Differences in Pre-operative Computed Tomography Based Radiomic Measurements of Osteoarthritic Patients with Walch B2/B3 and Walch A1/A2/B1 Glenoids

INTRODUCTION: The Walch glenoid classification system is commonly used by orthopedic surgeons to characterize the glenoid morphology of patients with glenohumeral arthritis. The Walch classification utilizes data from axial radiographs and/or computed tomography (CT) images, including glenoid bone surface morphology, humeral head subluxation, and glenoid retroversion to classify a glenoid into one of 7 different categories: A1, A2, B1, B2, B3, C, and D. Walch A glenoids are defined by a balanced shoulder with a centralized humeral head with A1 subtype demonstrating minor erosion compared to A2 glenoids with major erosion. In contrast, Walch B glenoids are defined by asymmetric forces resulting in posterior humeral head subluxation with B1 subtype demonstrating posterior subluxation but no erosion, B2 glenoids demonstrating posterior subluxation, posterior glenoid erosion, and a biconcavity, and B3 glenoids demonstrating more advanced medial/posterior erosion, creating a new concavity which is posteriorly oriented relative to its native position. It is not well understood how a Walch glenoid develops and progresses; however, it has been postulated that imbalances between the rotator cuff muscle size, shape, and quality may be responsible. Specifically, differences in rotator cuff muscle size and fatty infiltration rates between the anterior (i.e. subscapularis) and posterior (i.e. infraspinatus and teres minor) may be responsible for development of Walch B2/B3 glenoids. The goal of this study is to analyze pre-operative CT images of patients with glenohumeral arthritis to quantify and compare numerous radiomic features of the rotator cuff for patients with Walch A1/A2/B1 glenoids vs Walch B2/B3 glenoids, when stratified by gender in order to better characterize the muscles associated with these different glenoid classification types.

METHODS: 3D masks of the rotator cuff muscles from 2,638 patients (1283F/1355M; average age = 68.8 ± 8.6 yrs) with glenohumeral osteoarthritis were auto-segmented from pre-operative CT images obtained from 29 different clinical sites. PyRadiomics (v3.0.01) was used to extract standard radiomic features from the auto-segmented supraspinatus, subscapularis, infraspinatus, and teres minor muscles. For each muscle, six radiomic measures were then quantified. Using the built-in PyRadiomics pre-processing modules, CT images were normalized with the Z-score, resampled to an isotropic voxel size of 1.0x1.0x1.0mm, and discretized to a fixed bin count of 40. After processing, radiomic features were extracted and compared to quantify rotator cuff muscle characteristics for osteoarthritis patients with Walch A1/A2/B1 vs B2/B3 glenoids. Statistical analysis was performed using a two-tailed unpaired t-test, where $p<0.05$ defined significance.

RESULTS: Table 1 demonstrates that for both male and female patients, Walch B2/B3 glenoids are associated with greater amounts of glenoid retroversion and humeral head subluxation as compared to Walch A1/A2/B1 glenoids. When comparing anterior and posterior rotator cuff muscle volume, both male and female patients with Walch B2/B3 glenoids had a statistically smaller difference in anterior-to-posterior rotator cuff volume than patients with Walch A1/A2/B1 glenoids. Relatedly, Table 2 demonstrates that for both male and female patients, numerous differences in rotator cuff muscle size were identified between patients with Walch A1/A2/B1 and B2/B3 glenoids. Regarding muscle volume in female patients, the supraspinatus, subscapularis, and teres minor muscles were statistically smaller in B2/B3 glenoids as compared to A1/A2/B1 glenoids. No difference in infraspinatus muscle volume was observed in females. Regarding muscle volume in male patients, the subscapularis and teres minor muscles were statistically smaller in B2/B3 glenoids as compared to A1/A2/B1 glenoids; whereas, in contrast the infraspinatus was significantly larger in male patients with B2/B3 glenoids. No difference in supraspinatus muscle volume was observed in males. Regarding surface-to-volume ratios, the supraspinatus, subscapularis, and teres minor had significantly greater ratios in B2/B3 vs A1/A2/B1 glenoids in female patients; whereas, the subscapularis and teres minor had significantly greater ratios in B2/B3 vs A1/A2/B1 glenoids in male patients but statistically lower ratios for the infraspinatus. Table 2 demonstrates numerous differences in rotator cuff muscle shape between patients with Walch A1/A2/B1 and B2/B3 glenoids. Regarding elongation for female patients, both posterior rotator cuff muscles (i.e. infraspinatus and teres minor) were significantly more elongated in B2/B3 glenoids vs. A1/A2/B1 glenoids; whereas with male patients only the teres minor was significantly more elongated B2/B3 glenoids vs. A1/A2/B1 glenoids. Regarding flatness for both male and female patients, the supraspinatus, infraspinatus, and teres minor were significantly flatter in B2/B3 glenoids vs. A1/A2/B1 glenoids; in contrast, the subscapularis was significantly flatter in both male and female A1/A2/B1 glenoids vs B2/B3 glenoids. Regarding sphericity for both male and female patients, the subcapularis and teres minor had significantly less sphericity in B2/B3 glenoids vs. A1/A2/B1 glenoids; in contrast, the infraspinatus had significantly greater sphericity in B2/B3 glenoids vs. A1/A2/B1 glenoids. Finally, with the exception of the teres minor (which had significantly higher mean Hounsfield units in B2/B3 glenoids), no significant differences were observed in the mean (normalized) Hounsfield units between the rotator cuff muscles of patients with A1/A2/B1 glenoids vs. B2/B3 glenoids. See Figure 1 for representative 3D images of a Walch A1 and Walch B2 glenoid.

