and 75°, a significant narrowing of the AHI was still present at these positions in healthy baseball and softball athletes.

Collectively, the scapula demonstrates progressive upward rotation, scapular retraction (or external rotation), and posterior tilting during glenohumeral elevation in the scapular plane. Theoretically, all three of these scapular movements during arm abduction serve to "open" the subacromial space. Our findings suggest that other humeral and scapular kinematics factors may be responsible for the further narrowing of the AHI observed in our subjects with the addition of the load. Increases in scapular protraction have been reported during loaded scaption[80] and have been directly related to decreases in AHI.[88] Static analysis of baseball athletes at rest and 90° demonstrate greater scapular protraction when compared to matched (non-athlete) controls[74] and the uninvolved arm. Based on our lack of correlations between SUR and AHI and the trend

toward increased SUR at these higher elevation positions, we do not believe SUR to be related to these decreases in AHI. We sacrificed the ability to measure other scapular kinematics, such as tilting and protraction, in order to gain the ability to capture two-dimensional kinematic changes during dynamic and functional arm elevation using DFV.

Unlike two previous studies who found AHI gender differences at rest[81] and 30°,[34] we did not find significant AHI differences as a result of gender during either loaded or unloaded scaption. However, based on the small effect size ($D^2 = .112$) we may have detected a difference with a much larger number of subjects with the arm at the side and at 30°. The size of our difference in AHI between baseball and softball athletes with the arm at rest (unloaded = 2.2 mm, loaded = 2.2 mm) for both loaded and unloaded scaption was greater than the difference reported by Peterrson and Redlund-Johnell[81] (0.7 mm) in the same position with no muscle activity; however they had a much larger subject pool (88 men and 87 females). The size of our difference between baseball and softball athletes at 30° (unloaded = 0.7 mm, loaded = 1.0 mm) is similar to the difference reported by Graichen et al at 30° with no muscle activity (1.2 mm) however we had a much larger standard deviation.[34]

Graichen et al[34] suggested anthropometrics may be the cause of the gender difference at 30°; however, none of the anthropometric covariates we tested (arm length, height, and weight) were significant factors in our analysis. No significant gender differences were detected in the analysis of SUR, therefore we do not believe that SUR was responsible for the gender difference in AHI with the arm at rest or 30°. Although, all subjects were currently engaged in similar, but not identical, upper extremity strength programs; the influence of neuromuscular factors is unknown, as we did not measure muscle strength or activity differences between subjects. In the lower arm elevation positions the primary function of the rotator cuff is to provide stabilization

of the humeral head against the glenoid fossa and prevent superior migration of the humeral head during arm elevation. Subjects with stronger external rotators have smaller subacromial pressures which may be indicative of a larger subacromial space[104]. Fatigue of the external rotators has also been shown to result in increased superior humeral head migration.[15,91] We strongly recommend that further studies investigating gender differences in AHI take into account possible neuromuscular differences between subjects.

We acknowledge several limitations within our study. Clearly, we sacrificed the ability to measure 3-dimensional scapular kinematics, such as tilting and protraction, in order to gain the ability to capture one-dimensional kinematic changes during dynamic and functional arm elevation using DFV. Despite the limitations in using DFV to capture dynamic shoulder motions, we recommend further use of this imaging modality to capture dynamic motions. Based on the successful use of DFV in capturing humeral head migrations, we recommend further research involving SUR, humeral head migration and AHI. We observed high intra-subject variability in SUR measurements, which is not uncommon in the literature, but does introduce possible error into statistical decision regarding this variable. Based on the variability in SUR and the small effect sizes for the variables we measured, future investigations should employ larger subject pools to reduce the chance of a Type II error. Applications of our findings are limited to healthy baseball and softball athletes. Clear differences in scapular kinematics and for healthy and un-healthy baseball players have been previously established in the literature, making this population a unique group of subjects to study. We assume that differences between neuromuscular factors related to regular strength training and overhead throwing may exist between the baseball and softball athletes we studied and untrained populations. Much more research is needed to determine if untrained populations or those with different neuromuscular attributes demonstrate similar AHI and SUR changes during dynamic motion.

CONCLUSION

In conclusion, we observed that the addition of a load during a scaption exercise results in significantly greater narrowing of the AHI at 45°, 60°, and 75°, despite trends toward increases in SUR at these positions. We recommend that clinicians use caution when prescribing loaded scaption exercises, especially in subjects who may have further narrowing of the subacromial space or the current inflammation. The lack of correlation between the AHI and SUR, especially at positions in which the AHI decreased with the addition of the load, suggests that other kinematic factors in the shoulder, besides SUR, may play a more influential role in the size of the AHI. Further investigation into the relationship between other shoulder kinematics and AHI is necessary. Further research is necessary to determine if differences in gender or neuromuscular factors may play affect dynamic changes in AHI.

CHAPTER 4
EXPERIMENT 3: DYNAMIC ACROMIOHUMERAL INTERVAL AND SCAPULAR UPWARD ROTATION CHANGES IN TRAINED AND UNTRAINED FEMALES

Neer[75] classified subacromial impingement syndrome (SIS) as an overuse condition, especially in the overhead arm position, which is similar to the range of motion (60° - 120°) where impingement symptoms usually occur in patients.[7,28,71,105] The functional theory supports the notion that during arm abduction narrowing of the osseous AHI, through which the tendon of the supraspinatus pass, is believed to lead to SIS and injuries to the supraspinatus tendon.[7,61,71] Knowledge of changes to AHI during dynamic motion is important for clinicians in regards to prevention and treatment especially in populations that have demonstrated increased risk, such as overhead athletes.[59] Our previous work[94] provided evidence that the AHI progressively narrows during a scaption exercise, with further narrowing occurring at 60° and 75° with the addition of a load during the exercise in healthy, baseball athletes. Experiment 2 indicated that further narrowing of the AHI occurs with the addition of the load at 45°, 60°, and 75° in both baseball and softball athletes. Evidence from experiment 2 indicated that neither load nor gender affected SUR, and it does not appear that SUR is related to the narrowing of the AHI observed at 45°, 60°, or 75° with the addition of the load in healthy, overhead athletes. The further narrowing of AHI observed with the addition of the load,[94] may indicate caution in the prescription of the loaded scaption exercise. However, it is unknown if participation in regular overhead activities or increases in shoulder muscle strength result in relatively less or more narrowing of the AHI during dynamic arm elevation.

To date, no dynamic AHI comparisons between overhead athletes and untrained subjects have been performed. Wang et al[99] compared the static AHI of baseball athletes with (non-athlete) matched controls, and found no significant differences. Silva et al[87]reported smaller

static subacromial space measurements in junior elite tennis players as compared to controls. However, both of the previous comparisons between athletes and untrained subjects measured AHI using static positions with no muscle activity.[87,99] Activation of humeral abductors[34,37,43] and scapular protraction[88] have been shown to result in further narrowing of the AHI and emphasize the importance of analyzing AHI during active muscle contractions. Neuromuscular differences between athletes and untrained subjects are likely to result in changes to shoulder kinematics, especially during active shoulder motion, thus it seems imperative to study differences in subacromial space during active, dynamic motion.

Female overhead athletes are also at increased risk for SIS,[59] yet much of the previous shoulder kinematic research has focused on baseball athletes. In experiment 2, we presented the only known findings in the literature related to dynamic AHI changes in female overhead athletes. Untrained females in various age groups have demonstrated significantly weaker upper extremity strength scores as compared to untrained men,[2,51] with some estimating that men are 38% – 81% stronger than females.[31] However, female athletes demonstrate strength scores that are comparable or only slightly lower than male athletes,[65,89] More specific to external rotation strength, male swimmers and age matched controls demonstrated similar strength scores, whereas female swimmers were stronger and demonstrated a larger gap between their strength scores and those of age matched controls.[69] Collectively, the evidence indicates that specific comparisons between trained and untrained females may be necessary due to larger differences in neuromuscular factors as compared to their male counterparts.

Possible effects related to neuromuscular factors have gained support from previous findings related to alterations in scapular and humeral kinematics following muscle fatigue, especially in the rotator cuff. Following external rotator fatigue, subjects have displayed

decreased posterior tilt of the scapula[25,95] and increased scapular protraction.[95] Increases in scapular protraction have been directly related to narrowing of the AHI at rest.[88] Fatigue of the external rotators has also led to significantly more superior humeral head migration during loaded scaption.[15,91] Superior migration of the humeral head should lead to narrowing of the AHI, however measurement of the AHI was not performed in these studies. Werner et al[104] reported that subjects with stronger external rotators exhibited decreased subacromial pressures during arm elevation, however they did not report the external rotation strength scores and no statistical comparisons were made. Decreases in subacromial pressure was measured using a pressure transducer[104] and likely indicate widening of the subacromial space and AHI.

Further linkage of the influence of external rotation to narrowing of the AHI can be made when looking at data comparing neuromuscular differences between subjects with and without SIS. Decreases in external rotation muscle activity,[22 83] alterations in the strength ratios between internal and external rotation,[55,101] and absolute strength deficits of 28%[97] have been reported in SIS. External rotation strength has been reported to be between 13.3 and 15.0 kg in trained athletes[23] while studies of untrained subjects have reported much lower external rotation strength measures ranging between 7.3 and 9.5 kg.[8,9,49] While these findings describe neuromuscular differences specific to external rotators, it is unclear whether these strength differences existed before the onset of the pathology and if these differences directly relate to narrowing of the AHI. More dynamic investigations, especially between female overhead athletes and untrained females, are needed to determine if neuromuscular differences alter dynamic AHI.

Therefore, the purpose of the present study was to compare dynamic AHI and SUR changes and external rotator cuff strength between female, overhead athletes and untrained females. We hypothesized that female overhead athletes would demonstrate stronger external

rotation strength when compared to matched, untrained females. We also expected the untrained females to exhibit further narrowing of the AHI during loaded scaption.

METHODS

We recruited 15 healthy, female overhead athletes and 15 healthy, untrained, females from the general undergraduate population. Participant inclusion was based on no history of shoulder disorders or current shoulder, arm, neck or back pathology. To ensure that study participants were currently without pathology we administered a screening questionnaire and consulted with the team's Certified Athletic Trainer for overhead athlete participants. Additional participant inclusion criteria for untrained females were the lack of current or previous high school participation in overhead sport activities. Untrained females were assessed for possible signs of current shoulder impingement using the shoulder apprehension and relocation test, Neer impingement test, empty can test, and Hawkins-Kennedy test. We recruited 20 untrained females that met the inclusion criteria, but only included 15 in data analysis to ensure that no significant differences existed between age ($p=.071$), height ($p=.110$), or bodyweight ($p=.158$) between the athlete and untrained groups. Independent t tests were used to verify the homogeneity of subject groups. We also screened all participants for hooked acromion morphology according to Bigliani's criteria[6] using a standard outlet fluoroscopic radiograph[76]. Each participant signed an informed consent form approved by the University's Internal Review Board.

Instrumentation

We obtained all DFV sequences with an Orthoscan HD Mini C-Arm (Orthoscan, Scottsdale, AZ) that has a resolution of 1000 X 1000 pixels per image. The images were collected at 30 Hz and recorded using a digital video recorder. Videos were as transferred to a

computer and analyzed using OsiriX imaging software (version 3.6.1; open source software for MacOS X). The Osirix imaging software converts all DFVs into sequences of still frames. Pixel width calibration was determined by placing a radiopaque ruler on the image intensifier. A single pixel width calibration was determined individually for each participant.

Maximal Voluntary Isometric Contractions

Participants performed a series of warm-up exercises involving 6 repetitions of light elastic band internal and external shoulder rotation. The participants were led through stretching exercises for the shoulder muscles. Participants were then seated in a chair with the shoulder in the scapular plane and performed three six-second sets of maximal voluntary isometric contractions (MVIC) for shoulder external rotation using a stabilized handheld dynamometer. We replicated the subject positioning and stabilization methods for the handheld dynamometer of Kolber et al,[49] which previously demonstrated excellent test-retest reliability. MVIC values were averaged to produce a single external rotation MVIC value for each subject.

Imaging Protocol

The DFVs were obtained in a manner similar to that described in previous studies.[82,91,94] Due to limitations in positioning of the C-arm, participants were seated with the elbow fully extended, palm facing forward and the thumb towards the ceiling. The C-arm was rotated 30 degrees from the frontal plane, such that the X-ray beam was perpendicular with the plane of the scapula and adjusted for each subject until a single glenoid rim was present on the image. The posterior shoulder was placed in direct contact with the image intensifier to minimize image distortion. The height of the C-arm was adjusted for each participant so that the acromion and humeral shaft were clearly visible. A board guided the participant's movement to ensure that it remained within the scapular plane during all trials. A device was placed on the board, which

stopped scaption at 90° of elevation. The participants were instructed to remain in a normal, upright posture during all trials. One researcher monitored arm elevation during the trials, as well as any compensatory trunk or shoulder/arm movements.

Participants performed dynamic arm elevations in the scapular plane from the anatomical position to 90 degrees with and without resistance, in a counterbalanced manner. The hand remained in neutral position, with the palm facing forward and thumb towards the ceiling. The amount of resistance was adjusted for each participant based on anthropometrics,[52,56] which were calculated using bodyweight, height, and arm length. The participants were instructed to perform three consecutive trials of scaption, with approximately three minutes between the counterbalanced conditions. Each trial was performed at a speed of three seconds up and three seconds down and was controlled using visual and auditory cues. DFVs were only captured on the last two trials of each condition in order to minimize radiation exposure to the participants.

Radiographic Analysis

The best sequence of images out of two captured trials for each condition was used to calculate acromiohumeral interval (AHI) and humeral angle. AHI was calculated in a method similar to Petersson and Redlund-Johnell,[81] which was defined as the smallest vertical distance between the dense cortical line of the acromion and the most superior aspect of the humerus. Humeral angle was defined as the angle between a line drawn on the shaft of the humerus and a line drawn vertically. SUR position was defined in a method similar to Poppen and Walker,[82] as the angle between a line drawn from the superior tubercle of the glenoid to the inferior tubercle of the glenoid and line parallel to the axis of the body. A downward facing glenoid indicated a negative angle, while an upward facing glenoid was a positive angle. The same trained associate evaluated all radiographic images. AHI was only measured on the image frames that

corresponded to the following humeral angles: arm at side (hereafter referred to as 0°, 30, 60, and 90 degrees. Humeral angle values were selected to allow comparisons with the results from previous studies.[3,20,33,35,37]

Data Analysis

The effect of resistance on AHI during scaption was tested with a 2 x 2 x 4 repeated measures analysis of variance (ANOVA). The independent variables used were resistance (loaded and unloaded) and arm position (0°, 30°, 60°, and 90°). The dependent variable is the AHI, measured in millimeters. The independent between groups factor was training (untrained and trained). A separate 2 x 2 x 4 repeated measure ANOVA was performed with the same independent variables and the dependent variable was SUR. Pearson bivariate correlation tests were used to analyze the relationship between AHI and SUR at each humeral angle for both the unloaded and loaded conditions. The α level was set at .05 for all analyses. Relevant post hoc analysis was performed using paired t tests with a Bonferroni correction. Data analysis was accomplished with the following software packages: OsiriX, Excel (Professional Edition 2003; Microsoft Corp, Redmond, WA), and SPSS (version 17.0; SPSS inc, Chicago, IL).

RESULTS

Data was collected from 15 healthy softball and volleyball athletes and 15 healthy, untrained females. Age, weight and height values for the female overhead athletes were 19.5 ± 0.6 years, 69.9 ± 10.1 kg, and 1.70 ± .06 m, respectively. Age, weight and height values for the untrained females were 20.5 ± 1.8 years, 63.6 ± 13.3 kg, and 1.65 ± .09 m, respectively. The external rotator MVIC average for athletes and untrained females was 13.4 ± 1.6 kg and 7.9 ± 1.7 kg, respectively. Independent t tests indicated that athletes had significantly stronger external rotators ($t = -9.40$, $p < .001$). Average load used by the athletes was 2.73 ± .87 kg and average

load used by the untrained females was 2.5 ± .95 kg. Independent t tests indicated no significant difference (t = -.816, p = .422) between the loads used by the two groups.

Mauchly's test of sphericity indicated that the assumption of sphericity was violated, thus a Greenhouse-Geisser correction was applied to the degrees of freedom during the ANOVA tests. Table 5 provides descriptive statistics for the acromiohumeral interval during unloaded and loaded scaption.

