

Assessment of Deltoid Muscle Volume and Fatty Infiltration on Clinical Outcomes After Reverse Total Shoulder Arthroplasty

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Introduction: The biomechanical principles of reverse total shoulder arthroplasty (rTSA) rely on a functioning deltoid muscle to restore stability and function to a rotator-cuff deficient shoulder. With rTSA, the inverted concavities act as a fixed-fulcrum to convert the superiorly directed pull of the deltoid into arm elevation and rotation. The inverted concavities also medialize the center of rotation to increase the deltoid moment arm length and reduce the deltoid force required to generate motion relative to the native shoulder. While rTSA has been demonstrated to reliably treat a wide variety of indications, not all patients achieve the same magnitudes of improvement. Given this reliance on a functioning deltoid, it may be that pre-operative deltoid characteristics influence an individual's capability to achieve excellent clinical outcomes after rTSA. The goal of this pilot study is to analyze pre-operative computed tomography (CT) scans of rTSA patients with 2 years minimum follow-up to quantify deltoid muscle characteristics and correlate those deltoid measurements to clinical outcome measures in order to identify new relationships associated with good and poor clinical outcomes after rTSA.

Methods: Pre-operative CT images from 61 primary rTSA patients were used to characterize the deltoid muscle. The overall cohort of 61 rTSA was composed of 31 (28F/3M) patients classified as having "good" clinical outcomes and 30 (26F/4M) patients classified as having "poor" outcomes at 2-year minimum follow-up (29 months average). These patients were retrospectively selected from an IRB-approved multi-center clinical database of a single, platform shoulder arthroplasty system. This database collects demographic, implant, clinical and radiographic measures, including 4 ROM measures (active abduction, forward elevation, IR score, and external rotation) and 6 PROMs (SST, Constant, ASES, UCLA, SPADI, SAS). Patients with good and poor outcomes were selected based upon patient satisfaction ranking and magnitude of clinical improvement; patients were also matched for age, gender, and implant size to minimize variables between cohorts. Specifically, all patients had a 38mm glenosphere and a humeral liner + tray combination ≤ 2.5 mm offset. Deltoid morphological measures were: deltoid volume, deltoid length, cross-sectional area, deltoid muscle percent volume, deltoid fat percent volume, and moment arm lengths of the anterior, middle, and posterior heads of the deltoid. CT images were imported into Horos (Purview, Annapolis, MD) and images of the deltoid were segmented to create masks. Deltoid volume was calculated from the sum of the number of voxels in the mask times the voxel volume. Mean attenuation of the voxels within the deltoid volume was calculated in Hounsfield units. Hounsfield thresholding was used to classify voxels as fat, intermediate tissue, or muscle based on the attenuation of voxels (Fat: -190 to -30, Intermediate: -29 to 29, Muscle: 30 to 130). For each of the anterior, middle, and posterior heads of the deltoid, an algorithm was used to calculate a vector from the origin of the muscle to the center of the deltoid at the level of the humeral head center, from which, a static moment arm was calculated. A two-tailed t-test was used to compare mean values for each rTSA cohort and a Pearson correlation analysis was performed to measure the strength and direction of linear association between variables.

Results: Two-year minimum clinical outcomes for the 61 rTSA patients is presented in Table 1; deltoid muscle measurements associated with these patients are presented in Table 2. The only pre-operative difference between rTSA patients in the good and poor outcomes cohorts was that poor outcomes patients had deltoids with significantly larger cross-sectional area as compared to deltoids from good outcome patients. Table 3 presents the Pearson correlations between each deltoid measurement for the overall rTSA cohort and for the cohorts of good and bad outcomes demonstrating that numerous measurements were highly correlated with one or the other. Also presented in Table 3 are the Pearson correlations between the deltoid measurements and pre-operative and post-operative clinical outcomes for the overall rTSA cohort and for the cohorts of good and bad outcomes.