DISCUSSION: The results of this radiomic study demonstrate numerous differences in the size and shape of the rotator cuff muscles between Walch A1/A2/B1 and B2/B3 glenoids for both male and female patients with glenohumeral osteoarthritis. However, we did not observe that Walch B2/B3 glenoids were associated with an imbalance in anterior-to-posterior rotator cuff muscle size, in fact, we observed that B2/B3 glenoid patients (both male and female) had significantly less difference in muscle volume between their anterior-to-posterior rotator cuff muscles than A1/A2/B1 glenoids. Additionally, we did not observe that Walch B2/B3 glenoids were associated with poorer quality rotator cuff muscles as there was no difference in the mean (normalized) Hounsfield unit between subscapularis, supraspinatus, and infraspinatus muscles between A1/A2/B1 and B2/B3 glenoids. While these findings suggest that fatty infiltration may not be an etiological factor in the progression of Walch deformity; it should be noted that CT images with 71 different convolution kernels were analyzed in this study, and even when pro-processing techniques are performed, Hounsfield unit measurements can vary by convolution kernel and other image acquisition parameters. As such, additional work is necessary to analyze differences in pixel-level radiometric measurements between Walch cohorts when stratified by convolution kernel.

SIGNIFICANCE/CLINICAL RELEVANCE: Radiomic analyses can be used to more objectively quantify a patient's anatomy, morphology, and/or pathology. This radiomic analysis of the rotator cuff muscles from 2,638 patient CT images suggest that anterior-to-posterior rotator cuff muscle volume imbalances and anterior-to-posterior muscle fatty infiltration are not different between Walch A1/A2/B1 vs Walch B2/B3 glenoids.

Table 1. Comparison of Average Demographics, Standard Radiographic Measurements, and Muscle Volume Measurements between Glenohumeral Osteoarthritis Patients with Walch A1/A2/B1 vs B2/B3 Glenoids, Stratified by Gender.

	Patient Age (yrs)	**Glenoid Retroversion**	**Humeral Head Subluxation**	**Beta Angle**	**Subscapularis Volume (cm^3)**	**Combined Infraspinatus + Teres Minor Volume (cm^3)**	**Anterior/Posterior Rotator Cuff Assessment of Imbalance: Difference in Subscapularis Volume and Combined Infraspinatus + Teres Minor Volume (cm^3)**
All A1/A2/B1 (n=1452)	69.1 ± 8.5	8.9 ± 7.1	56.7 ± 8.7	82.3 ± 7.3	144.1 ± 48.0	129.2 ± 43.0	14.8 ± 19.8
All B2/B3 (n=1186)	68.3 ± 8.7	18.2 ± 7.6	69.0 ± 11.2	81.5 ± 8.4	154.1 ± 49.4	144.3 ± 45.9	9.9 ± 19.7
P Value	**0.0330**	**<0.0001**	**<0.0001**	0.0622	**<0.0001**	**<0.0001**	**<0.0001**
Female A1/A2/B1 (n=840)	70.3 ± 8.2	7.6 ± 7.0	56.3 ± 8.5	82.5 ± 7.0	112.4 ± 22.8	101.5 ± 20.5	11.0 ± 14.6
Female B2/B3 (n=443)	70.8 ± 7.9	16.7 ± 7.8	69.4 ± 11.0	81.3 ± 8.0	106.0 ± 21.2	99.5 ± 19.7	6.5 ± 12.8
P Value	0.3849	**<0.0001**	**<0.0001**	**0.0430**	**<0.0001**	0.0974	**<0.0001**
Male A1/A2/B1 (n=612)	67.4 ± 8.6	10.6 ± 6.9	57.3 ± 8.8	81.9 ± 7.6	187.5 ± 38.8	167.4 ± 35.9	20.1 ± 24.2
Male B2/B3 (n=743)	67.0 ± 8.8	19.1 ± 7.4	68.8 ± 11.3	81.6 ± 8.6	182.8 ± 37.7	170.9 ± 35.0	11.9 ± 22.7
P Value	0.3635	**<0.0001**	**<0.0001**	0.5897	**0.0259**	0.0641	**<0.0001**

Table 2. Comparison of Average Standard Radiomic Measurements between Glenohumeral Osteoarthritis Patients with Walch A1/A2/B1 vs B2/B3 Glenoids, Stratified by Gender.