TABLE 6. Descriptive statistics for acromiohumeral intervals (AHI) during unloaded and loaded scaption female overhead athletes (n=15) and untrained females (n=15).

	Unloaded Scaption		Loaded Scaption	
	Athletes (Mean ± Std)	**Untrained** (Mean ± Std)	**Athletes** (Mean ± Std)	**Untrained** (Mean ± Std)
0°	9.6 ± 1.6 mm*	7.9 ± 1.4 mm	8.9 ± 2.0 mm*	6.7 ± 2.1 mm
30°	6.7 ± 1.2 mm*	4.3 ± 1.9 mm	5.7 ± 1.2 mm*	3.7 ± 2.0 mm
60°	3.6 ± 0.9 mm	3.0 ± 1.2 mm	3.4 ± 1.0 mm*	2.4 ± 1.4 mm
90°	4.2 ± 1.5 mm	4.3 ± 1.9 mm	3.8 ± 1.5 mm	3.7 ± 1.6 mm

*indicates significant difference (p <.05) between athletes and untrained at that position and load condition.

Arm abduction position had a significant effect on AHI (F = 123.1, p <.001), where the mean AHI for both groups during loaded and unloaded scaption was maximal with the arm at the side (8.3 mm) and declined significantly (p < .001) during arm elevation until 60° (3.1 mm). The mean AHI for both groups during loaded and unloaded scaption increased significantly (p < .001) between 60° (3.1mm) and 90° (4.0 mm). The addition of the load resulted in significantly greater AHI narrowing for both groups (F = 23.5, p < .001) at 0° (p = .003), 30° (p = .005), 60° (p=.003), and 90° (p = .036). Differences between the two groups during loaded and unloaded scaption are presented in Figure 4. Athletes had a significantly larger overall AHI than the untrained females (F= 10.6, p = .003), with significant differences between the two groups

during unloaded scaption at 0° (p=.004) and 30° (p=.001) and during loaded scaption at 0° (p=.005), 30°(p=.002), and 60°(p=.036).

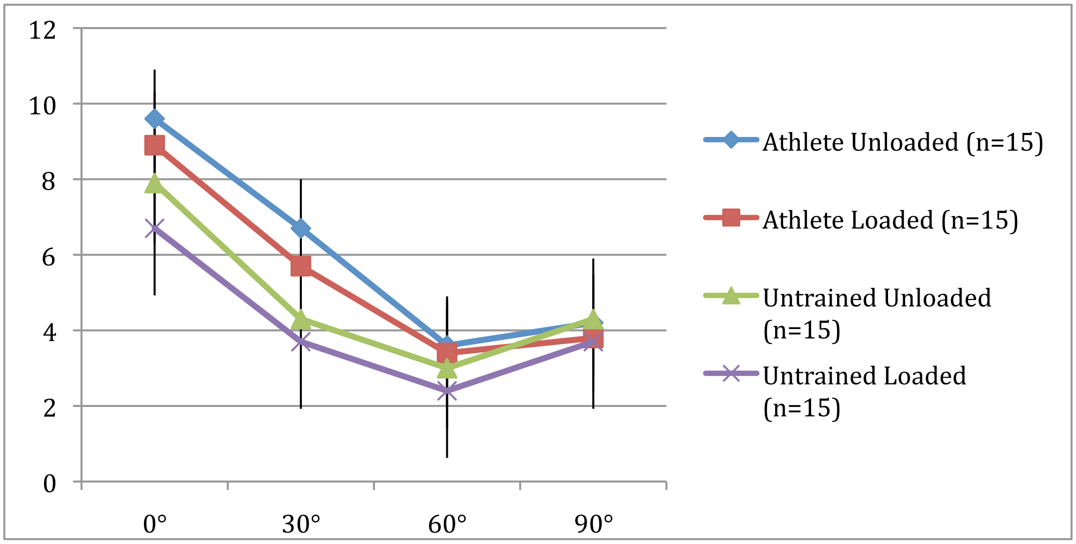

FIGURE 6. Graph of acromiohumeral intervals (AHI), measured in millimeters.

Scapular Upward Rotation Changes

Mauchly's test of sphericity indicated that the assumption of sphericity was violated, thus a Greenhouse-Geisser correction was applied to the degrees of freedom during the ANOVA tests. Table 6 provides descriptive statistics for scapular upward rotation during unloaded and loaded scaption.

TABLE 7. Descriptive statistics for scapular upward rotation position during loaded and unloaded scaption in female overhead athletes (n=15) and untrained females (n=15).

	Unloaded Scaption		Loaded Scaption	
	Athletes (Mean ± Std)	**Untrained** (Mean ± Std)	**Athletes** (Mean ± Std)	**Untrained** (Mean ± Std)
0°	-1.7 ± 7.4° *	-8.4 ± 9.5°	-4.8 ± 10.2° *	-14.4 ± 7.7°
30°	3.1 ± 6.3°	-2.9 ± 9.9°	3.7 ± 7.5° *	-4.7 ± 9.2°
60°	10.7 ± 4.6° *	4.5 ± 7.1°	10.7 ± 6.2°	5.1 ± 8.7°
90°	17.8 ± 6.1° *	10.3 ± 4.6°	18.9 ± 7.3° *	13.3 ± 6.2°

* indicates significant difference (p<.05) between athletes and untrained at that position and load condition.

As the arm was abducted both groups demonstrated increases in SUR (F=354.7, p < .001), with significantly greater upward rotation between each position (p <.001). The addition of the load did not result in a significant main effect (F = .78, p = .383), however the interaction between load and position indicated a significantly more downward/negative position at 0° (p < .001) and a significantly more upward/positive position at 90° (p = .009) with the addition of the load. Overall, the female athletes demonstrated significantly greater SUR as compared to untrained females (F = 8.2, p = .008).

FIGURE 7. Graph of scapular upward rotation position, measured in degrees.

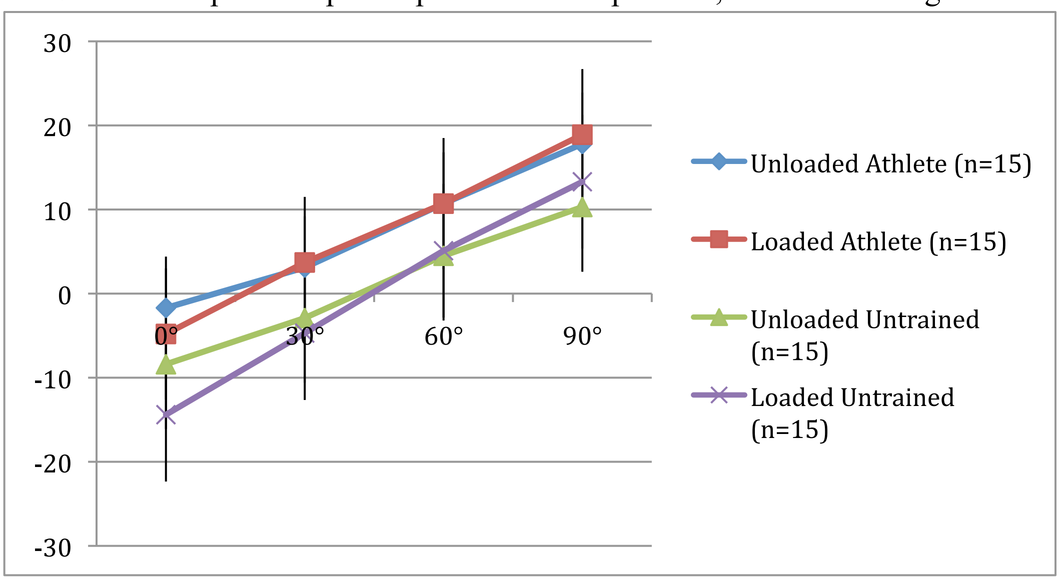

TABLE 8. Correlations between AHI and SUR at each arm angle (N = 30).

Arm Angle	Unloaded Scaption	Loaded Scaption
0°	r =.445* p = .014	r =.449* p = .013
30°	r =.611* p < .001	r = .660* p < .001
60°	r = .381* p = .038	r =.513* p = .004
90°	r =.054 p = .775	r = -.151 p = .427

* indicates significance p < .05

Correlations between AHI and SUR

Significant correlations ($p < .05$) between AHI and SUR were observed at 0°, 30°, and 60° during both loaded and unloaded scaption. All correlation values are listed in Table 7.

DISCUSSION

Our results indicate that female overhead athletes had stronger external rotators and a wider subacromial space. The mean external rotation strength scores for the two groups (athletes = 13.4 kg, untrained = 7.9 kg) are consistent with previous handheld dynamometry assessments of professional baseball pitchers[23] and males and females across a variety of age groups.[9,49] Female athletes had a significantly larger AHI at 0° and 30° during unloaded scaption and at 0°, 30° and 60° during loaded scaption. On average the untrained group had an AHI that was 2.05 mm smaller between 0° - 30° during unloaded scaption and 1.73 mm smaller between 0° - 60° during loaded scaption. Previous AHI comparisons between athletes and sex and age matched controls have demonstrated no differences at 0° and 90° in the scapular plane[99] and smaller AHI values for tennis athletes at 0° and 60° in the frontal plane[87] however, both studies measured the AHI during using static positions and no muscle activity. Our findings of a significantly larger AHI between 0° and 60° are in direct contrast to previous AHI comparisons between athletes and controls.[87,99] We believe much of the difference is due to the analysis of AHI during dynamic muscle activity, as compared to static and passive positioning used in previous studies. Significant alterations in AHI have been noted during muscle activity[34,43] and differences in neuromuscular factors between trained athletes and untrained controls are more likely to be present during functional and dynamic arm motions. We believe our results present a strong case for differences in AHI based on external rotation strength and overhead activity training.

Previous studies indicate that fatigue of the external rotators appears to result in significant changes to glenohumeral and scapulothoracic kinematics that may impact AHI, including increased superior movement of the humeral head[15,91] and decreased posterior tilt of the scapula.[25] Werner et al[104] also alluded to the influence of the external rotators in the size of the subacromial space by indicating that subjects with stronger external rotators had less pressure on the bursa within the subacromial space during arm elevation. While the weaker, untrained, subjects in our study did not present any signs or symptoms of impingement, significant weakness of the external rotators has been reported in patients with SIS.[4,97,101] Our dynamic AHI differences between relatively strong, female athletes and weak, untrained females provides further evidence of the important role the external rotators play in the size and maintenance of the subacromial space. Further research is necessary to determine the relationship between external rotation strengthening protocols and dynamic AHI.

No differences in the size of the AHI were observed at 90° between the female athletes and the untrained females, which indicate that external rotation strength differences and frequency of overhead activities do not affect the size of the dynamic AHI at this position. The external rotators are believed to play a significant role in stabilizing the humeral head against the glenoid fossa and opposing the superior forces of the deltoid during arm elevation between 0° and 60°.[1,44,82,86] EMG analysis of the rotator cuff muscles during scapular plane arm elevation has demonstrated peak activity of the infraspinatus and teres minor (external rotators) between 30° and 60°, with a gradual decline as the arm continues to elevate.[1] In addition, fatigue of the external rotators has been shown to result in scapular kinematic changes that may decrease the subacromial space, such as decreased posterior tilt, but only between 0° and 60° of arm

elevation.[25,95] Thus, it appears that weakness of the external rotators has the most impact on AHI during lower arm elevation positions.

Significant narrowing of the AHI was observed in both groups between 0°, 30°, and 60°. The narrowing observed during early arm elevation is consistent with the trends observed in our previous work[94] and other in-vivo analyses of AHI.[5,20,34,35,43] Based on the mean AHI for both groups at 0° (8.3 mm), the AHI was 62% smaller at 60° (3.1 mm). Previous reports of AHI during muscle activity have been reported to range between 3.7 mm and 7.6 mm at 60°.[5,20,35] Our findings in this third experiment indicate at smaller AHI at 60° than our previous two experiments with the same methodology. However, the lower overall AHI value is likely due to the inclusion of untrained subjects, who appear to have significantly smaller AHI values than the athletes in the current and previous studies. Our dynamic investigations of AHI during active arm motion also differ from previous in-vivo investigations in regards to patient positioning (supine vs. seated) and imaging modality (MRI vs. fluoroscope). We believe that patient positioning may be a key factor, as supine positioning eliminates the effect of gravity on the shoulder and does not represent functional arm kinematics.

The early stages of arm elevation narrowed the AHI, however, it significantly widened between 60° and 90°. Of the four previous studies that report in-vivo AHI measurements between 60° and 90°,[5,33,35,43] we are the only study to report a significant increase in the AHI at 90°. Bey et al[5] is the only study to previously measure AHI changes during dynamic motion in a functional upright position, and they report a 3.4 mm AHI at 60° and a 1.2 mm AHI at 90°. Bey et al[5] used the contralateral, asymptomatic, shoulder of rotator cuff repair patients with a mean age of 63.2 years in contrast to the young, healthy athletes and untrained female subjects in our study. Differences in load, plane of motion, and experimental techniques may also contribute to

the increase in AHI we observed at 90°. Differences in AHI values at 90° may have limited clinical significance as the supraspinatus tendon generally does not lie within the AHI beyond an average of 72°.[5,11,14] Further study in functional positions between 60° and 90° is necessary before it can be determined if narrowing or widening of the AHI occurs during dynamic motion.

The addition of the load during scaption resulted in significant narrowing of the AHI at all arm elevation positions for both groups. The application of the load resulted in significant narrowing of the AHI at 0° and 30°, whereas our previous investigations did not reveal significant decreases in the AHI at 0° or 30° with the addition of a load. We believe this difference may be partially explained by the inter-individual variations in neuromuscular and kinematic responses to the application of loads. Load related alterations in shoulder kinematics, such as increased scapular protraction,[80] have been reported during early arm elevation and may also partially explain the narrowing we observed at 0° and 30°. The load related AHI narrowing we report at 45°, 60°, and 75° are consistent with our earlier findings.[94] Narrowing of the AHI during loaded scaption did not result in any clinical signs or symptoms of impingement during our testing sessions, but accounts for an 11%-14% decrease in unloaded AHI throughout arm elevation. It is important to note that the current study did not find a significant interaction between load and training; both athletes and untrained subjects experienced narrowing of the AHI related to the addition of the load. When loads are added to the scaption exercise in subjects with weak external rotators, who demonstrated smaller AHI values between 0° and 60°, further load related narrowing of the AHI might place the supraspinatus tendon in jeopardy of injury. Athletes with strong external rotators may be able to sustain load related narrowing of the AHI without compromising the contents of space, since their initial AHI is normally wider. In cases

of inflammation, osteophytes or existing SIS, an 11%-14% further narrowing may also become clinically significant, making loaded scaption potentially injurious.

SUR is an important component of synchronous shoulder function between the scapula and humerus, resulting in elevation of the lateral acromion away from the humeral head. Although decreased SUR has been observed in SIS patients,[26,60,89] two previous *in-vivo* investigations of AHI and SUR have reported only moderate correlations at 30°(experiment 2) and changes in AHI without changes in SUR during different muscle activities.[37] Our results indicate that female athletes have a more upward/positive scapular position than untrained females, with significant differences occurring at 0°, 60°, and 90° during unloaded scaption and at 0°, 30°, and 90° during loaded scaption. The female athletes also demonstrated a more upward/positive scapular position at 30° unloaded and 60° loaded, both of which approached significance (p = .56 and p = .52, respectively). Although researchers have not established the quantitative amount of SUR that is necessary for adequate shoulder function, decreases in SUR are believed to increase injury rates.[13,42,47,53,60,62,64,78,100] We also observed significant correlations between AHI and SUR during both loaded and unloaded scaption at arm elevation angles of 0° - 60°, indicating that a more positive/upward scapular position resulted in widening of the AHI. Thus, it is possible that the more negative/downward scapular position we observed in the untrained females may increase their risk for shoulder injuries, especially related to narrowing of the subacromial space between 0° and 60°.