Overall deltoid volume was moderately positively correlated to 4 of 6 pre-operative PROM scores (Constant, ASES, UCLA, and SAS) and moderately positively correlated to 1 post-operative SAS score for patients in the poor outcome cohort. However, overall deltoid volume was not correlated to any pre-operative or post-operative PROM for the overall cohort or patients in the good outcome cohort. Deltoid length was moderately positively correlated with pre-operative max weight for the overall cohort and the poor outcome cohort, and also correlated to the pre-operative SAS score for the poor outcome cohort. Deltoid length was negatively correlated to post-operative active abduction for the good outcome cohort. Deltoid length was also moderately positively correlated to post-operative max weight and the post-operative Constant and SAS scores for the poor outcome cohort. Deltoid cross-sectional area was not correlated to any pre-operative or post-operative outcome measure for any patient cohort. Similarly, mean anterior, middle, and posterior deltoid moment arm measurements were not correlated to any pre-operative outcome measure for any patient cohort; however, the mean anterior deltoid moment arm was observed to be moderately positively correlated to the post-operative UCLA score and the mean middle deltoid moment arm was moderately positively correlated to post-operative active abduction for the poor outcome cohort. Mean deltoid Hounsfield units were moderately positively correlated to the pre-operative and post-operative IR score for the poor outcome cohort, moderately positively correlated to post-operative active forward elevation for all cohorts, moderately positively correlated to post-operative max weight and the Constant score for the overall cohort and the poor outcome cohort, and moderately positively correlated to the post-operative SST and SAS scores for the poor outcome cohort. Deltoid muscle percent volume was moderately positively correlated to pre-operative and post-operative active forward elevation and to 4 of 6 pre-operative PROM scores (SST, Constant, SPADI, and SAS) for the good outcome cohort. Deltoid muscle percent volume was also moderately positively correlated to the pre-operative IR score and the post-operative SAS score for the poor outcome cohort. Deltoid muscle percent volume was also moderately positively correlated to active post-operative max weight and post-operative Constant score for both the overall cohort and poor outcome cohort. Numerous moderately negative correlations were associated with the pre-operative and post-operative outcome measures for Hounsfield measurements in the intermediate range. Deltoid fat percent volume was moderately negatively correlated to pre-operative IR score, to 3 of 6 pre-operative PROM scores (Constant, ASES, and SAS), and to the post-operative max weight for the good outcome cohort. Deltoid fat percent volume was also moderately negatively correlated to the post-operative SAS score for the poor outcome cohort.

Discussion: This pilot study identified numerous deltoid measurements that correlated with pre-operative and post-operative clinical outcomes for the overall rTSA cohort and for patients with both good and poor outcomes. All deltoid measurements analyzed in this study can be obtained from CT-based pre-operative planning software; given the wide-spread adoption of planning software, an improved understanding of the relationship between deltoid morphology and clinical outcomes has potential to improve pre-operative decision making and also better predict post-operative outcomes, if these measures are integrated within the software. This study has several limitations. First, the use of pre-defined good and poor outcome cohorts may introduce some selection bias, future work should analyze a more uniform and normalized patient cohort. Second, 61 patients is a relatively small sample, future studies should increase the number of patients to better represent the rTSA population and improve study power to increase the probability of identifying deltoid measurements that are relevant and meaningful to rTSA clinical outcomes. Third, this study utilized CT scans of multiple image kernels, future work should quantify the impact of different kernels on Hounsfield unit-based threshold measurements. Finally, our linear correlation analysis was relatively simple and did not assess the predictive accuracy associated with any image measurement, future work should utilize more advanced machine-learning based techniques to investigate the capability of these CT image-based deltoid measurements to predict post-operative outcomes after rTSA.

Significance: Numerous CT image-based deltoid measurements, including deltoid volume, deltoid length, and deltoid muscle/fat percentage were correlated to pre-operative and post-operative rTSA clinical outcomes, knowledge of these relationships has the potential to improve surgical decision making and better predict post-operative clinical outcomes.