Supraspinatus	**Volume (cm^3)**	**Surface-to-Volume Ratio**	**Elongation**	**Flatness**	**Sphericity**	**Mean (Normalized) HU**
Female A1/A2/B1	39.9 ± 7.2	0.249 ± 0.020	0.289 ± 0.029	0.177 ± 0.022	0.575 ± 0.025	-0.066 ± 0.141
Female B2/B3	38.6 ± 6.9	0.252 ± 0.022	0.289 ± 0.029	0.185 ± 0.024	0.574 ± 0.025	-0.058 ± 0.144
P Value	**0.0017**	**0.0140**	0.8769	**<0.0001**	0.9164	0.3784
Male A1/A2/B1	63.0 ± 12.8	0.218 ± 0.023	0.313 ± 0.034	0.184 ± 0.027	0.564 ± 0.031	-0.095 ± 0.133
Male B2/B3	63.1 ± 12.1	0.217 ± 0.021	0.317 ± 0.034	0.195 ± 0.027	0.567 ± 0.029	-0.094 ± 0.136
P Value	0.9117	0.1744	0.0563	**<0.0001**	0.0526	0.8749
Subscapularis	**Volume (cm^3)**	**Surface-to-Volume Ratio**	**Elongation**	**Flatness**	**Sphericity**	**Mean (Normalized) HU**
Female A1/A2/B1	112.4 ± 22.8	0.215 ± 0.026	0.692 ± 0.065	0.200 ± 0.027	0.474 ± 0.034	0.377 ± 0.098
Female B2/B3	106.0 ± 21.2	0.225 ± 0.030	0.685 ± 0.067	0.195 ± 0.027	0.464 ± 0.033	0.376 ± 0.100
P Value	**<0.0001**	**<0.0001**	0.0877	**0.0006**	**<0.0001**	0.9189
Male A1/A2/B1	187.5 ± 38.8	0.179 ± 0.027	0.745 ± 0.073	0.216 ± 0.030	0.484 ± 0.038	0.347 ± 0.094
Male B2/B3	182.8 ± 37.7	0.182 ± 0.024	0.751 ± 0.073	0.211 ± 0.032	0.476 ± 0.037	0.339 ± 0.090
P Value	**0.0259**	**0.0066**	0.1297	**0.0057**	**0.0003**	0.1048
Infraspinatus	**Volume (cm^3)**	**Surface-to-Volume Ratio**	**Elongation**	**Flatness**	**Sphericity**	**Mean (Normalized) HU**
Female A1/A2/B1	80.5 ± 17.0	0.214 ± 0.027	0.487 ± 0.041	0.167 ± 0.024	0.533 ± 0.037	0.375 ± 0.132
Female B2/B3	81.5 ± 16.6	0.211 ± 0.039	0.497 ± 0.043	0.179 ± 0.025	0.540 ± 0.037	0.382 ± 0.136
P Value	0.3342	0.1702	**<0.0001**	**<0.0001**	**0.0015**	0.3375
Male A1/A2/B1	135.6 ± 31.2	0.174 ± 0.025	0.499 ± 0.042	0.182 ± 0.030	0.552 ± 0.043	0.348 ± 0.125
Male B2/B3	141.9 ± 30.2	0.168 ± 0.022	0.506 ± 0.041	0.196 ± 0.027	0.563 ± 0.038	0.344 ± 0.124
P Value	**0.0004**	**<0.0001**	**0.0015**	**<0.0001**	**<0.0001**	0.5736
Teres Minor	**Volume (cm^3)**	**Surface-to-Volume Ratio**	**Elongation**	**Flatness**	**Sphericity**	**Mean (Normalized) HU**
Female A1/A2/B1	21.0 ± 5.7	0.338 ± 0.044	0.274 ± 0.040	0.162 ± 0.024	0.531 ± 0.032	0.010 ± 0.120
Female B2/B3	18.1 ± 5.3	0.361 ± 0.055	0.279 ± 0.051	0.169 ± 0.025	0.525 ± 0.036	-0.003 ± 0.135
P Value	**<0.0001**	**<0.0001**	**0.0499**	**<0.0001**	**0.0070**	0.0884
Male A1/A2/B1	31.5 ± 8.8	0.308 ± 0.050	0.275 ± 0.040	0.165 ± 0.028	0.512 ± 0.037	-0.030 ± 0.135
Male B2/B3	29.0 ± 8.8	0.320 ± 0.050	0.277 ± 0.041	0.171 ± 0.028	0.508 ± 0.037	-0.053 ± 0.131
P Value	**<0.0001**	**<0.0001**	0.4804	**<0.0001**	**0.0287**	**0.0016**

Figure 1. Representative Depiction of Scapular Bone and Rotator Cuff Muscle 3D CT Reconstructions of a Patient with a Walch A1 Glenoid (left) and a Walch B2 Glenoid (right); Associated Radiomic Measurements are Shown.