While SUR was greater at 90° for the athletes during both loaded and unloaded scaption, the athlete's AHI was not significantly different than the untrained females at 90°. Furthermore, the AHI and SUR were not significantly correlated at this arm angle, leading us to believe that other scapular and humeral kinematic factors besides SUR are more closely related to the AHI at

90°. We believe the lack of significant correlations between AHI and SUR in previous investigations are likely due to differences in dynamic versus isometric shoulder movements[37] and assessment of a relatively homogenous population (experiment 2). Due to the high variability in both AHI[33-35] and SUR that has been noted both in athletic[74,89,93] and non-athletic populations[19] it may be necessary to study large groups or distinctly different populations in order to find true statistical differences. It is also important to note that we were only capable of collecting scapular position information in one plane, while the scapula is free to move in two other planes. While we report a moderately positive relationship between increases in SUR and widening of the AHI, other scapular motions, such as posterior tilt and retraction may result in widening of the subacromial space and should be considered in further investigations of the relationship between AHI and scapular kinematics.[60,88]

The addition of the load resulted in a more downward/negative scapular position at 0° and a more upward/positive scapular position at 90°, but did not alter the SUR at 30° or 60° for both athletes and untrained females. Despite external rotation strength differences between the two groups, the SUR in athletes and untrained females responded similarly to the load. Controversy exists within the literature regarding the effect of an external load on SUR, with some authors reporting that the load has no effect,[19,72] other studies reporting that loads increase SUR, [29,70,80] and some reporting that loads decrease SUR.[50] Our findings related to the effect of load on SUR are most similar to the findings in experiment 2 and Forte et al[29] who reported increased SUR at 60° and 90° with the addition of a 5% of body mass load. Forte et al[29] did not report the absolute position of the scapular at 0°, thus it is not possible to compare our results at this position. However, it does seem plausible that the addition of a load at 0° is likely to cause a downward force on the arm and scapula, resulting in a more negative/downward position at 0°.

Studies have indicated that loads may also have impacts on scapular tilting[29,80] and protraction[80] which should also be considered when evaluating the effects of load on scapular kinematics and AHI. It is interesting to note that although we demonstrate significant correlations between the SUR and AHI between 0° and 60°, additional narrowing of the AHI at 90° with the load was observed despite significant increases in SUR at 90°. This may indicate that adding a load during scaption results in narrowing of the AHI, regardless of increases observed in SUR.

Several limitations exist in our current study, most of which are related to the one-dimensional imaging nature of the DFV. The subacromial space is a three-dimensional area that is potentially impacted by translations and rotations of the humeral head and scapular movements about three axes, however we were only able to measure changes about one dimension (scapular upward rotation). A major limitation of our study was the inability to measure other scapular and humeral head movements during dynamic motion. While DFV has been recently used in several dynamic studies related to the shoulder,[84,90,91,94] there is clearly some sacrifice in image quality as compared to static images. Radiographic images do not allow for visualization of soft tissue structures such as the articular cartilage or supraspinatus muscle, thus we were not able to indicate when the supraspinatus muscle was in closest proximity to the acromion during dynamic motion. However, single plane analysis of the AHI is widely used by orthopedists to evaluate the size of the subacromial space and for diagnostic purposes related to rotator cuff injury.[18,32,81] We strongly believe that despite the limitations, dynamic analysis of AHI using DFV is functional and enhances the understanding of AHI changes during common shoulder motions.

The goal of this study was to examine dynamic AHI and SUR changes in between trained and untrained female subjects, but our results may not be applicable outside these specific

populations. Several authors have demonstrated that overhead athletes have different shoulder kinematics,[30,74,77,89,92] upper extremity strength values,[17] and alterations depending on sports seasons[92] however; the specific adaptations across sports and genders have not yet been classified. Thus, our findings of a larger AHI in softball and volleyball players as compared to untrained females may not be present in other athletic populations and may be season specific. Clearly, more dynamic AHI and SUR measurements are needed across various athletic and non-athletic populations. We measured isometric strength of the external rotators however; the function of these muscles during the deceleration phase in throwing is eccentric. Further research may wish to include more clinically relevant eccentric strength measurements. Future studies should also investigate the influence of external rotation strengthening protocols and fatigue resistance to determine whether positive changes in these variables improve dynamic AHI.

CONCLUSIONS

In conclusion, our study demonstrates that healthy female athletes with stronger external rotators had a significantly wider AHI between 0° and 60° and significantly more SUR as compared to healthy untrained females. Based on previous *in-vivo* reports of AHI ranging from 2.4 to 12.8 mm the narrowing we observed in the untrained females could represent between 13% to 83% of the AHI between 0° and 60°. AHI narrowing of this magnitude could increase their injury risk, especially in cases of increased overhead use. While narrowing of the osseous AHI is a multifactor issue, correlations indicated that increased SUR is significantly related to a wider AHI between 0° and 60°. Increased SUR may be one of the factors involved in the maintenance of a wider AHI during arm elevation in female athletes. Future research should

attempt to determine if external rotation strength protocols and scapular position changes could improve dynamic AHI.

Regardless of differences in strength and SUR, both groups experienced an 11%-14% narrowing of the AHI with the application of an external load during scaption. While the application of the load did not result in clinical symptoms of impingement during our three trials of loaded scaption, increased exercise volume or the presence of inflammation may lead to impingement to the contents within the subacromial space when a load is added to scaption exercises. It is also important to note that female athletes with greater SUR also experienced narrowing of the AHI with the load and significant AHI narrowing was present at 90° despite increased SUR at this position for all subjects. This indicates that load induced narrowing of the AHI may be related to other glenohumeral kinematics beside AHI. As the AHI normally experiences narrowing with arm elevation, an additional narrowing of 11% -14% may be especially problematic for those who have a smaller space, osteophytes, inflammation, or other pathological factors. Greater external rotation strength may enlarge the AHI and could be considered a requirement prior to the initiation of loaded scaption, but greater external rotation strength did not appear to alter the narrowing we observed with the addition of the load. Further research of dynamic AHI changes during loaded scaption in pathological populations is warranted, however, our results suggest that clinicians should be cautious when prescribing loaded scaption.

CHAPTER 5: SUMMARY AND CONCLUSIONS

Subacromial impingement syndrome (SIS) has been related to overuse in the overhead arm position[75] with increased incidence in overhead athletes[13,59] and those who participate in frequent overhead work related tasks, such as construction workers.[10] The functional theory of subacromial impingement syndrome (SIS) proposes that narrowing of the subacromial space may be injurious to the supraspinatus tendon as it passes under the acromion and inserts on the greater tuberosity of the humerus.[7,14,63,71] The acromiohumeral interval or distance (AHI) has been established in previous research as a quantitative method for evaluating the size of the subacromial space.[18,20,32-35,37,41,81] Narrowing of the AHI has been observed during static analysis in rotator cuff injuries and during arm elevation and abduction muscle activity in healthy subjects,[18,20,32-35,37,41,81] but some controversy exists regarding narrowing of AHI in subjects with SIS.[16,20,21,40,41] However, static imaging may underestimate superior glenohumeral translations[90] and may not represent the same neuromuscular mechanics or AHI changes that are seen during dynamic arm motions.

This dissertation contained a series of three experiments that examined dynamic AHI changes during scapular plane arm motions in male and female overhead athletes and untrained females. The first experiment investigated dynamic AHI changes between 0° and 75° in healthy, baseball athletes during loaded and unloaded scaption. The second experiment compared AHI and scapular upward rotation (SUR) changes between softball and baseball athletes during loaded and unloaded scaption between 0° and 75 °. The third experiment investigated AHI and SUR changes between 0° and 90° during loaded and unloaded scaption exercises in female athletes and untrained females with external rotation strength differences.

Similar to previous static investigations of AHI, significant narrowing of the AHI during arm elevation until 60° was observed in all three experiments. The AHI values at 0° for the first two experiments involving athletes (12.6 mm and 12.0 mm, respectively) are larger than those previously reported in the literature (average of 5 studies = 8.4 mm).[5,20,41,87,99] However, AHI was measured during the transition from eccentric arm lowering to concentric arm elevation whereas previous studies all captured AHI at rest. The inclusion of untrained control subjects in the third study resulted in a smaller AHI value at 0° (8.3 mm) that is similar to previous studies using untrained subjects.[5,20,41] Thus, static analysis of the AHI at 0° may underestimate the actual AHI during dynamic arm movements, especially in athletes. Although the AHI narrowed approximately 63% between 0° and 60°, the dynamic measurements of AHI at 60° during unloaded scaption (4.4 mm) are very similar to previous static analysis with muscle activity at 60° (average of 3 studies = 4.2 mm),[5,35,43] emphasizing the need to examine AHI during muscle activity or dynamic motion. Previous static reports of AHI changes without muscle activity may not accurately represent the changes that occur during functional arm movements. Based on the findings in this dissertation and previous research, it is recommended that all future investigations of AHI be performed during muscle activity.

In contrast to previous AHI studies, a widening of the AHI between 60° and 90° was observed in the third study. Similar widening trends between 60° and 75° were also apparent in the first two experiments, but not significant, however it possible that a type II error occurred due to the small sample sizes. Four previous studies demonstrated further narrowing of the AHI between 60° and 90°,[5,33,35,43] however three of those were performed in supine positions,[33,35,43] which may significantly alter the effect of gravity on shoulder kinematics. Bey et al[5] measured the AHI while standing, but subjects performed arm elevation in the frontal plane instead of the

more functional scapular plane. Variations in the narrowing of the AHI has been observed when comparing frontal and scapular plane measurements.[99] Clearly, further research during upright and scapular plane motion is needed to verify the observation of widening of the AHI between 60° and 90° in healthy subjects.

One of the most significant findings of this dissertation was the additional AHI narrowing observed during loaded scaption in all three experiments. In experiment 3 the addition of the load caused significant narrowing at all arm positions, however in experiments 1 and 2 we did not observe load related narrowing at 0° or 30°. While these differences cannot be completely explained, inter-subject differences in shoulder kinematics and anatomical differences in the humeral angle with the arm at the side may provide some explanation. At 60°, the narrowest AHI position observed in all three studies, the addition of the load resulted in a 10% - 12% decrease in the AHI. While no subjects complained of pain during loaded scaption trials, increased exercise volume or the presence of inflammation may lead to impingement of the supraspinatus tendon within the subacromial space. Subjects with SIS, who already have a narrow AHI,[35,41] may also suffer injury if performing loaded scaption exercises. Based on the findings of this dissertation, loaded scaption exercises are not recommended for patients who may already have a compromised subacromial space. Further exploration of load related effects to AHI during various shoulder exercises are necessary, especially with different amounts of load.

No significant gender differences in AHI between healthy baseball and softball athletes were reported, but further gender analysis in both athletic and non-athletic populations using much larger sample sizes may be necessary. Anthropometric factors, such as bodyweight, height, and arm length displayed no statistical differences during experiment 2, but no

comparisons of the neuromuscular differences between the male and female athletes were performed. Evidence related to the impact of neuromuscular factors on AHI was found in experiment 3, where female athletes displayed significantly stronger external rotators, a wider AHI between 0° and 60° and more SUR. Strong evidence exists in the literature regarding weakness of the external rotators and increased shoulder injury risk,[22,55,83,96,101] but this is the first direct link between weakness and size of the AHI. Based on previous *in-vivo* reports of AHI ranging from 2.4 to 12.8 mm, the narrowing we observed in the untrained females could represent from 13% to 83% of the AHI between 0° and 60°. Narrowing of this magnitude could result in significant impingement of the structures within the subacromial space during repetitive overhead movements, and may necessitate preventative external rotation strengthening.

Narrowing of the three-dimensional subacromial space is likely related to a multitude of scapular and glenohumeral kinematics. Digital fluoroscopic video was used to capture shoulder kinematics during dynamic motion, but limits visualization to only one of three scapular motions, SUR. Although researchers have not established the degrees of SUR that are necessary for adequate shoulder function, decreases in SUR are believed to increase injury rates.[13,42,47,53,60,62,64,78,100] SUR measurements in experiments 2 and 3 displayed large subject variability, indicated by large standard deviation values, and a consistent pattern of increasing SUR during arm elevation. No gender differences in SUR were apparent between baseball and softball athletes, but female athletes had significantly more SUR than untrained females. Previous research has also reported that athletes have more SUR,[74,77] which may further open the subacromial space and serve as an injury protection mechanism. Comparisons between exact SUR positions in the literature are extremely difficult due to the wide array of measurement devices and techniques, however due to the large inter-subject variability an exact SUR value

may have limited clinical significance. Based on the evidence from this dissertation, further training interventions aimed at increasing SUR in non-athletic populations may be helpful for clinicians.

Previous research suggests that SUR serves to elevate the lateral acromion and open the subacromial space during arm elevation, however there has been some discrepancy in cadaveric studies[46]and only one previous in-vivo investigation attempted to link AHI and SUR, but was unsuccessful[37] No clear relationship between SUR and AHI was apparent in experiment 2, which may be due to the high variability within each variable for both baseball and softball athletes and the relatively small subject pool. A stronger and more consistent relationship between SUR and AHI was observed in experiment 3 during loaded and unloaded scaption between 0° and 60°. Experiment 3 results indicated that a more positive/upward scapular position resulted in widening of the AHI between 0° and 60° and may be one of the factors related to the larger AHI observed in female athletes compared to untrained females. Thus it seems that the relationship between SUR and AHI is more apparent when comparing different population groups, but requires more research using large sample sizes to determine if a relationship between these two factors exists in other populations. It is also important to note that these findings do not exclude the existence of further relationships between AHI and other scapular motions, such as posterior tilt and retraction.[60,88]

Controversy exists within the literature regarding the effect of an external load on SUR, with some authors reporting that the load has no effect,[19,72] other studies reporting that loads increase SUR, [29,70,80] and some reporting that loads decrease SUR.[50]. Both experiments 2 and 3 indicated that loaded scaption results in a more downward/negative scapular position at 0° and a more upward/positive scapular position at 90°, but no load related changes in SUR were

observed at 30° or 60°. Although increased SUR was observed during loaded scaption at 90°, the AHI was smaller at this position, suggesting that other kinematic factors may play a more prominent role in the maintenance of AHI at this position. Studies have indicated that loads may impact scapular tilt[29,80] and scapular protraction[80] which should also be considered when evaluating the effects of load on scapular kinematics and AHI. Baseball, softball, and untrained females experienced similar SUR with the addition of the load, therefore differences in gender, external rotation strength or athletic experience do not seem alter the responses of SUR to the load. However, more research with larger sample sizes is recommended before firm conclusions can be made regarding population and load related differences in SUR.

In conclusion, this dissertation included a series of three experiments that provide significant insight into dynamic AHI changes between 0° and 90°, especially in regards to overhead athletes. DFV proved to be a reliable and functional method for capturing and measuring dynamic shoulder kinematics and is recommended for future dynamic investigations of joint kinematics. In general, AHI is maximal with the arm at the side and narrows until 60° during scaption. Evidence from this dissertation indicated an enlargement of the AHI between 60° and 90°, which is contrary to reports from static analysis of AHI. Gender differences in AHI or SUR within the overhead athlete population were not apparent, but athletes with stronger external rotators had a larger AHI and more SUR than gender-matched controls, which supports previous evidence regarding the influence of neuromuscular factors on the subacromial space. The application of the load during scaption resulted in narrowing of the AHI in all subjects, regardless of gender, athletic participation, or external rotation strength. Evidence of a positive relationship between SUR and AHI was found, however due to the significant variability in SUR more investigation is required. Despite increased SUR during loaded scaption, narrowing of the

AHI was still observed, indicating that other scapular kinematic factors may also play a role in maintenance of the space.

Based on the collective results from these three studies, the following dynamic shoulder kinematic investigations are recommended. Dynamic comparisons between patients with SIS, other shoulder pathologies and healthy controls will provide further diagnostic and etiological insight into SIS. Further examination of the load related changes in AHI using different loads and during other commonly utilized shoulder rehabilitation exercises would enhance rehabilitative decision-making and exercise prescription. Finally, an external rotation strengthening intervention, including pre and post dynamic AHI analysis, would provide further insight in regards to the treatment and prevention of SIS.