Table 1. Comparison of 2-Year Minimum Pre-operative and Post-operative Clinical Outcomes for all rTSA Patients and those Patients Classified as Having Good and Poor Outcomes

Pre-operative Outcomes, Post-operative Outcomes	Active Abduction	Active Forward Elevation	IR Score	Active External Rotation	Max Weight	SST	Constant	ASES	UCLA	SPADI	SAS
All Patients (n=61)	77.4 ± 27.3, 116.5 ± 34.1	99.8 ± 38.5, 137.5 ± 33.9	3.9 ± 1.7, 4.8 ± 1.9	19.1 ± 19.5, 43.9 ± 21.2	2.0 ± 2.3, 7.2 ± 4.5	4.1 ± 2.9, 9.3 ± 3.2	39.8 ± 14.4, 64.3 ± 19.0	34.8 ± 16.3, 74.6 ± 25.8	13.2 ± 4.1, 28.2 ± 7.3	83.9 ± 21.1, 32.8 ± 32.6	47.1 ± 11.1, 74.0 ± 17.3
Good Outcome Patients (n=31)	70.2 ± 24.4, 137.4 ± 21.1	92.3 ± 35.4, 159.4 ± 14.6	3.6 ± 1.8, 5.9 ± 0.9	18.4 ± 19.4, 54.8 ± 16.3	2.0 ± 1.8, 10.5 ± 3.2	4.1 ± 3.0, 11.7 ± 0.6	36.9 ± 12.9, 81.7 ± 7.0	34.4 ± 17.3, 97.1 ± 2.8	12.8 ± 4.1, 34.1 ± 0.9	81.7 ± 22.3, 4.6 ± 4.7	45.3 ± 11.7, 89.1 ± 4.3
Poor Outcome Patients (n=30)	82.9 ± 29.0, 94.8 ± 31.5	107.5 ± 40.6, 115.0 ± 33.6	4.2 ± 1.6, 3.6 ± 1.8	19.8 ± 20.0, 32.5 ± 19.9	2.1 ± 2.7, 4.9 ± 3.9	4.0 ± 2.8, 6.7 ± 2.7	42.7 ± 15.3, 52.0 ± 14.5	35.2 ± 15.4, 51.4 ± 16.4	13.6 ± 4.1, 22.0 ± 5.7	86.2 ± 20.0, 62.0 ± 20.9	49.0 ± 10.2, 58.3 ± 10.2
P Value (Good vs Poor for Pre-op, Post-op)	0.0687, <0.0001	0.1223, <0.0001	0.1621, <0.0001	0.7852, <0.0001	0.8596, <0.0001	0.8971, <0.0001	0.1447, <0.0001	0.8472, <0.0001	0.4552, <0.0001	0.4099, <0.0001	0.1827, <0.0001

Table 2. Comparison of CT Based Deltoid Muscle Measurements for all rTSA Patients and those Patients Classified as Having Good and Poor Outcomes

	Deltoid Volume (mL)	Deltoid Length (mm)	Deltoid Cross-Sectional Area (cm ²)	Mean Deltoid Hounsfield Unit	Deltoid Muscle Hounsfield	Deltoid Intermediate Hounsfield	Deltoid Fat Hounsfield	Anterior Deltoid Moment Arm	Middle Deltoid Moment Arm	Posterior Deltoid Moment Arm
All Patients (n=61)	439.5 ± 124.6	254.8 ± 58.0	33.9 ± 8.2	52.7 ± 14.0	82.7% ± 10.4%	13.6% ± 8.6%	3.7% ± 2.1%	31.6 ± 4.0	40.2 ± 5.7	56.5 ± 9.4
Good Outcome Patients (n=31)	416.7 ± 125.0	253.9 ± 53.8	31.5 ± 8.4	54.2 ± 15.1	84.3% ± 12.2%	12.1% ± 10.3%	3.7% ± 2.3%	31.5 ± 4.4	39.8 ± 6.4	54.7 ± 10.3
Poor Outcome Patients (n=30)	463.1 ± 121.8	255.7 ± 62.8	36.3 ± 7.3	51.1 ± 12.9	81.0% ± 8.2%	15.2% ± 6.4%	3.7% ± 2.1%	31.7 ± 3.7	40.5 ± 5.1	58.3 ± 8.2
P Value (Good vs Poor for Pre-op, Post-op)	0.1475	0.9078	0.0224	0.3906	0.2276	0.1496	0.9233	0.8583	0.6134	0.1335

Table 3. Correlation of CT Based Deltoid Muscle Analysis Measurements to Pre-operative and Post-operative Outcome Measures for all rTSA Patients and those Patients Classified as Having Good and Poor Outcomes at 2-Years Minimum Follow-up. Green highlight for High-Correlation Coefficients ≥ 0.6 ; Yellow highlight for Moderate-Correlation Coefficients >0.4 & <0.6 .

Pearsons Correlations (All Patients, Good Outcomes, Poor Outcomes)	Deltoid Volume (mL)	Deltoid Length (mm)	Deltoid Cross-Sectional Area (cm ²)	Mean Deltoid Hounsfield Unit	Deltoid Muscle Hounsfield	Deltoid Intermediate Hounsfield	Deltoid Fat Hounsfield	Anterior Deltoid Moment Arm	Middle Deltoid Moment Arm	Posterior Deltoid Moment Arm
Deltoid Length (mm)	0.690, 0.711 0.691									
Deltoid Cross-Sectional Area (cm ²)	0.523, 0.446, 0.545	-0.178, -0.265, -0.117								
Mean Deltoid Hounsfield Unit	0.361, 0.516, 0.285	0.566, 0.668, 0.485	-0.204, -0.138, -0.212							
Deltoid Muscle Hounsfield	0.270, 0.427, 0.238	0.434, 0.473, 0.448	-0.146, 0.055, -0.204	0.874, 0.749, 0.956						
Deltoid Intermediate Hounsfield	-0.251, -0.424, -0.227	-0.427, -0.474, -0.448	0.172, -0.039, 0.219	-0.867, -0.742, -0.950	-0.993, -0.989, -0.995					
Deltoid Fat Hounsfield	-0.307, -0.372, -0.262	-0.396, -0.399, -0.399	0.020, -0.094, 0.107	-0.773, -0.661, -0.870	-0.876, -0.886, -0.902	0.812, 0.807, 0.856				
Anterior Deltoid Moment Arm	0.265, 0.324, 0.216	0.155, -0.010, 0.329	0.187, 0.445, -0.007	0.167, 0.118, 0.211	0.207, 0.121, 0.270	-0.183, -0.065, -0.263	-0.271, -0.275, -0.268			
Middle Deltoid Moment Arm	0.418, 0.532, 0.323	-0.053, 0.111, -0.215	0.711, 0.625, 0.798	-0.090, -0.023, -0.126	-0.128, -0.146, -0.105	0.147, 0.164, 0.125	0.034, 0.071, 0.005	0.096, 0.370, -0.098		
Posterior Deltoid Moment Arm	0.465, 0.483, 0.418	0.165, 0.206, 0.133	0.462, 0.445, 0.423	0.135, 0.146, 0.172	0.091, 0.042, 0.171	-0.062, -0.010, -0.151	-0.190, -0.135, -0.243	-0.002, 0.285, -0.211	0.605, 0.601, 0.607	
Preop Active Abduction	0.113, -0.132, 0.246	-0.032, -0.192, 0.121	0.192, 0.074, 0.176	-0.010, 0.179, -0.103	-0.066, 0.225, -0.179	0.062, -0.218, 0.149	0.068, -0.215, 0.293	-0.135, -0.151, -0.141	-0.014, -0.047, -0.019	0.009, 0.072, -0.115
Preop Active Forward Elevation	0.237, 0.064, 0.333	0.227, 0.146, 0.320	0.056, -0.093, 0.068	0.336, 0.417, 0.331	0.258, 0.419, 0.230	-0.252, -0.414, -0.242	-0.242, -0.373, -0.147	-0.056, -0.088, -0.042	-0.126, -0.163, -0.128	0.042, 0.084, -0.055