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APPENDIX A: IN-VIVO AHI FINDINGS

Author	Imaging	Position	N	Load	AHI 0°	AHI 30°	AHI 45°	AHI 60°	AHI 75°	AHI 90°
Graichen et al (1999)	MRI	Supine, scapular plane	12	No load, passive	-	7.0 ± 1.6 mm	-	6.7 ± .92 mm	-	5.4 ± 2.3 mm
Graichen et al (1999)	MRI	Supine, scapular plane	4 male, 6 female	Load 1 kg, isometric	-	-	-	4.7 ± 2.4 mm	-	4.1 ± 2.5 mm
				No load, passive	-	-	-	6.7 mm	-	5.4 mm
Graichen et al (2001)	MRI	Supine, scapular plane	7 male, 7 female	Load 1 kg, isometric	-	-	-	-	-	4.15 ± 2.2 mm
				No load, passive	-	7.55 ± .85 mm	-	-	-	6.3 ± 1.9 mm
Hinterwimmer et al (2003)	MRI	Supine, scapular plane	6 male, 6 female	Load 15 N isometric	_	5.5 ± 1.7 mm	-	4.4 ± 1.9 mm	-	2.8 ± 1.8 mm
Herbert et al (2003)	MRI	Seated, frontal plane	30	No load, isometric	8.4 mm*	-	-	-	@70 ° 7.0 mm*	5.0 mm*
Desmeules et al (2004)	US	Seated, frontal plane	13	No load, isometric	9.9 ± 1.5 mm	-	8.3 ± 1.9 mm	7.6 ± 1.7 mm	-	-
Wang et al (2005)	US	Seated, scapular plane	16 male controls	No load, passive	6.9 ± 1.6 mm	-	-	-	-	6.7 ± 2.0 mm
			12 baseball		7.8 ± 3.6 mm					7.6 ± 2.2 mm
Bey et al (2007)	Bi-plane Xray, CT	Standing, frontal plane	9 male, 2 female	Load 1.36kg, dynamic	7.1 mm	6.0 mm	5.1 mm	3.4 mm	2.1 mm	1.2 mm
Silva et al (2010)	US	Frontal plane	31 male tennis, 22 female tennis	Not reported	8.79 ± 1.5 mm	-	-	7.19 ± 1.5 mm	-	-
			9 male controls, 11 female controls	Not reported	9.8 ± 1.4 mm	-	-	7.62 ± 1.5 mm	-	-
Thompson et al (2010) Experiment 1	DFV	Seated, scapular plane	13 baseball	No load, dynamic	12.8 ± 2.1 mm	6.9 ± 2.7 mm	5.2 ± 2.1 mm	5.3 ± 2.1 mm	6.1 ± 3.3 mm	-
				Mean load 3.6 kg, dynamic	12.5 ± 2.3 mm	7.0 ± 2.5 mm	4.7 ± 1.4 mm	4.1 ± 1.7 mm	4.6 ± 2.5 mm	-
Experiment 2	DFV	Seated, scapular plane	11 baseball, 10 softball	No load, dynamic	11.8 ± 1.9 mm	7.4 ± 2.8 mm	5.3 ± 1.8 mm	4.6 ± 1.6 mm	5.4 ± 1.8 mm	-
				Mean load 3.2 kg, dynamic	12.1 ± 2.4 mm	7.2 ± 2.5 mm	4.5 ± 1.3 mm	3.7 ± 1.3 mm	4.4 ± 1.4 mm	-
Experiment 3	DFV	Seated, scapular plane	15 female athlete, 15 female control	No load, dynamic	8.7 ± 1.7 mm	5.5 ± 1.9 mm	-	3.3 ± 1.1 mm	-	4.3 ± 1.7 mm
				Mean load 2.6 kg, dynamic	7.8 ± 2.3 mm	4.7 ± 1.8 mm	-	2.9 ± 1.3 mm	-	3.9 ± 1.5 mm

APPENDIX B: SUBACROMIAL SPACE AND SUBACROMIAL IMPINGEMENT SYNDROME

A General Examination
Submitted to the Graduate Faculty of the
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Doctor of Philosophy

in

The Department of Kinesiology

by
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INTRODUCTION

The shoulder is a complex joint that requires a functional balance between stability and mobility. Anatomically the shoulder joint is an articulation between the head of the humerus and the glenoid fossa of the scapula. Unlike many other moveable joints in the body where only the distal segment moves during motion, much of the nearly 360 degrees of total shoulder motion require movement of both the humerus and the scapula. As compared to the hip, the other ball and socket joint in the human body, the bony configuration of the relatively large humeral head and small and shallow glenoid fossa offers less joint stability but permits the large amount of motion capable at the joint. While a large degree of motion is necessary to perform simple tasks, such as combing your hair and pulling a wallet out of your back pocket, the lack of bony stability places a large demand on the soft tissue structures to stabilize the joint. Failure of these static (ligaments and joint capsule) and dynamic (rotator cuff and scapular muscles) structures may lead to significant joint instability and injury. Epidemiological estimates indicate that nearly 20-30% of the general population will report shoulder pain, with the prevalence increasing greatly with age [72] and participation in overhead sports [62].

Subacromial impingement syndrome (SIS) is a common disorder affecting the shoulder joint and signs of impingement have been reported in 74% of patients complaining of shoulder pain [89]. Impingement at the shoulder joint can be divided into two major types, internal and external. Internal impingement is a termed used to explain pathological changes to the undersurface of the supraspinatus and infraspinatus tendons as they become entrapped between the humeral head and the posterior-superior glenoid labrum[37]. Internal impingement is a normal physiological finding during excessive abduction and external rotation of the humerus, especially during the late cocking phase in throwing. External impingement, or subacromial impingement

syndrome (SIS), involves compression of the anatomical structures within the subacromial space, especially the tendons of the rotator cuff. As the humerus moves into flexion or abduction, decreases in subacromial space may result in "impingement" of the rotator cuff tendons and subacromial bursa between the humeral head and the acromion.

To date, the exact mechanism and underlying etiology of SIS has yet to be determined. Much of the research efforts have focused on scapular and glenohumeral kinematics and some of the indirect factors (muscle activity, posture) related to altered kinematics[6,12,56,67,82]. Despite the present research findings, the role of scapular and glenohumeral kinematics during continuous, active motion is still uncertain and no conclusive link has been made between shoulder kinematics and subacromial space in non-pathological populations. Consequently, since no clear mechanism for SIS has emerged, decisive guidelines regarding prevention, non-surgical treatment and rehabilitation of this disorder have not been determined.

The purpose of this literature review is to present research findings relative to normal and impingement related subacromial space measurements. The paper will begin with a short explanation of the common osseous deviations found in subacromial anatomy that impact the subacromial space and a discussion of research findings indicating a critical range of abduction between 30°-90° in which physical impingement of the contents within the subacromial space is likely to occur. Further examination of the variability in subacromial space measurements, will be followed by evidence of subacromial space narrowing in impingement related pathologies. As the positions of the scapula and humerus can directly affect the size of the subacromial space, a short summary of normal shoulder kinematics and proposed alterations in impingement patient's scapular and glenohumeral kinematics will be presented. Finally, several research questions arising from this literature review will be presented.

1.0 ETIOLOGY AND ANATOMY

1.1 Etiology

Neer, [86] who was one of the first to define external SIS, divided this progressive disorder into three stages. Stage 1 is related to overuse in the overhead arm position (a flexed and abducted humerus) and causes inflammation, including edema in the subacromial bursa and the supraspinatus tendon. Neer[86] postulates that most stage 1 patients are typically twenty-five years old or less. Patients who ignore stage one and continue to use the arm in the overhead position may develop stage 2, characterized by thickening of the bursa and fibrosis and damage to the supraspinatus and infraspinatus tendons. Stage 2 patients are typically twenty-five to forty years old. Further use may lead to stage 3, which is often seen in patients above the age of forty and results in tearing or fraying of the supraspinatus and infraspinatus tendons, possible rupture of the long head of the biceps tendon and alterations on the surface of the humeral head. As SIS progresses the patient loses functionality of the shoulder and suffers from increased pain. [6,60,61,74] While SIS may affect a variety of patient populations, increased incidence of SIS has been noted in athletes who participate in repetitive overhead sports, such as tennis, baseball, and swimming.[6,13]

Mechanisms behind the development of SIS are still widely debated. [6,67,82,118] Possible mechanisms can be globally divided into two categories, structural and functional. Structural mechanisms are believed to cause degenerative changes to the rotator cuff as a result of overuse or trauma to the rotator cuff tendons. Subsequent to damage of the rotator cuff, kinematic differences, muscle imbalances, osteophytes and other factors leading to impingement then occur. Alternatively, the functional theory follows that damage to the rotator cuff tendons is due to mechanical impingement within the subacromial space due to abnormal function of the

shoulder/arm. Potential functional mechanisms include, posture, altered scapular kinematics, superior glenohumeral translations, range of motion abnormalities and capsular instabilities/tightness. Often patients suffering from SIS do not seek immediate care, thus making it difficult for clinicians to determine the stage of impingement progression and the factors initially present.

1.2 Subacromial Anatomy

The subacromial space is created by several anatomical structures. The superior surface of the head of the humerus and the superior rim of the glenoid define the inferior border of the space, while the superior border is defined by the acromion, acromioclavicular joint, and coracro-acromial ligament. Abnormalities of the coracoacromial arch, and specifically the coracoacromial ligament have been implicated by several, as a possible site of impingement and a possible cause of impingement.[14,33,38,101,116,124] Alternatively, several studies have identified alterations in the coracoacromial ligament as a symptom of SIS, not a causative factor in the development of SIS.[101,116] To date, there have been no conclusive findings that suggest that the coracoacromial ligament plays a role in the development of impingement. The contents of the subacromial space include: humeral articular cartilage, joint capsule, supraspinatus tendon, subacromial bursa and acromial periosteum.[34] The subacromial bursa is directly inferior to the acromion and the acromioclavicular joint. Underneath the bursa lie the tendons of the rotator cuff. Of the four rotator cuff muscles (supraspinatus, infraspinatus, teres minor, subscapularis), the supraspinatus tendon is most susceptible to impingement within the subacromial space due to its insertion on the superior facet of the greater tubercle of the humerus. The greater tubercle of the humerus is the most superior surface of the humerus and passes under the acromion during arm abduction. The tendon of the infraspinatus inserts on the greater tubercle posterior-inferior

to the supraspinatus and its anterior fibers may also be subjected to contact with the anterior acromion in certain shoulder positions. Posteriorly, the tendon of the teres minor and anteriorly, the tendon of the subscapularis, are rarely involved as the insertions do not lie under the superior border of the subacromial space.

Several static glenohumeral joint constraints lie beneath the tendons of the rotator cuff including the joint capsule, superior glenohumeral ligament, coraco-humeral ligament, and middle glenohumeral ligament. The tendon of the long head of the biceps lies beneath the joint capsule and shoulder ligaments and transverses superiorly between the greater and lesser tubercles of the humerus before it inserts into the superior labrum on the glenoid. Depending upon the position of the humeral head, the long head of the biceps tendon may lie in the subacromial space. The occurrence of SIS may create inflammation and irritation of the static joint constraints of the shoulder and the long head of the biceps, but rarely does the development of SIS directly injure these structures.

Impingement may result from one or both of the following, an increase in the volume of the contents within or around the space, or a narrowing of the borders of the space. Increased volume of the soft tissue structures that lie in the space (supraspinatus tendon and subacromial-subdeltoid bursa) or border the space (coracoacromial ligament) may be a result of trauma and inflammation or hypertrophy/thickening of the tissues. A decrease in the space due to the position or structure of osseous borders (acromion or humeral head) may occur as a result of osteophyte formations, morphological changes, or alterations in scapular and glenohumeral kinematics. The remainder of this review will only focus on the literature related to changes in the subacromial space as a function of the positions and structure of the osseous borders.

Determining how and when changes in the osseous borders impact the subacromial space is crucial to understanding the pathogenesis of the disease, effective treatments, and interventions.

1.2.1 Acromion Morphology

Significant variations in the size, shape, and angle of the acromion have been noted by several investigators and are suspected to be significant factors in the development of SIS.[7,15,25,86,87,96,115] Males have demonstrated significantly longer, wider and thicker anterior process dimensions than women,[87] however it is impossible to determine whether this sex difference in the size and shape of the acromion increase or decrease the incidence of shoulder pathologies. Distributions in acromion morphology, specific to length, width and thickness do appear to be consistent across the ages.[87] Neer[86] was the first to propose that variations in acromial morphology, especially the slope of the anterior aspect of the acromion, were responsible for SIS and associated with rotator cuff tears. However, Bigliani[5] proposed the first uniform classification system for the acromion based on the sagittal plane view of anatomical specimens. After study of 139 shoulders from 71 cadavers three major classifications of acromion morphology based on the amount of inferior surface curvature of the anterior-lateral acromion were developed. Type I (17% incidence) exhibited a flat undersurface, type II (43% incidence) had some curvature, and type III (40% incidence) were hooked inferiorly on the anterior aspect. This subjective classification system has since been applied to acromia using multiple imaging types and is often used in the literature to report acromion morphology despite the poor-moderate intraobserver reliability and interobserver repeatability when using radiographs and subjective analysis.[10,53] Some have suggested that morphological differences may be a result of external factors such as strength of the external rotators[59] and function.[107]

Based on the poor reliability and lack of conclusive evidence, it may still be necessary to separate subjects based on gender, age and function.

Acromial morphology has produced mixed results when used as a classification mechanism between SIS, other shoulder pathologies, and non-symptomatic patients.[3,7,15,25,83,96,115] Some shoulder pathology patients have exhibited differences in acromial morphology, specifically in regards to greater curvature of the undersurface of the acromion,[3,31,83,113] yet the exact nature of the relationship between acromion morphology and rotator cuff tears and impingement has been difficult to determine due to poor interobserver reliability[53,126] and the use of a subjective classification scheme.[117] Increased reliability has been demonstrated by the use of more objective measurement techniques,[15,117] including the use of a lateral acromion angle[3,117] and three dimensional modeling.[15] The objective measurement of lateral acromion angle was first described by Banas and colleagues[3] as the angle created by the intersection of a line parallel to the acromion undersurface and a second line parallel to the face of the glenoid. Lower lateral acromial angles were found to be a significant predictor of rotator cuff disease, with healthy shoulders demonstrating an average lateral acromial angle of 80°.[3] Toivonen and colleagues[113] introduced the acromial angle as another objective measurement of the undersurface of the acromion. The acromial angle is determined by the intersection of a line along the undersurface of the acromion and a line extending from the tip of the hook to the junction of the hook. Acromial angles displayed significant separation into three groups, which the authors classified as type 1 (0°-12° acromial angle), type II (13°-27° acromial angle), and type III (greater than 27° acromial angle). A significant association between rotator cuff tearing and increasing acromial angles has been reported.[25,113] The use of the lateral acromion angle has demonstrated acceptable values of interobserver reliability (ICC = 0.69)[117]

when using radiographs evaluated by experienced viewers, and the acromial angle has demonstrated good interobserver using radiographs[113] however no intraclass correlation coefficients (ICC) values were noted by the authors. Subjective[71] and objective[15] classification of the acromial morphology has failed to predict or classify SIS subjects, providing possible evidence of a distinct difference in etiologies between rotator cuff tears and SIS. The mix of subjective and objective classification schemes may be partially responsible for the lack of conclusive findings related to SIS patients, yet based on the enhanced reliability findings from objective classification schemes, more research using objective classification schemes and clearly defined and differentiated patient groups is needed. Recently, several authors have indicated that osseous impingement, due to acromion morphology, is not the primary cause of SIS,[71]{Chang, 2006 #154 lending further support for the functional based etiologies such as muscle imbalances or altered shoulder kinematics during motion.

2.0 SUBACROMIAL SPACE MEASUREMENTS

2.1 Critical Regions of Impingement

Various combinations of imaging modalities (radiographs, magnetic resonance images, and stereophotogrammetry) have been used to study subacromial anatomy and identify critical regions of impingement during selected static positions of the shoulder. Collectively, these findings [11,14,34,93,122,124] have lead to the conclusion that beyond 90° of neutral abduction in the scapular plane the greater tubercle of the humerus has rotated so that the subacromial space no longer contains the insertion of the supraspinatus tendon, thus eliminating the possibility of impingement of the tendon. Analysis [11,14] of the subacromial space in cadaver shoulders during passive motion has identified 60° of elevation in both the sagittal and scapular plane as critical

zones, since they place the rotator cuff directly under, or in contact with, the coracoacromial arch. Burns and Whipple[14] also noted contact between the supraspinatus tendon and the coracoacromial arch at 30° during flexion with internal rotation and at 45° during abduction with external rotation and flexion. Based on these findings, evaluation of the subacromial space above 90° does not appear to be clinically applicable to impingement of the rotator cuff. However, it should be noted that all of these studies involved static analysis of the relationships between subacromial anatomical structures and may not represent relationships experienced in dynamic human movement. Furthermore, all of these studies used cadavers (generally, over the age of 50 years) with no reported history regarding shoulder trauma or injuries. Cadaver models display changes to the properties of the shoulder tissues and dissection may result in changes to the normal fascial relationships and shoulder joint pressures. The scapula was often fixed, thus prohibiting normal scapulothoracic motion seen during normal human shoulder movements. No mention was made of the subacromial bursa during these studies, which could represent an additional soft tissue structure that may or may not be involved in SIS below and above 90° of elevation. The use of imaging modalities may be important, as currently only magnetic resonance (MR) and computed tomography (CT) provide visualization of the soft tissue (muscles, ligaments, tendons, bursa, cartilage) and bony structures. However, MR and CT imaging are very costly and are often limited to static analyses that place the subject supine. More investigations, especially during dynamic, in vivo movements below 90°are necessary to determine the exact relationships of subacromial anatomical structures during selected glenohumeral movements.