Preop IR Score	0.122, -0.058, 0.260	0.229, 0.162, 0.322	-0.039, -0.176, -0.021	0.251, 0.110, 0.448	0.337, 0.257, 0.490	-0.323, -0.188, -0.527	-0.339, -0.431, -0.262	-0.024, -0.052, -0.006	-0.012, -0.008, -0.040	0.054, 0.009, 0.030
Preop Active External Rotation	-0.144, -0.207, -0.101	-0.227, -0.243, -0.211	-0.019, 0.074, -0.123	-0.104, -0.161, -0.050	-0.039, 0.035, -0.081	0.022, -0.034, 0.047	0.101, -0.033, 0.224	-0.176, -0.334, -0.045	-0.107, -0.007, -0.193	0.002, 0.061, -0.059
Preop Max Weight	0.270, 0.060, 0.391	0.406, 0.361, 0.453	-0.096, -0.292, 0.004	0.335, 0.303, 0.364	0.243, 0.156, 0.290	-0.249, -0.135, -0.306	-0.175, -0.170, -0.182	0.096, 0.055, 0.125	-0.124, -0.197, -0.080	-0.055, -0.216, 0.018
Preop SST	0.087, -0.002, 0.194	0.204, 0.208, 0.199	-0.064, -0.191, 0.064	0.195, 0.170, 0.219	0.250, 0.404, 0.148	-0.266, -0.399, -0.191	-0.148, -0.358, 0.067	-0.225, -0.138, -0.311	-0.044, -0.112, 0.019	0.093, 0.031, 0.160
Preop Constant	0.228, -0.049, 0.398	0.240, 0.170, 0.359	0.086, -0.194, 0.198	0.277, 0.281, 0.340	0.245, 0.495, 0.263	-0.245, -0.475, -0.295	-0.201, -0.445, -0.087	-0.059, -0.072, -0.047	-0.087, -0.136, -0.040	0.096, 0.153, 0.018
Preop ASES	0.239, 0.017, 0.490	0.258, 0.189, 0.352	0.154, -0.059, 0.370	0.154, 0.102, 0.215	0.272, 0.416, 0.189	-0.265, -0.393, -0.209	-0.255, -0.427, -0.077	0.038, 0.119, -0.043	0.053, -0.084, 0.178	0.224, 0.107, 0.337
Preop UCLA	0.200, -0.129, 0.505	0.149, 0.015, 0.312	0.178, -0.084, 0.376	0.150, 0.076, 0.240	0.208, 0.311, 0.177	-0.204, -0.296, -0.193	-0.192, -0.313, -0.082	-0.107, -0.120, -0.102	0.018, -0.144, 0.141	0.230, 0.057, 0.350
Preop SPADI	-0.105, 0.064, -0.338	-0.227, -0.162, -0.320	0.077, 0.257, -0.150	-0.279, -0.202, -0.337	-0.356, -0.429, -0.305	0.373, 0.441, 0.332	0.234, 0.322, 0.146	0.103, 0.098, 0.111	0.060, 0.337, -0.195	-0.169, -0.020, -0.351
Preop SAS	0.253, -0.057, 0.560	0.245, 0.139, 0.395	0.100, -0.128, 0.241	0.252, 0.173, 0.390	0.315, 0.400, 0.336	-0.304, -0.358, -0.367	-0.310, -0.470, -0.154	-0.045, -0.039, -0.063	-0.011, -0.090, 0.039	0.219, 0.129, 0.257
Post-op Active Abduction	-0.128, -0.299, 0.179	-0.175, -0.510, 0.011	0.013, 0.297, 0.249	0.058, -0.363, 0.188	0.115, -0.213, 0.130	-0.141, 0.216, -0.139	0.007, 0.172, -0.077	-0.002, -0.003, 0.027	0.173, 0.044, 0.406	-0.043, -0.034, 0.181