Attempts to create dynamic shoulder models, in which muscle forces were simulated on cadavers to produce humeral elevation, have resulted in similar findings of impingement

between the subacromial soft tissues and the anterior-lateral acromion during a 30-90° arc of arm elevation. Flatow and colleagues{Flatow, 1994 #86} used stereophotogrammetry to record subacromial contact between the humerus and the anterior portion of the acromion only, during all positions of arm elevation. Stereophotogrammetry involves the placement of small optical alignment targets that are rigidly fixed to bones or tissues of interest. Two cameras then take simultaneous pictures at each position and a mathematical model is then utilized to determine relationships between the optical targets in three-dimensional spaces. In the range of 60°-120°, contact of the anterior acromion was focused at the insertion of the supraspinatus tendon.[34] These findings support Neer's theory [86] that the anterior-lateral acromion is primarily involved in impingement of the supraspinatus tendon, however they fail to address what is occurring in the 0°- 60° range of abduction. Another dynamic shoulder model study[124] using ten cadavers revealed peak forces between the humeral head and the acromion between 51° and 82° of glenohumeral joint motion in the scapular plane, however the placement of the single sensor under the entire coracoacromial arch resulted in small changes to the joint orientation. The use of five smaller sensors placed within the coracoacromial arch produced similar acromial pressures,[93] with maximum pressures under the acromion occurring at 48° (±4°) of abduction with neutral rotation, 43° (±6°) of abduction with internal rotation, and 50° (±6°) of abduction with external rotation. While the use of simulated muscle forces during humeral elevation provides a more realistic model, investigators are forced to use a standardized set of force models throughout the entire motion. This fails to replicate the variability of muscle forces between subjects and even within subjects at different points in the range of motion. Furthermore, fixation of the scapula prevents normal scapulothoracic motion and may further cloud understanding in vivo shoulder motion. Also, the continued use of cadavers presents limitations

related to age, medical history, and changes in tissue properties. While these dynamic shoulder models offer some improvement in study design, they still fail to account for other subacromial soft tissues such as the subacromial bursa and capsular ligaments, and do not represent in vivo joint pressures and positions.

In vivo measurement of subacromial pressure has only been performed in one study, [122] due to subject recruitment and methodological difficulties, yet the results are comparable to earlier findings. A catheter was placed in the subacromial bursa of eleven volunteers. A pressure transducer was placed outside the skin, at the tip of the catheter, and pressures were recorded during active abduction in the scapular plane (30°, 60°, 90°, and maximal possible abduction) and in the sagittal plane at 90° of flexion. While there was substantial variability between patients, mean peak pressures were found at 60° of abduction in the scapular plane and at 90° of flexion in the sagittal plane. A significant limitation to this study was that while active motion was used, subjects were required to remain static at each measurement position for 20 seconds to allow for leveling off of the pressure. In-vivo magnetic resonance (MR) imaging of the subacromial space reports the closest proximity of the supraspinatus muscle to the acromion was found in the Hawkins clinical examination position of 90° forward flexion with internal rotation.[40,92] The use of the three-dimensional MR visualization of the subacromial space also led researchers to confirm earlier cadaver findings related to the proximity of the supraspinatus tendon to the acromion between 30° and 90° of elevation, however differences in shoulder rotation may be important in determining the exact position in which the supraspinatus is most likely impinged. Unfortunately neither the pressure transducers nor the MR imaging allowed for active and continuous motion during analysis of the subacromial anatomy structures.

Summary

Collectively, these studies serve to point to a critical range of possible subacromial impingement between 30° and 90°, however the relationship of subacromial anatomy structures remains elusive during active and continuous shoulder motions. Both research and medicine sought more exact clarification on the nature of the subacromial space at rest and during arm motions. Further analysis of subacromial critical regions began to focus on more objective analysis of the subacromial space, including physical measurement of the subacromial space, during in-vitro and in-vivo analysis through a wide array of imaging modalities.

2.2 Normal Subacromial Space Measurements

Golding[39] first reported subacromial space narrowing as one of many radiological signs associated with rotator cuff injuries. Subjective radiographic analysis of 150 cases led Golding[39] to define the subacromial space as ranging between 7 and 13 mm, yet no information was given concerning the methods of measurement nor any case related histories. Further investigations into the use of subacromial space as a diagnostic indicator for rotator cuff injuries followed, yet little attention was given to understanding the subacromial space in non-pathological populations or during various shoulder positions. Early analysis of the subacromial space measured from 175 standard anterior-posterior (AP) radiographs of emergency room cases with negative findings of trauma revealed a 6.6 - 13.8 mm range in males and 7.1 - 11.9 mm range in females.[94] All of the radiographs were taken while the patient was supine and with the arm stationary, which may have altered the osseous anatomy compared to the standing or seated functional positions of normal shoulder motion. While these early measurements provided a foundational range for pathological normal values of subacromial space, they failed to provide normal ranges across differing populations and throughout the shoulder motion.

Using a dynamic shoulder model to simulate arm elevation in cadavers, Flatow and colleagues[34] described normal contact between the rotator cuff and the undersurface of the anterior-lateral acromion and also measured the distance between the two bony landmarks that define the subacromial space (acromiohumeral interval) in various cadaver positions. The osseous acromiohumeral interval (AHI), measured using standard AP radiographs, decreased from 11.1 (±1.4) mm at 0° to 4.8 (±2.5) mm at 120° of arm elevation. Interestingly, Flatow[34] did not capture the AHI between 0° and 60° of arm elevation in the scapular plane. While muscle forces and natural joint positions were simulated during the experiment, the use of cadavers does present a significant limitation in understanding the normal range for subacromial space in vivo. Using a similar method of AP radiographs with the arm in external rotation at rest, only 4 out of 84 patients admitted to the Emergency Department with acute shoulder trauma and absence of fractures were reported to have an AHI less than 7mm.[12] No AHI range was provided by the authors, and it was assumed that the shoulders studied were previously asymptomatic, however little patient demographic data or previous medical history was given. It also should be noted that the position in which the shoulder is placed during radiographic evaluation may significantly affect the proximity of the greater tuberosity to the anterior-lateral edge of the acromion and is an important methodological consideration when comparing results. In cadaver studies [11,14,34] it has been noted that external rotation places the greater tuberosity posterior to the anterior-lateral edge of the acromion and thus, may inaccurately represent true AHI.

Radiographs have come under some scrutiny when used to evaluate subacromial space, as they only project the bones onto one plane and do not allow for multi-dimensional visualization of the space or other soft tissue structures within the space. Graichen and colleagues[43] pioneered a three dimensional visualization of the subacromial space using MR

imaging on healthy shoulders during various arm positions. AHI was measured at 30°, 60°, 90°, 120°, and 150° in neutral rotation and at 90° in both external and internal rotation while the subjects were in supine position. All elevations were conducted in the scapular plane and the arm was positioned passively during the examination. The minimal distance between the acromion and the humerus was calculated from reconstructed 3D images of the shoulders from five subjects. Average minimal AHI for all positions ranged from 4.4 (± 37.13%) to 7.9 mm (±18.18%), however considerable variability existed between subjects. Furthermore, significant variability between male and female AHI measurements have been noted, especially at 30° of abduction[41] and at rest[94] At this time it seems prudent to perform separate analyses based on gender when measuring AHI. Graichen and colleagues[43] were the first to confirm earlier findings from cadaver models [34], regarding a significant decrease in subacromial space during higher arm elevations. At 30° of elevation in the scapular plane and neutral humeral positioning, healthy individuals in this study demonstrated an average AHI of 6-10 mm, and although this space narrowed during further arm elevation, notably from 120-150°, the insertion of the supraspinatus did not remain within this subacromial space past 30° when the arm was in neutral rotation. However, the AHI was found to contain the supraspinatus muscle insertion at 90° with internal rotation and at 30°, 60° and 90° with external rotation. This discrepancy highlights the importance of consistent patient positioning and the possible need to separate by gender while measuring AHI.

Subsequent investigations[41,42] with similar techniques resulted in complementary findings. Average AHI values were noted between 6.98 mm (±0.75 mm) and 8.18 mm (±1.0 mm) at 30°, 6.7 mm at 60°, and 5.91 mm (±1.90 mm) to 6.67 mm (±1.96 mm) at 90°. Supine MRI measurements [92] of the AHI during classic impingement sign clinical tests, the Neer

position of 160° forward flexion and the Hawkins position of 90° forward flexion with internal rotation, also confirm earlier findings relative to decreased subacromial space during arm elevation. Collectively, these studies of subacromial space using MR provide further knowledge regarding normal values of the space during various arm positions in vivo. However, due to the configuration of the MR system, subjects were all measured while supine with the shoulder placed passively in position. With the exception of swimming, few functional arm movements take place in the supine position and thus, more functional measures of the subacromial space are needed.

Seated MR measurements [49,98] of subacromial space are less common and have produced slightly contradictory results. Ten healthy shoulders (4 males, 6 females) underwent seated MR imaging during shoulder flexion between 50° and 130° and shoulder abduction between 70° and 110°with progressive narrowing of the AHI during arm elevation and the most significant narrowing occurring at 110° of flexion in the sagittal plane and abduction in the frontal plane.[49] Seated MR measurements included active movement by the subjects, but required an eight second hold at each position to acquire accurate images and were not performed in the scapular plane. On the contrary, Roberts et al [98] noted an increase from resting AHI when compared to AHI from 120° - 160° of forward flexion. Subjects were imaged while seated at rest, during the two impingement test positions (Hawkins and Neer) and at 120°, however in the Neer position and 120° the subject's arms were suspended passively at the wrist by a hanging strap.[98] This passive suspension of the arm in the seated position is significantly different than any of the other previous seated or supine MR imaging methods utilized and may produce an unnatural downward leverage force at the humeral head, thus artificially widening the AHI in these positions. While the seated position is more functional than the supine positioning, it still does

not accurately represent AHI changes during active, continuous motion within the most functional plane of movement, the scapular plane.

The use of muscle activity during measurements of AHI appears to be extremely important. The influence of muscle activity on AHI measurements is well supported by the findings of Graichen and colleagues[41,42,44] who have repeatedly demonstrated narrowing of the AHI during isometric muscle activity with MR imaging. Isometric muscle activity has produced a 30% reduction in the absolute AHI during adduction and a 58% reduction in the absolute AHI during abduction.[44] Based on these large reductions in the AHI during isometric activity it seems important, and more clinically relevant, to measure AHI during some form of muscle activity.

Ultrasound, a more cost effective and less harmful, imaging modality has also been used to measure variations of AHI in normal subjects at rest and during isometric activity.[1] Longitudinal views of the subacromial space in healthy volunteers at rest ranged between 18.3 – 29.4 mm,[17] however substantially different measurement techniques, relative to MR and radiograph studies, were employed. The authors measured subacromial space as the distance between the apex of the greater tuberosity and the infero-lateral edge of the acromion. At rest, the greater tubercle is normally positioned lateral to the acromion, thus the measurement over-estimates the space available to the soft tissue structures under the acromion. Using a more traditional measurement of the AHI, that is, the smallest distance between tip of acromion and humeral head, sonographic measurements at 0°, 45°, and 60° of abduction demonstrate similar patterns of narrowing during arm elevation.[23] Significant narrowing of the AHI occurred between 0° (9.9 ± 1.7 mm) and 45° (8.3 ± 1.9 mm), however no further significant differences in narrowing occurred between 45° and 60° (7.6 ± 1.7 mm). Due to constraints in measuring

techniques, data were not available past 60°, thus it is difficult to know whether this narrowing continues throughout arm elevation or how these ultrasound measures compare to MR and radiographic measures past 60° or in the more functional, scapular, plane. It also should be noted that only 13 healthy subjects were used, gender effects were not reported, and the subjects were asked to actively hold each position while ultrasound measurements were taken. Comparison between sonographic and radiographic measurements of AHI found resulted in similar findings between these imaging modalities in pathological shoulders.[1] This provides support for the use of this imaging modality, however dynamic analysis remains difficult with this modality and physicians are more likely to use MR and radiograph imaging for diagnostic purposes.

In light of the changes in AHI based on isometric muscle activity, dynamic muscle activity that is encountered during continuous arm motion is also likely to cause changes in normative AHI values. The only dynamic, in-vivo study of AHI was performed on the contralateral shoulders of rotator cuff repair patients.[4] Using bi-plane radiographs and re-constructed computed tomography (CT) images, the subacromial space ranged from 2.3 to 7.4 mm during weighted, active arm elevation in the frontal plane between 0° and 60°. Similar to previous findings, Bey and colleagues[4] noted a decrease in subacromial space during motion, with the smallest recorded space at 60° of abduction. It is difficult to compare whether 60 ° truly represents the most significant narrowing during motion, as data was not presented past 60°. These findings represent the smallest reported normal ranges, however it seems unlikely that the AHI is as small as 2.3 mm based on sonographic reports of normal supraspinatus thickness between 4 mm[119] and 6 mm[17] within the subacromial space. It is important to note that a standardized weight was not used, thus it is difficult to determine exactly how the weight

affected the subacromial space for each individual. Also, subjects performed this exercise in the frontal plane, which may represent another source of disparity with MR and radiographic findings in the scapular plane. Despite these methodological differences, the smaller subacromial space measurements detected during active and continuous motion may be an indication of significant differences in the space during passive, active-static, and active-continuous arm motion.

Summary

Based on this literature, the subacromial space may range between 2.3 and 13.8 mm in normal shoulders. There is a general consensus that the subacromial space is maximal at 0° and narrows during arm elevation, however, considerable debate still exists on which point in the range of motion the subacromial space is the smallest. MR appears to offer the best visualization of the three dimensional space, yet presents significant limitations related to patient positioning, supine versus seated or standing, and motion allowed, active-static versus active-continuous. Comparison between radiographic and MR imaging of the AHI reveal that objective measurement of the AHI on radiographs has slightly higher reliability (ICC = 0.84) than MR (ICC = 0.81).[117] Comparison between radiographic and MR imaging of the AHI has consistently demonstrated a slightly smaller AHI with MR imaging.[102] Smaller MR values may be explained by ability of this imaging technique to visualize the humeral head articular cartilage, allowing examiners to exclude the thickness when measuring AHI. Radiographs to not allow for visualization of the humeral head articular cartilage, which has exhibited an average measurement ranging between .89 mm and 1.44 mm.[43,106] However it has been suggested that this difference may be clinically unimportant as both radiographs and MR have both produced strong correlations between symptoms of SIS and AHI. Based on the current expense and

limitations of MR, more dynamic radiographic studies, such as digital fluoroscopy, may help fill in the gaps related to changes in AHI during dynamic arm motion. Based on a comprehensive review the AHI literature, the most important gap appears to be the lack of dynamic, in-vivo AHI analysis on healthy subjects.

2.3 Subacromial Space Measurements in Pathological Populations

2.3.1 Rotator Cuff Pathologies

Early investigations into subacromial space focused primarily on the identification of a narrowed space as a diagnostic indicator of rotator cuff tears. Golding[39] was the first to link a narrow AHI with rotator cuff injuries. Several early radiological and necropsy studies[19,39,121] of rotator cuff pathology patients resulted in the general consensus that an AHI less than 7 mm was a possible diagnostic indicator of full rotator cuff tears. Emphasis was placed on superior migration of the humeral head, due to lack of sufficient humeral head compression against the glenoid by the torn supraspinatus, as the cause of a narrowed AHI. However, these early investigations failed to distinguish between different types and severities of rotator cuff tears and were either performed post-mortem or after surgical confirmation of the tear, making it difficult to determine whether the narrowing of the AHI is present in all types of rotator cuff pathologies.