Post-op Active Forward Elevation	-0.022, 0.184, 0.131	0.184, 0.304, 0.277	-0.211, -0.029, -0.025	0.400, 0.499, 0.441	0.396, 0.437, 0.389	-0.408, -0.400, -0.388	-0.284, -0.487, -0.347	0.048, 0.174, 0.055	-0.027, -0.061, 0.052	-0.121, 0.106, -0.025
Post-op IR Score	-0.032, -0.211, 0.300	0.159, 0.027, 0.370	-0.293, -0.336, -0.060	0.302, 0.040, 0.435	0.353, 0.187, 0.389	-0.378, -0.189, -0.397	-0.196, -0.155, -0.304	0.063, 0.051, 0.130	-0.156, -0.351, -0.067	-0.181, -0.293, 0.016
Post-op Active External Rotation	-0.199, -0.173, -0.076	-0.043, -0.057, -0.027	-0.220, -0.147, -0.032	0.044, -0.071, 0.020	0.099, 0.045, 0.004	-0.114, -0.024, -0.015	-0.024, -0.102, 0.044	-0.075, -0.339, 0.116	-0.203, -0.287, -0.139	-0.192, -0.104, -0.108
Post-op Max Weight	0.159, 0.285, 0.312	0.381, 0.217, 0.449	-0.146, 0.265, -0.021	0.518, 0.313, 0.491	0.451, 0.297, 0.411	-0.453, -0.213, -0.414	-0.379, -0.395, -0.361	0.234, 0.293, 0.257	0.033, 0.194, 0.083	0.113, 0.524, 0.128
Post-op SST	-0.075, 0.098, 0.154	0.077, -0.077, 0.254	-0.219, 0.292, -0.035	0.303, 0.251, 0.429	0.372, 0.348, 0.453	-0.402, -0.335, -0.465	-0.194, -0.337, -0.348	0.119, 0.224, 0.259	0.016, 0.171, 0.113	-0.101, 0.180, 0.080
Post-op Constant	0.049, -0.077, 0.356	0.352, 0.170, 0.459	-0.227, -0.128, 0.138	0.536, 0.380, 0.521	0.484, 0.341, 0.463	-0.503, -0.290, -0.476	-0.338, -0.354, -0.363	0.205, 0.204, 0.323	0.000, -0.068, 0.201	-0.049, 0.184, 0.078
Post-op ASES	-0.095, -0.102, 0.250	0.060, -0.175, 0.294	-0.255, 0.179, -0.010	0.166, -0.109, 0.214	0.234, 0.014, 0.258	-0.269, -0.038, -0.275	-0.057, 0.060, -0.150	0.073, -0.256, 0.318	-0.037, 0.042, 0.058	-0.150, 0.133, 0.050
Post-op UCLA	-0.083, -0.080, 0.211	0.069, 0.109, 0.213	-0.198, -0.157, 0.142	0.182, 0.297, 0.176	0.238, 0.320, 0.206	-0.264, -0.297, -0.210	-0.097, -0.343, -0.166	0.168, -0.218, 0.490	0.031, -0.084, 0.216	-0.167, 0.112, -0.025
Post-op SPADI	0.156, 0.063, -0.047	-0.017, 0.199, -0.159	0.283, -0.239, 0.122	-0.211, 0.006, -0.335	-0.286, -0.152, -0.378	0.321, 0.153, 0.397	0.100, 0.126, 0.247	-0.037, -0.106, -0.150	0.013, -0.181, -0.099	0.107, -0.125, -0.171
Post-op SAS	-0.052, -0.209, 0.492	0.145, 0.035, 0.585	-0.259, -0.281, 0.110	0.282, 0.132, 0.546	0.338, 0.266, 0.516	-0.364, -0.235, -0.518	-0.181, -0.324, -0.443	0.066, -0.200, 0.353	-0.081, -0.371, 0.054	-0.157, -0.127, 0.097