Several prospective reviews of rotator cuff pathology patients have confirmed the conclusion that an AHI less than 7 mm is a definitive diagnostic finding in total/significant rotator cuff tears [25,69] and tears involving multiple tendons.[88] Multiple tendon rotator cuff tears, especially those that involve the infraspinatus, and significant fatty degeneration of the infraspinatus and supraspinatus muscles are the most likely to present with an AHI less than 7 mm.[88] Interestingly, all of these studies have compared the injured shoulder to normal AHI

ranges, not the contralateral shoulder nor matched controls. CT analysis of the AHI in rotator cuff patients using the contralateral shoulder as the healthy control failed to demonstrate significant AHI narrowing, however the patients were supine and in complete muscle relaxation during imaging which represents a large methodological departure from previous investigations.[63] It has also been suggested[12] that AHI narrowing might be a congenital versus pathological condition based on stenosis of the subacromial space, without superior migration of the humerus, however this was only found to occur in 25 out of 1,560 shoulder patients seeking care and no longitudinal studies have been performed to determine if this stenosis is truly congenital. Furthermore, it is also important to note that the AHI in rotator cuff pathologies has only been measured in the resting neutral position. Since narrowing of the AHI has been found in normal subjects during arm elevation, it may be more clinically and diagnostically relevant to measure the AHI in pathological patients under dynamic conditions.

The only investigation of AHI in rotator cuff tear patients beyond the resting position indicates that AHI may be even smaller than the previous diagnostic distance of 7 mm. Supine MRI measurements of AHI at 30° and 90° in 3 patients with full thickness rotator cuff tears indicated substantially smaller distances (3 mm and 1 mm, respectively) when compared with the healthy contralateral shoulder.[42] While this represents an extremely small subject population, it does present some support for measuring AHI in shoulder pathologies beyond the resting position. Much more evidence is needed to determine which angle of arm elevation provides the most definitive difference in AHI and more standardized patient positions are needed in order to create a reliable diagnostic exam. Furthermore, as rotator cuff tears involve damaged and dysfunctional muscle tissue, it is necessary to evaluate AHI during dynamic arm elevations so that clinicians and physicians can better appreciate how muscle dysfunction affects shoulder

kinematics. Further investigations are still needed to determine if narrowing of the AHI is a symptom or cause of rotator cuff pathology.

2.3.2 Impingement Pathologies

According to Neer's [86] classification of SIS, the most severe stage of impingement involves rotator cuff tearing, thus analysis of AHI in early stage SIS patients may provide evidence as to the cause of rotator cuff pathology. Unfortunately, the use of multiple imaging modalities and methodological differences when analyzing AHI in early stage SIS has not provided clear evidence. Radiological analysis of the AHI at rest (0° abduction) found that only 8 of 36 acute impingement patients exhibited an AHI less than 7 mm[48] and seated MRI measures demonstrated no significant difference between the affected and healthy contralateral shoulder.[49] However, an AHI less than 8 mm was reported for all impingement subjects measured with supine MRI[25] and sonographic analysis indicated a significant difference between impingement affected shoulders and the contralateral side.[17] In addition to the different imaging modalities and patient positions utilized to measure AHI, the inconclusive findings may be a result of relatively small number of patients studied, different patient inclusion criteria, the lack of separate gender analysis, and the wide group of ages studied.

Measurement of AHI beyond the resting position in impingement subjects has also produced inconsistent results, but is likely a result of methods of testing and analysis. A 68% decrease in the subacromial space, with an average 3 mm decrease in AHI has been demonstrated with MRI imaging near 90° abduction when comparing the impingement affected shoulder to the contralateral, healthy shoulder during isometric muscle contractions.[42] However, no differences were found when subjects were passively positioned at 30°, 60°, or 90° and the muscles remained relaxed.[42] The lack of difference in passive positions beyond 0° supports the

theory that muscle dysfunction plays a significant role in narrowing of the AHI during arm motions. This may also explain the lack of consistency regarding narrowing of the AHI when measured at the resting position. Ultrasound measures of AHI during isometric contractions at 0°, 45°, and 60° have demonstrated significant narrowing of the AHI for impingement subjects between 0° and 45°, but failed to produce any differences between impingement shoulders and unmatched, healthy controls.[23] It may be that impingement disorders do not produce significant enough changes in the AHI to overcome the normal variability between subjects, especially when not matching subjects by age or gender. It should be noted that significant differences in AHI between impingement and healthy shoulders have only been found when using the patient's contralateral (healthy) shoulder for comparison, no studies have been conducted using matched controls.

Summary

Collectively, studies involving pathological populations indicate that narrowing of the AHI with the shoulder at 0° is a reliable sign of significant rotator cuff tears,[19,25,39,69,88,121] yet may only occur in some SIS patients with the shoulder at rest.[17,25,48] While it is well accepted that the AHI narrows during arm elevation, there have been no studies to determine if rotator cuff patients exhibit exaggerated narrowing during arm elevation. Significant narrowing of the AHI near 90° abduction in SIS patients has been demonstrated only when comparing the affected to the contralateral shoulder and during isometric shoulder muscle activity.[42] Further analysis of the AHI at 0° and throughout dynamic arm elevation is needed to determine if pathological populations exhibit further narrowing during arm elevation. In order to create a diagnostic indicator for SIS, it may also be useful to determine the point during motion at which the most significant narrowing occurs in SIS subjects. Despite the progress, a lack of information still

hampers efforts to determine whether narrowing of the AHI is present in early stage SIS and leads to the development of rotator cuff tears, or is merely a symptom of a torn rotator cuff.

3.0 SHOULDER KINEMATICS AND SUBACROMIAL SPACE

3.1 Normal Shoulder Kinematics

Normal scapular and humeral motion is important for a fully functional upper extremity. One of the primary roles of the scapula during arm motion is to rotate synchronously with the humerus to provide elevation of the acromion[56,118] and avoid contact of the rotator cuff tendons with the anterior acromion. The idea that an abnormally positioned acromion, resulting from altered scapular kinematics during active motions, is the true cause of subacromial pain is well supported by clinicians,[13,56,67,71,81,118] but a direct link has not emerged in the literature. Pathological populations have also demonstrated significant alterations in humeral kinematics,[58,123] which is believed by clinicians to be either a result or consequence of shoulder dysfunction.

3.1.1 Scapular Kinematics

The scapula is known to rotate about three distinct axes. Medial (downward) and lateral (upward) rotation occurs about an anterior-posterior axis and involves movement of the inferior angle medially (downward) or laterally (upward). The superior-inferior axis is used to classify protraction (external rotation) and retraction (internal rotation) and involves movement of the lateral border anteriorly or posteriorly. Anterior and posterior tilting of the scapula occurs about a medial-lateral axis and involves movement of the acromion anteriorly or posteriorly. Several methods including, radiology, electromagnetic tracking devices, bone pins, ultrasound, and MRI have been used to analyze the 3-D movements of the scapula in asymptomatic individuals during arm abduction.[9,21,27,32] Collectively, the scapula demonstrates progressive upward rotation,

external rotation, and posterior tilting during glenohumeral abduction in the scapular plane. Theoretically, all three of these scapular movements during arm abduction serve to "open" the subacromial space.

Discrepancies in 3-D measurement techniques for scapular kinematics have lead to differences in measurement values for upward rotation, posterior tilt and external rotation during arm abduction. Varieties of subject populations, testing positions, instructions and methods of analysis have contributed to the mixed results arising from much of the research. There also appears to be a significant amount of intra-subject variability of scapular kinematics across trials within the same day,[112] although the extent of this variability is debated.[99] Despite uncertainty, the indications are that about 50 degrees of upward rotation is common during arm abduction in the scapular plane.[32,52,75,95] Values describing posterior rotation of the scapula during scapular plane abduction have not been as consistent with reports ranging from -6 degrees to 40 degrees.[27,32,66,75,95] Researchers also generally agree that some degree of external rotation occurs during scapular plane abduction, however, widely disparate values (1-24 degrees) have been reported.[27,32] As expected, the scapula moves differently when the arm is passively, rather than actively, moved and more external (protraction) and lateral (upward) rotation was found in subjects who actively raised their arms.[27] Differences in scapular kinematics have also been noted when comparing eccentric and concentric activity.[9] Differences between scapular behaviors during active and passive motion may explain some of the previously reported disparities in the amount of scapular motion during arm abduction and highlights the importance of future investigations into the scapular behaviors during active motion.

Population specific analysis of scapular kinematics is lacking, but initial investigations have reported some differences based on age and occupation. Older subjects demonstrated

decreases in posterior tilt at 0° and 90° and decreases in upward rotation at 90° [30] and overhead construction workers displayed small but significantly different scapular kinematics as compared to normal subjects.[9] Throwing athletes have exhibited differences in both resting posture and scapular kinematics when compared to healthy controls[85] and unilateral overhead athletes have also demonstrated asymmetries in scapular resting posture between the dominant and non-dominant arm.[90] These differences seem to support the findings of increased SIS in older patients and overhead activity participants, however no solid link between scapular kinematic changes and subacromial space measures has been established within these populations. It seems reasonable to expect that frequent overhead activity and regular participation in upper extremity strength training programs will result in a specific pattern of neuromuscular behavior that may create unique scapular kinematic behaviors and thus result in unique changes to the subacromial space. Fatigue, especially of the external rotators, appears to diminish the ability of the scapula to tilt posteriorly during arm elevation, [28,114] and thus may lead to decreases in subacromial space. Interestingly, subjects with stronger external rotators demonstrated a decrease in subacromial pressures throughout all abduction positions.[122] Sonographic analysis of healthy baseball athletes has demonstrated significantly thicker supraspinatus tendons as compared to age matched, non-athletic, healthy controls[119] which would seem to suggest greater subacromial pressures and a higher chance for impingement. It is possible that different neuromuscular control patterns for those who regular participate in overhead activities or strengthening exercises may create adaptations in scapular and glenohumeral kinematics that allow for better maintenance, and possibly enlargement, of the subacromial space despite the thicker, space filling, supraspinatus tendon. Therefore, while the possibility of population specific scapular kinematic patterns seems likely, further study is warranted, particularly in athletic and aging

populations that may exhibit unique neuromuscular patterns affecting both scapular kinematics and possibly the subacromial space.

3.1.2 Glenohumeral Kinematics

The position of the humeral head on the face of the glenoid has been studied frequently in relation to rotator cuff injuries, as the rotator cuff is thought to play an important role in stabilizing or keeping the humeral head centered in the glenoid fossa during static[16] and dynamic[111] arm activities. The position of the humeral head during arm abduction is a function of its' movement relative to the center of the glenoid fossa. Interestingly, the reference point on the glenoid fossa is not stationary for the scapula itself is capable of significant motion during arm abduction. Computer-cadaver models[35,123] have indicated that superior inclination of the glenoid facilitates superior humeral head migration by decreasing the muscle forces necessary to cause superior translation, however in-vivo investigations[8] have not reported a significant relationship between glenoid inclination and humeral head migration. Discrepancies in these findings are most likely due to differences in measurement techniques and subject populations, however, it is likely that glenoid inclination along with rotator cuff function and muscular firing patterns are all factors in superior humeral head migration. Thus, when comparing across populations or groups it is important to measure humeral head position relative to the center of the glenoid, and to compare total humeral head migration differences between similar abduction ranges.

Static radiographic analysis demonstrates that the humeral head moves very little during both weighted and un-weighted arm abduction and often remains at or below the center of the glenoid during the entire motion of normal subjects.[16,24,65,91,95,104,111,125] Graichen and colleagues[45] reported a superior position of the humeral head relative to the glenoid at 60° of

isometric abduction, followed by inferior migration and a more centered humeral head between 90° and 120°. This discrepancy may be due to the use of an open MRI, rather than standard AP radiographs, to calculate humeral head position. Normal migration totals have been reported to vary between 0-1.7 millimeters,[16,91,95,104,111] however several different ranges of abduction have been measured making it difficult to compare between studies. Although there appears to be a small discrepancy on normal migration totals during abduction, it remains significant in light of the fact that the subacromial space can be as small as 2.3 mm.[4]

In-vivo dynamic measurements of humeral head migration are difficult to accomplish, as it requires digital equipment that is capable of real time imaging of the bony tissues. Hallström and colleagues[47] used dynamic radiosterometry, which places tantulum markers into bony landmarks under local anesthesia, to capture motion via film exchangers. Unlike the previous static, radiographic studies they noted a superiorly positioned humeral head between 0° and 60° of arm abduction. However their measurements were based on a static scapula, which is not representative of in-vivo scapular motion during arm abduction and may have altered the accuracy of their results. Teyhen and colleagues[111] used digital fluoroscopic video (DFV) to measure in-vivo humeral head migration during dynamic arm abduction on young males and found results similar to static radiographic studies.[24,65,125] DFV demonstrated good to excellent inter-rater reliability, however the authors recommended increasing the video resolution in order to increase the response stability of the images acquired. The use of DFV appears to be a promising method for studying dynamic kinematics and may be preferred over the more invasive radiosterometry. While the results from the Teyhen et al[111] confirm that average humeral head superior migration is small (0.79 mm) during arm abduction, more in-vivo dynamic

measurements on females, different age groups, athletic populations and patient populations are necessary to further solidify normal humeral head migration during abduction.

If humeral head migration is clinically relevant to the subacromial space, it is necessary to simultaneously measure the acromiohumeral interval and humeral head migration. While researchers and clinicians speculate that superior humeral head migration in excess of 1.5 mm[16] may lead to subacromial space narrowing and thus subacromial impingement, no studies to date have definitively linked the two. This information may be especially important to clinicians who often prescribe weighted arm abduction exercises in the scapular plane to treat and prevent shoulder dysfunctions.

3.1.3 Scapulohumeral Rhythm

The relationship between motion of the scapula and motion of the humerus during arm elevation is often referred to as scapulothoracic and glenohumeral rhythm (or scapulohumeral rhythm). Based on one-dimensional radiographic analyses of scapular and humeral rotation, the scapula normally exhibits 60°-65° of motion while the humerus displays between 100°-120°.[36,52,95] Slightly lower values (58°-64°) for scapular motion have been reported during scapular plane abduction,[2,26] however the motion was not measured in-vivo. Combined, these two ranges allow the arm to abduct approximately 160°-180°. As the glenohumeral joint abducts and brings the greater tubercle closer to the deep surface of the acromion, the acromion must laterally (upwardly) rotate to allow free passage of the subacromial structures. Based on static radiographic analysis of normal shoulders during arm abduction, the scapula appears to engage in a "setting" phase with relatively little rotation during the first 30° of abduction, but after this point it is a significant contributor to arm abduction. Evidence indicates that during the first 30° of abduction, scapulohumeral rhythm is close to 2:1, that is, for every 2° of humeral rotation, 1°

of scapular rotation occurs,[36,52,70,91,95,100] however significant variability within the first 30° of motion has been noted by several investigators.[52,70,91,100] Scapulohumeral rhythm past 30° of abduction appears to be dependent on the plane of motion studied, although all findings seem to suggest greater scapular rotation in this phase, as compared to the 0-30° phase. Scapulohumeral rhythm measurements above 30° in the scapular plane demonstrate approximately a 1.5:1 ratio (1.5° of humeral rotation for every 1° of scapular rotation).[36,70,91,95]

Alterations in normal scapulohumeral rhythm can potentially affect the subacromial space interval, yet no distinct relationship between the two variables has been established. A decrease in scapular rotation (resulting in a larger scapulohumeral rhythm ratio) during motion may prevent the acromion from elevating, which will result in encroachment of the greater tubercle on the acromion and a subsequent decrease in the subacromial space. The relationship between scapulohumeral rhythm and subacromial space seems to be most relevant in the 30°-90° range of arm elevation, as this appears to be the range in which the greater tubercle of the humerus lies directly under the anterior-lateral edge of the acromion.[34,43]

Other investigations into scapulohumeral rhythm have focused on differences in motion and muscle activity. Active motion analyses of scapulohumeral rhythm have reported slightly different ratios across partial and complete elevation ranges [27,32,51,80,97,109]. Neither motion velocity [22,32] nor eccentric/concentric [9] activity have produced significant differences in scapulohumeral rhythm within subjects. During active, dynamic arm elevation a smaller scapulohumeral rhythm may be present [27,32], as compared to passive and static positions, although a definitive ratio has not yet been clearly established. Loading the arm during elevation[57,78], and fatigue of the rotator cuff musculature[18,77] has been shown to decrease scapular rotation which may increase the likelihood of impingement during weighted arm

abduction exercises in some populations. Clearly the amount and type of muscle activity is an important consideration when analyzing scapulohumeral rhythm, however definitive information related to the positive and negative effects of external loads on scapulohumeral rhythm has not been established. Furthermore, clinicians often prescribe active loaded and unloaded rehabilitation exercises for shoulder dysfunction patients, making knowledge of how different loads affect dynamic scapulohumeral rhythm a clinically important finding.

Several different static scapulohumeral ratios have been proposed in the literature, yet a definitive ratio has not been clearly established for dynamic motion. Inconsistent findings in regards to the effects of age [20,21,84,109], ranges of motion studied, and analysis methods utilized have created more questions than answers. Many of these studies [9,27,32] were conducted using three-dimensional electromagnetic tracking software devices, and thus represent some error due to skin movement artifact. Furthermore, the axis of rotation for the scapula appears to change as the arm is elevated [2,51,95], possibly introducing errors into electromagnetic tracking analysis methods. It is also possible that significant variability between subjects, due to differences in muscle activation patterns and strength may play a role in the inconsistent scapulohumeral ratios that have been presented.

Summary

In summary, scapular and humeral movements during arm abduction appear to vary across different populations and may be affected by a variety of factors. Normal subjects seem to exhibit upward rotation, external rotation and posterior tilting of the scapular and little or no humeral head migration during arm abduction in the scapular plane. Exact values for scapular motions and humeral head migration are varied due to the multitude of measurement techniques, types of motion studied, and the differences in subject populations. Knowledge of normal ranges

for these motions is important diagnostically as well as in preventative and rehabilitative plans. Much more in-vivo analysis and population based research is necessary to determine the exact range of normal scapular and humeral kinematics during arm motion.

The coupled upward rotation of the scapula and humerus, known as scapulohumeral rhythm, is also important to normal functioning of the shoulder and clinicians believe it plays a vital role in maintenance of the subacromial space during movement. It is generally accepted that initial arm elevation includes more humeral than scapular rotation. Dynamic analysis of scapulohumeral rhythm also indicates that the relationship between scapular upward rotation and humeral abduction is not linear [20,21,27,51,57,70,75]. As arm elevation increases the scapula appears to rotate more, resulting in a smaller scapulohumeral ratio, yet the exact point in the range of motion in which this occurs is controversial [2,20,27,51,75]. Currently, very few population specific scapulohumeral rhythm ratios have been established. There is a need for further population specific analysis of dynamic, in-vivo scapulohumeral rhythm and its exact relationship to subacromial space.

3.2 Shoulder Kinematics in Impingement Patients

3.2.1 Scapular Kinematics

Subjects with shoulder pain and dysfunction have collectively demonstrated significant changes in scapular kinematics[29,46,50,60,61,64,67,68,73,74,76,108,120], however discrepancy exists as to the specific type and amount of scapular variations involved in SIS. Of all scapular motions during arm abduction, upward rotation appears to the most significant and is thought to be very important in maintenance of the subacromial space during abduction[67,82]. Decreased upward rotation results in decreased superior movement of the acromion and thus, as the humerus elevates during arm abduction it is more likely to contact the underside of the acromion.

Evidence for decreased upward rotation in SIS subjects has been presented in four of eight studies[29,60,64,108], with one investigator reporting increased[73] upward rotation and three studies reporting no difference[46,50,68] in upward rotation between SIS and normal subjects. Posterior tipping serves to elevate the anterior edge of the acromion during arm abduction, and may be important in allowing for adequate clearance of the subacromial structures during arm motion[67,82]. Of the studies that have investigated posterior tilt in symptomatic subjects, four of six have reported decreases[29,60,64,68] in posterior tilt in SIS populations, with one investigator reporting no significant difference[50] and one reporting an increase[73] in posterior tilt. Less is understood about internal rotation of the scapula, however it is thought that internal rotation without humeral head alterations is believed to permit greater humeral head external rotation, and thus allow the greater tuberosity to move away from the anterior-inferior edge of the acromion and open the subacromial space. Three of seven studies involving SIS subjects demonstrated increased scapular winging[120] or internal rotation[50,64] during scapular plan abduction, yet the majority (four of seven) of the studies[29,60,68,73] indicated no significant differences in internal rotation between SIS subjects and normal subjects.

Scapular upward rotation necessitates further discussion, as several studies involving injury or dysfunction of the rotator cuff have resulted in much different results as compared to studies of SIS patients. Four studies involving tears of the rotator cuff[79,91,125] and nerve blocks[76] of the suprascapular nerve (supraspinatus and infraspinatus innervation) have demonstrated increased upward rotation of the scapula. Further evidence that changes in scapular kinematics, more specifically scapulohumeral rhythm, are compensatory not causative of rotator cuff tears has been obtained by several studies[79,91,103,125]. Rotator cuff tear subjects demonstrate an increased reliance on scapular motion contributions during humeral elevation, however the

reduction of pain appears to reverse this trend [103]. Increased upward rotation for subjects with rotator cuff tears has been proposed as a compensatory mechanism in order to increase subacromial space and limit compression and pain, improve the length tension relationship between the deltoid and the cuff muscles, or to compensate for rotator cuff weakness[67,79,91,103,125]. This is opposite of the findings related to SIS that seem to suggest that decreased upward rotation of the scapula may be a causative factor in the development of this pathology. The results of increased upward rotation for rotator cuff dysfunction are much more clear than the mixed evidence that seems to suggest decreased upward rotation in SIS subjects. Mixing impingement subjects with those with rotator cuff tears or sampling only a small number of impingement subjects has lead to further complications when documenting changes in scapulohumeral rhythm in SIS subjects. Graichen and colleagues indicated that a small subset of SIS patients exhibited alterations in scapulohumeral rhythm, more specifically increased scapular rotations[46], but these findings need further support before being generalized to all SIS subjects. Interestingly, while SIS is thought to lead to rotator cuff injury, the changes in scapular kinematics between the two pathologies may not be the same. More work that clearly separates these two pathological populations is necessary in order to fully understand shoulder kinematic changes and whether they are a compensation for the pathology or a cause of the pathology.

The reported discrepancies are not surprising based on the wide variety of methods used to evaluate these complex three-dimensional scapular positions, including radiographs, 3-D electromagnetic sensors, ultrasound, and MRI analysis. Several studies[60,64,73] used electromagnetic surface sensors, which have been known to produce skin motion artifact,[75] and may introduce additional error into the already small measurement. Small sample sizes in several of the previous studies resulted in limited statistical power for detecting differences in

scapular motion. Pooling across genders and age groups has also been a common, practice despite findings of different static, scapular resting positions between normal men and women[84] and different age groups[21,30]. Additionally, athletes have demonstrated significantly different scapular positioning[85], which may introduce additional error when comparing pathological populations to different types of "normal" populations. The lack of population and function specific subject pools may explain some of the previous variability[75] reported in scapular motion. Furthermore, differences in defining SIS patient populations and excluding those with rotator cuff tears may also have lead to significant differences in the types of patients included for analysis. Since the specific etiology of SIS is still unknown, it is possible that sampled populations exhibited a wide variety of etiologies, resulting in less consistent differences for the SIS group when compared to the normal subjects. Clearly, much more research into the normal scapular positions for gender, ages, and functional populations is needed to compare against matched populations with pathological shoulders. Collectively, it appears that SIS patients exhibit some changes in scapular kinematics, however the specific nature of the change and whether this is a cause or effect of SIS remains uncertain.

3.2.2 Glenohumeral Kinematics

Abnormal functioning and/or injury of the rotator cuff muscles appear to alter normal glenohumeral kinematics, and result in greater superior glenohumeral migration[104,110]. Cadaveric models[58,123] of shoulder joints in motion have suggested that greater superior glenoid inclination (is associated with greater superior migration of the humeral head and thus a tendency towards impingement and rotator cuff tears. Glenoid inclination angle is a permanent osseous superior – inferior tilt of the glenoid face, without changes in the position of the scapular body with normal glenoid inclination angles reported to vary between 90.7° and 100.5° [8,46] However,

investigations of cadavers with unilateral rotator cuff tears[54], in-vivo CT scans[8], and MRI analysis[42] of patients with unilateral rotator cuff tears have not demonstrated a relationship between glenoid inclination and rotator cuff tears or humeral head translations[8]. Patients with documented rotator cuff tears[24,91,125] have demonstrated significant superior migration of the humeral head during at least one position during scapular plane abduction. In one study significant superior translation was noted in 47% of patients at 0°, 67% at 45°, 80% at 90°, 79% at 120° and 56% at maximum elevation[91]. However, other studies did not report significantly abnormal superior migration of the humeral head in rotator cuff tear patients until 40°[24] and 60°[125] of abduction, leaving some doubt as to when in the motion abnormal superior migration is likely to occur. Similar findings of excessive superior glenohumeral migration have also been reported after fatigue of the rotator cuff musculature[16,111], providing more evidence that the rotator cuff is an important factor in maintenance of the subacromial space due to its ability to keep the head of the humerus centered in the glenoid fossa during abduction.

Studies of humeral head migration in SIS subjects are limited and present inconsistent results. Poppen and Walker[95] reported superior migration of the humeral head in some patients with shoulder pain but included a variety of diagnoses which resulted in inconsistent findings. Radiographic analysis of SIS subjects demonstrated no difference in the humeral head position at rest, but a significantly greater superior migration as the arm was abducted thru 20° increments[24]. However, Ludewig and Cook[65] found no significant difference in superior – inferior humeral head position when comparing the SIS shoulders of construction workers to their unaffected shoulders using electromagnetic sensors during active arm abduction. A small, but significant increase in anterior positioning of the humerus was noted in the SIS group[65]. Anterior translation is likely to bring the greater tuberosity of the humerus closer to the anterior

edge of the acromion and may indirectly lead to decreased subacromial space, however much more three-dimensional analysis of the subacromial space with humeral head positions is necessary before conclusions can be made. Differences between these two studies are likely a combination of different measurement techniques (radiographs vs. electromagnetic sensors) and subjects utilized. Deutsch et al[24] only used subjects with pain for one year with overhead activities and a positive impingement sign/test, however Ludewig and Cook[65] described a more stringent inclusion and exclusion criteria, but did not diagnostically rule out the possibility of rotator cuff injury or the presence of osteophytes. Deustch and colleagues[24] also did not report on the function or occupation of the subjects, whereas Ludewig and Cook[65] studied construction workers who routinely performed overhead work. In light of all the methodological differences, it is not surprising that contradictory findings were reported. Much more work is needed to determine if SIS subjects consistently demonstrate altered glenohumeral kinematics. While pain and inflammation may be present in the rotator cuff tendons in a SIS subject, the rotator cuff remains intact and may be functional enough to prevent superior migration of the humeral head.

Summary

In summary, rotator cuff tears appear to significantly impair centering of the humeral head in the glenoid fossa during arm abduction, thus leading to decreased subacromial space. However, research involving SIS subjects and glenohumeral kinematics is limited, and no consistent theme has emerged to describe glenohumeral kinematic alterations during scapular plane abduction.

3.3 Direct Influences on Subacromial Space

Despite the discrepancies found in the literature on the specific scapular alterations that occur, collectively, it is clear that SIS populations demonstrate at some type of scapular

kinematic alterations. Differences in scapular kinematics between normal and impingement subjects have been reported to range from 4-8 degrees [60,61,64,68,74]. While a 4 degree difference in scapular kinematics may not seem to be significant, at 60 degrees of abduction Bey and colleagues [4] indicated that the subacromial space is only 2-3 mm, thus even small angular changes in the position of the scapula may significantly affect the subacromial space at this position of arm abduction. Static, supine MR evaluations[40,42,44] have further supported the theory that alterations in scapular kinematics decrease the subacromial space, yet the supine positioning does not accurately replicate normal, gravity-influenced motion. Active shoulder movement has demonstrated significant reductions in the subacromial space of SIS affected shoulders[42], yet it is unclear which scapular motions positively increase subacromial space and those which negatively decrease subacromial space. To date, it appears that only two studies have directly linked specific scapular positions to subacromial space[55,105]. A very small study using four healthy subjects, positioned supine and using sandbags to hold the scapula in protracted and retracted positions, revealed a decrease in anterior subacromial space with protraction of the scapula[105]. However, due to the supine nature of the subjects and the use of sandbags to "alter" scapular position it is likely that none or some combination of recognized scapular motions (external/internal rotation, upward/downward rotation, anterior/posterior tilting) occurred. Furthermore, this study was performed in the absence of muscle activity, which has consistently demonstrated changes in both scapular positioning and subacromial space measurements. Simulation of scapular positions on cadaver models found that posterior tilting and internal rotation had no effect on subacromial space, while upward rotation actually decreased subacromial space[55]. This finding is contrary to popular clinical theory, but indicates the need for significantly more research that links scapular kinematics and subacromial space prior to

further clinical decisions based only on theory. Admittedly, scapular modeling is inherently difficult due to the three-dimensional scapular rotations about three axes. This results in significantly complex scapular positions throughout arm movement and necessitates further in-vivo analysis rather than a reliance on cadaveric or computer modeling. The differences in scapular, and especially acromion, morphology in asymptomatic subjects[59,87,117] remain pertinent to the discussion of shoulder kinematics and subacromial space, especially in the cases of studies that use computer or cadaver based modeling of the shoulder or the placement of external electromagnetic sensors to predict/measure shoulder kinematics and then make assumptions about concurrent changes to the subacromial space. Subjects with wider, thicker or more curved acromion may have relatively less subacromial space regardless of kinematic abnormalities. Based on the differences in scapular morphology discussed above, more in-vivo and direct measurement of shoulder kinematics and related subacromial space is necessary. Thus, as of now, it is a popular clinical assumption that altered scapular kinematics contributes to narrowing of the subacromial space and SIS but research has failed to consistently support this notion.

SUMMARY AND RESEARCH QUESTIONS

SIS involves compression of the anatomical structures, most notably the supraspinatus portion of the rotator cuff, within the subacromial space. The subacromial space is three-dimensional space that is created by the osseous borders of the acromion and the humeral head, with objective measurements referred to as AHI. The etiology behind SIS is poorly understood despite significant research investigations related to subacromial space and shoulder kinematic changes in normal and SIS affected patients. Differences in shoulder anatomy, specifically the

shape of the distal acromion, based on age, gender and pathology have been reported, and are thought to be important indicators of rotator cuff pathology but relationships between SIS and acromion morphology and the coracoacromial ligament have not been firmly established. Based mainly on cadaver studies, the supraspinatus portion of the rotator cuff appears to come in closest proximity to the anterior-lateral acromion between 30° and 90° of scapular plane abduction, however rotation of the humerus (internal, neutral, or external) is capable of altering the exact arm abduction angle in which impingement is most likely. Objective measurements of the AHI have been obtained using a variety of imaging modalities and methodological approaches, leading to a large range (2.3 mm – 13.8 mm) of normal AHI values. AHI significantly narrows during arm abduction, however considerable debate still exists as to where in the range of motion the AHI is smallest. Isometric and dynamic muscle activity significantly narrows the AHI and should be considered an essential element for determination of normal AHI values. Rotator cuff tears result in an AHI value less than 7 mm, but patients with SIS do not always demonstrate narrowing of the AHI. Further research should better define population specific, normal values of the AHI during dynamic motion and distinguish between SIS and rotator cuff pathologies more stringently.

Alterations in shoulder kinematics are believed to be a clinically important factor in SIS, however whether the alterations result in changes to the subacromial space remain unclear. Scapular and humeral kinematics during arm motion vary significantly across populations and under different conditions. Damage to the rotator cuff appears to impair centering of the humeral head on the glenoid fossa and lead to increased scapular upward rotation during arm abduction. However, some SIS patients have trended towards decreases in scapular upward rotation and normal head positioning during arm abduction. SIS patients exhibit some alterations in scapular

kinematics, yet the exact type and amount is not clear in the literature. The direct influences of scapular and glenohumeral kinematic changes on subacromial space have only been studied twice, and presents significant limitations in light of previous methodological issues discussed. Much more in-vivo, dynamic and population specific research is needed before normal kinematic values can be established, however researchers must also form more direct relationships between shoulder kinematics and subacromial space measurements. Narrowing of the subacromial space remains clinically important in the prevention and rehabilitation of impingement related pathologies, however much more research is needed that directly defines how dynamic motion affects the space, what is a normal and abnormal AHI value within different population groups demonstrating increased incidences of SIS, and if and how alterations in shoulder kinematics directly affect the subacromial space.

RESEARCH QUESTIONS

1. What are the dynamic, in-vivo subacromial space measurement values in normal subjects during shoulder motions?
2. What are the dynamic, in-vivo subacromial space measurement values in overhead athletes during shoulder motions?
3. Is the dynamic, in-vivo subacromial space altered in SIS subjects?
4. How can clinicians best maintain or increase the subacromial space in SIS subjects?
5. What is the relationship between shoulder kinematics and subacromial space during dynamic, in-vivo shoulder motions?

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APPENDIX C: DISSERTATION DATA

EXPERIMENT 1

ID	sex	athlete	age	heightcm	armlengthcm	weightkg	mm0	mm30	mm45	mm60	mm75	Wmm0	Wmm30	Wmm45	Wmm60	Wmm75
BB01	1	1	21	180.98	82	80	14.09	8.33	5.64	4.29	5.84	13.62	7.03	5.63	3.67	3.74
BB02	1	1	20	175.01	78	81.82	11.08	5.27	5.27	5.27	5.63	11.99	6.18	4.13	2.91	4.12
BB03	1	1	20	179.83	81	95.27	10.35	4.18	2.81	2.54	5.29	9.81	6.12	4.49	2.53	3.03
BB04	1	1	19	179.07	82	89.36	10.72	4.18	4	3.81	3.82	10.53	4.38	3.68	2.19	3.29
BB05	1	1	20	195.58	85	90.18	13.62	9.26	6.84	8.32	13.45	13.8	5.09	3.81	6	8.17
BB07	1	1	20	181.61	84	94.45	13.8	5.83	4.45	4.1	5.09	13.8	7.45	5.81	4.18	4.36
BB08	1	1	21	172.72	81	76	10.53	8.72	5.09	3.09	3.63	9.1	8.29	5.19	3.15	3.5
BB09	1	1	21	184.15	83	87.64	15.26	13.44	9.99	7.81	7.99	14.71	12.9	5.81	5.27	6.18
bb10	1	1	22	175.26	76	83.73	12.49	4.56	4.18	4.41	5.86	12.71	8.17	4.18	3.63	4.42
bb11	1	1	21	179.71	82	86.91	12	4.72	2.54	4.54	4.18	12.71	5.27	2.55	2.72	2.73
bb12	1	1	18	180.98	82.5	86.82	10.8	5.57	2.98	4.18	0	10.9	3.45	2.54	2.91	0
bb13	1	1	19	179.71	77	85.09	16.29	7.36	6.67	9.48	9.27	17.58	10.15	6.29	6.27	8.16
bb16	1	1	19	165.74	74.2	71.55	15.44	8.18	7.63	6.9	8.9	11.28	6.58	7.06	7.91	8.58

EXPERIMENT 3
UNLOADED SCAPTION

ID	gender	athlete	age	htm	armlength	wtkg	mm0	mm30	mm45	mm60	mm75	S0	S30	S45	S60	S75
BB24	1	1	19	1.78	0.72	90.45	14.17	7.09	5.45	4.9	4.18	-18.21	-13.47	-12.15	0.89	6.34
bb28a	1	1	19	1.79	0.8	82.09	16.35	7.45	4.54	4.18	4.91	-12.9	-6.42	-2.82	-0.29	7.16
BB28b	1	1	19	1.86	0.78	96.36	11.62	6.9	5.09	4	8.35	-7.26	-2.76	8.43	15.5	21.39
BB26	1	1	21	1.8	0.8	94.09	13.99	12.24	5.64	4.86	3.89	-16.01	-4.88	4.42	6.21	13.48
BB29	1	1	19	1.75	0.73	81.36	12.53	7.26	5.81	3.27	2.54	-14.51	-8.65	-6.96	1.51	6.8
BB30	1	1	19	1.73	0.7	85.09	12.53	5.09	3.81	4.73	4.73	-19.36	-13.61	-8.5	-5.45	2.5
BB020	1	1	20	1.75	0.79	81.82	11.08	5.27	5.27	5.27	5.63	-12.67	-1.79	-0.3	3.62	8.49
BB030	1	1	20	1.79	0.81	95.27	10.35	4.18	2.81	2.54	5.29	-10.55	-10	-6.85	-2.79	1.51
BB080	1	1	21	1.72	0.81	76	10.53	8.72	5.09	3.09	3.63	1.42	9.37	15.16	18.4	21.91
BB090	1	1	21	1.84	0.83	87.64	15.26	13.44	9.99	7.81	7.99	-3.34	1.31	1.87	1.69	6.67

SB01	2	1	19	1.63	0.71	70.09	8.54	4.36	4.18	3.81	5.45	-17.84	-14.39	-9.71	-8.41	-0.7
SB02	2	1	20	1.61	0.71	57.27	10.72	5.81	3.81	2.72	4	-18.2	-10.71	-8.91	-2.83	5.89
SB03	2	1	21	1.61	0.72	80.36	10.88	10.69	6.61	4.47	4.66	-14.82	-0.69	4.94	11.24	12.24
SB04	2	1	19	1.72	0.73	80.18	10.72	3.64	2.91	2.36	2.91	-12.37	-8.64	-3.54	-2.65	6.61
SB05	2	1	20	1.68	0.74	77.27	11.4	10.64	7.98	6.27	7.41	-8.28	-3.07	2.75	8.8	10.02
SB06	2	1	19	1.65	0.72	74.09	11.21	10.81	5.7	4.72	4.52	-3.18	2.91	4.87	15.13	19.95
SB07	2	1	19	1.62	0.72	56.73	10.35	4	4	7.46	6.9	-19.15	-15.58	-11.8	-7.57	4.6
SB08	2	1	20	1.68	0.74	73.91	11.97	4.54	4.13	4.75		-12.4	-7.73	12.38	14.24	
SB09	2	1	19	1.67	0.73	62.91	12.71	5.63	2.72	2	4.18	-18.67	-10.85	-7.25	-1.41	4.36
SB11	2	1	20	1.7	0.76	83.91	9.45	7.08	6.72	5.99	7.63	-16.31	-10.99	-8.88	-2.19	5.55
SB12	2	1	18	1.59	0.72	63.09	11.08	7.26	6.9	5.09	5.63	-9.37	-0.81	2.29	8.51	15.68

EXPERIMENT 2 LOADED SCAPTION

ID	mmW0	mmW30	mmW45	mmW60	mmW75	SW0	SW30	SW45	SW60	SW75
BB24	12.53	5.99	4.18	2.72	2.72	-20.5	-7.33	-2.4	6.9	13.9
bb28a	16.32	10.17	3.26	2.91	4	-16.73	-7.3	-1.01	7.09	11.93
BB28b	11.44	4.91	4	4.9	7.26	-18.3	-8.1	5.59	12.04	15.38
BB26	14.41	9.99	5.38	4.61	3.46	-16.75	-2.7	-2.01	6.38	8.92
BB29	12.9	10.53	4.9	2.72	3.27	-9.78	-4	-3.88	-4.21	9.36
BB30	13.99	5.45	4.18	4.36	4.9	-27.08	-15.43	-13.48	-8.43	3.02
BB020	11.99	6.17	4.13	2.91	4.12	-12.63	-4.17	0.94	9.88	17.25
BB030	9.81	6.12	4.49	2.53	3.03	-18.12	-7.95	-5.22	1.23	3.4
BB080	9.1	8.29	5.19	3.15	3.5	1.18	6.82	15.08	20.97	28.38
BB090	14.71	12.89	5.81	5.27	6.18	-10.88	0.66	2.16	7.31	11.93
SB01	10.42	7.28	3.74	3.34	4.13	-8.82	-3.06	2.13	8.09	12.82
SB02	11.14	4.18	2.59	1.19	2.39	-17.09	-1.65	4.25	7.73	19.08
SB03	10.35	8.96	5.17	4.18	4.98	-18.3	-5.8	-1.85	5.17	8.58
SB04	8.75	3.5	2.33	2.14	1.94	-13.58	-6.94	-1.65	2.19	13.29
SB05	14.35	7.27	5.63	5.27	6.18	-24.95	-5.23	-4.31	3.39	8.26
SB06	10.54	10.55	6.37	3.58	3.39	5.96	7.01	8.75	12.01	12.95
SB07	10.9	5.63	3.81	4.54	4.91	-18.09	-5.23	-2.06	6.77	13
SB08	11.82	4.54	3.09	3.27	4.18	-25.38	-16.42	-9.88	-0.29	11.58
SB09	11.99	5.45	2.91	2.18	4.73	-26.52	-14.12	-10.09	-2.76	3.76
SB11	9.63	7.63	6.72	5.99	5.45	-15.99	-8.81	-1.87	2.22	5.35
SB12	10.67	6.45	6.04	5.44	5.03	-14.1	3	6.71	11.79	14.57

EXPERIMENT 3
UNLOADED
SCAPTION

ID	athlete	AGE	Heightm	BWkg	Load	ERAVG	AHI0	AHI30	AHI60	AHI90	S0	S30	S60	S90
F10	0	19	1.64	60.91	5	18.9	6.78	4.84	3.63	2.91	-11.5	-3.09	6.32	9.64
F11	0	18	1.54	55.64	4	19.73	9.49	4.62	4.88	8.2	-3.45	-1.43	6.04	14.55
F12	0	23	1.66	89.64	10	18.07	7.22	2.99	3.74	4.98	-15.5	-11.02	-5.23	5.44
F14	0	20	1.78	82.09	9	19	6.54	1.7	1.21	1.94	-24.99	-21.14	-3.81	7.57
F15	0	21	1.69	53.45	4	19.63	7.99	3.4	1.7	3.87	-12.11	-9.54	1.35	8.78
F16	0	20	1.73	56.64	4	12.17	10	2.58	3.08	4.36	-4.26	4.29	13.14	16.01
F17	0	19	1.54	66.55	6	11.13	7.02	3.63	2.91	3.63	-9.98	-3.95	0.99	9.68
F18	0	20	1.57	73.91	7	19.57	4.6	2.42	3.15	6.29	-17.2	-11.31	-2.59	3.79
F4	0	19	1.65	58.55	4	16.37	8.48	7.26	3.39	3.15	14.04	15.19	15.89	18
F5	0	23	1.54	49.36	3	13.4	8.48	2.92	2.42	4.36	-13.89	-11.16	-0.89	6.25
F7	0	22	1.73	59.27	5	15.67	9.75	6.92	3.33	3.08	-3.76	7.17	11.89	14.07
F8	0	19	1.53	44.45	3	19.83	8.97	7.18	5.64	7.69	-5.85	1.07	4.58	8.43
F19	0	20	1.7	84.91	7	22.23	6.96	4.57	1.8	1.79	-16.77	-11.43	1.79	6.32
F9	0	20	1.7	57.36	4	12.3	7.99	7.26	3.39	5.09	2.94	11.82	16.86	17.58
SB3	1	20	1.73	85.64	10	28.5	7.68	6.44	3.74	2.7	3.49	7.01	14.06	20.46
SB3	1	20	1.81	70.55	6	31.13	12.4	9.59	3.28	3.51	-7.92	0.53	7.52	9.75
SB3	1	19	1.66	80.18	8	27.63	10	5.9	5.9	6.93	4.63	6.97	14.53	21.97
SB3	1	19	1.64	60.64	4	29.67	8.65	4.44	3.04	3.27	-3.77	-0.23	14.4	23.19
SB3	1	19	1.68	63	5	24.93	10.17	6.56	4.12	5.57	15.05	15.67	19.44	29.45
SB3	1	19	1.72	84.45	9	31.1	8.72	7.34	3.44	3.45	-11.73	-7.2	4.09	8.32
SB3	1	20	1.64	55.91	4	28.13	13.08	7.26	4.65	5.81	-6.67	-3.77	7.75	23.33
SB3	1	20	1.71	64.09	5	26.63	9.93	6.54	2.42	1.21	6.55	11.22	15.62	22.35
SB3	1	19	1.68	62.09	5	33.57	8.48	6.06	3.15	4.36	-4.73	-1.48	4.08	13.88
VB1	1	20	1.8	77.27	7	37.23	10.1	8.32	4.16	4.56	1	4.71	12.89	21.9
VB3	1	19	1.73	84.09	8	34.3	9.37	7.41	3.27	3.49	-5.52	4.51	8.27	13.26
VB4	1	19	1.66	69.09	5	27.83	8.28	7.19	2.83	5.01	1.67	5.79	12.45	15.38
VB5	1	20	1.78	64.09	5	27.5	11.01	5.51	3.44	2.98	-2.39	7.22	9.57	17.7
SB4	1	21	1.6	58.18	4	27.07	8.97	6.23	3.74	4.74	-1.46	0.81	11.42	15.18
F2	0	24	1.8	62.18	6	22.4	8.47	2.99	1.27	3.24	-3.65	0.19	1.12	8.3
VB2	1	19	1.66	69.32	5	26.7	7.63	5.88	2.62	5.88	-13.22	-5.5	4.97	10.25

EXPERIMENT
3
LOADED
SCAPTION

ID	LAHI0	LAHI30	LAHI60	LAHI90	LS0	LS30	LS60	LS90
F10	6.54	6.3	2.66	2.66	-8.33	4.12	9	14.36
F11	7.44	4.36	4.87	5.13	-10.48	7.95	24.51	25.37
F12	5.23	2.99	2.49	5.98	-21.2	-13.47	-7.21	5.36
F14	5.09	2.18	0.73	1.94	-26.14	-13.67	-1.91	9.8
F15	7.51	2.66	0.97	2.18	-16.93	-2.39	1.46	12.03
F16	3.33	2.56	1.28	1.79	-19.13	-3.5	11.14	21.05
F17	5.81	1.94	0.97	3.15	-9.01	-7.84	2.61	12.07
F18	3.39	2.18	2.91	5.57	-21.78	-17.76	-2.88	8.07
F4	9.2	7.99	2.66	2.91	5.19	10.44	17.24	22.85
F5	7.99	3.15	2.66	4.12	-18.47	-9.16	1.13	13.62
F7	9.49	3.08	2.31	3.08	-11.89	2.06	7.94	9.45
F8	7.69	7.18	5.9	5.64	-11.79	-1.31	9.04	17.55
F19	8.62	2.57	1.92	4.95	-21.74	-20.53	-7.09	3.04

F9	8.72	4.12	2.42	5.33	-10.98	1.64	6.79	12
SB3	8.05	6.22	3.47	2.19	5.74	7.6	8.08	25.43
SB3	11.54	5.64	2.56	3.85	-11.05	-3.13	2.7	13.58
SB3	10	6.93	6.41	6.16	6.83	12.17	18.05	22.48
SB3	7.63	5.95	2.67	3.04	5.4	11.91	17.92	29.25
SB3	8.72	4.84	3.64	3.39	13.19	17.87	23.56	33.68
SB3	8.72	7.37	4.36	3.21	-13.97	4.43	8.83	9.6
SB3	13.37	7.85	4.65	6.39	-8.68	-0.43	10.31	20.66
SB3	8.96	6.3	2.42	1.21	0	4.72	7.71	20.56
SB3	8.72	4.6	2.91	4.36	-8.13	-3.09	5.68	15.85
VB1	9.71	5.15	2.97	4.36	0.5	7.74	12.92	22.76
VB3	8.72	4.8	2.84	2.4	-14.07	1.64	14.35	17.1
VB4	6.76	5.67	3.05	5.23	-11.57	-4.37	7.27	15.24
VB5	11.01	5.28	3.26	2.75	-5.12	8.07	14.75	16.72
SB4	6.23	5.98	3.49	4.73	-4.27	0.55	6.41	15.66
F2	3.74	1.99	1.49	1.74	-13.27	-7.02	4.48	13.45
VB2	6.1	3.28	2.62	4.36	-26.2	-10.81	1.29	4.95

VITA

Melissa Thompson serves as an Instructor in the undergraduate CAATE-Accredited Athletic Training Education Program in the Department of Kinesiology at LSU. She supervises and advises students in the Concentration in Athletic Training. She teaches courses in the Athletic Training Concentration as well as cadaver based anatomy and biomechanics courses for the Department of Kinesiology. Thompson serves as the faculty advisor for the Athletic Training Student Organization, Alpha Tau Sigma. She is a Certified Athletic Trainer who has practiced in a variety of settings. Most recently she served as the Athletic Trainer for the LSU Student Health Center and Recreation Sports. She has also worked as an athletic trainer for several high school outreach programs, a physical therapy clinic, and at the United States Military Academy (Army) in West Point, New York.

Thompson worked as a Graduate Assistant Athletic Trainer at the University of Virginia, where she earned her master's degree in an NATA Accredited Post-Professional Athletic Training Education Program. She also has served as an intern athletic trainer for the Hughston Sports Medicine Foundation. Thompson earned her bachelor's degree from Truman State University in Exercise Science where she was an Athletic Training Student for four years. She is married to Keith Thompson and has two sons.