Proof-of-Concept Finite Element Modelling of Effect of Tissue Induction on Rotator Cuff Tears

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Purpose

To simulate two-dimensional scenarios of scaffold-induced tissue augmentation of the supraspinatus tendon to demonstrate the efficacy of biological augmentation in articular-sided tears, bursal-sided tears, and intra-tendinous tears. Moreover, sensitivity of the stress and strain reduction in the supraspinatus tendon to the mechanical properties of the induced tissue was also investigated and summarized.

Method Description

A two-dimensional finite element mesh was generated for an articular-sided tear, a bursal-sided tear, and an intra-tendinous tear, respectively, based on previous CT images of the rotator cuff,[1] at the neutral position. The CT image was read by MIMICS®, masked based on gray-scale, and exported as an .IGES file. The .IGES file was then imported into ABAQUS®, where the finite element mesh was generated. The thickness of the tendon was modified to 3.3 mm. Tendon thickness was determined from a group of 38 preserved cadaveric specimens in which tendon thickness was measured at the insertion point and the start of the muscle body, and the average of these two readings was 3.3 mm (unpublished data, Rotation Medical, Inc.).

The supraspinatus tendon junction was modelled as a tie with the humeral head, and the articulation/ gliding surface of the supraspinatus tendon was modelled as standard hard contact with the humeral head surface. The distal end of the humeral head was fixed in all degrees of freedom, and the horizontal force and boundary conditions were prescribed to the proximal end of the supraspinatus muscle.[1] The horizontal tension was prescribed as 110 N uniformly distributed transversely along the supraspinatus muscle (Figure 1).

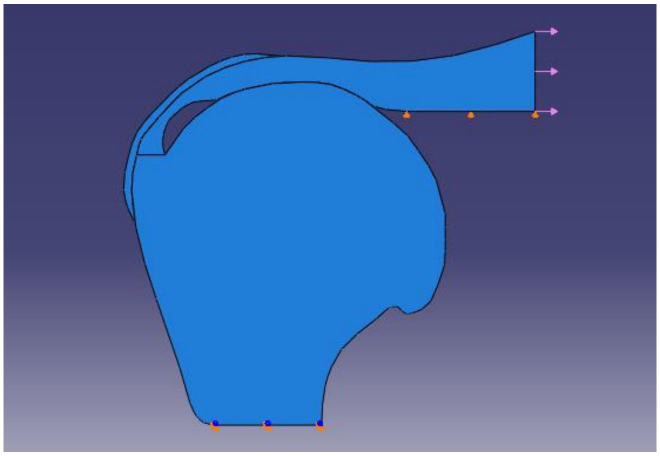

Figure 1. Boundary conditions of the FE simulation using articular-sided tear with scaffold as an example.

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[1] Sano H, Wakabayshi I, Itoi E, 2006. Stress distribution in the supraspinatus tendon with partial-thickness tears: an analysis using two-dimensional finite element model. *J Shoulder Elbow Surg* 15: 100-05.

The tendon, bone, and scaffold-induced layer of new tissue were modelled as linear isotropic elastic materials, with Young's modulus for the bone of 13.8 GPa and Poisson's ratio of 0.3 and Young's modulus for the tendon of 168 MPa and Poisson's ratio of 0.497, all obtained from the literature.[1] New tissue with three different Young's moduli were simulated: (1) 100% of the Young's modulus of tendon; (2) 85% of Young's modulus of tendon; and (3) 70% of the Young's modulus of the tendon. Poisson's ratio of the new tissue was 0.497. Nonlinear Newtonian static stress analysis was performed with ABAQUS® Standard solver. New tissue thicknesses of 1 mm and 2 mm were evaluated.

Principal stress and principal strain in the supraspinatus tendon under each condition were output, and the maximal values in the region of the tear are reported.

Results

Results consistently showed that the maximal principal stress and strain were reduced in the tendon with the scaffold-induced new tissue as compared to the original tendon tear. The greater the Young's modulus of the new tissue, the more significant the reduction in tendon stress and strain in the region of the tear (Tables 1 through 6).

Figure 2 depicts the principal stress and strain in the supraspinatus tendon under each condition: articular-sided tear with and without the scaffold-induced new tissue, bursal-sided tear with and without the scaffold-induced new tissue, and intra-tendinous tear with and without the scaffold-induced new tissue.

Table 1. Maximal principal stress and strain in the tear region for a 2 mm thick layer of new tissue with 100% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	With New Tissue	Reduction (%)
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	71.24	47.62
Max. Principal Strain	8.24×10^{-1}	4.28×10^{-1}	48.06
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	59.88	55.97
Max. Principal Strain	8.01×10^{-1}	3.55×10^{-1}	55.68
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	68.59	39.83
Max. Principal Strain	6.85×10^{-1}	4.12×10^{-1}	39.85

Table 2. Maximal principal stress and strain in the tear region for a 2 mm thick layer of new tissue with 85% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	With New Tissue	Reduction (%)
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	75.14	44.75
Max. Principal Strain	8.24×10^{-1}	4.58×10^{-1}	44.42
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	65.3	51.99
Max. Principal Strain	8.01×10^{-1}	3.87×10^{-1}	51.69
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	71.79	37.03
Max. Principal Strain	6.85×10^{-1}	4.31×10^{-1}	37.08

Table 3. Maximal principal stress and strain in the tear region for a 2 mm thick layer of new tissue with 70% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	**With New Tissue**	**Reduction (%)**
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	80.55	40.77
Max. Principal Strain	8.24x10^{-1}	4.94x10^{-1}	40.05
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	70.95	47.83
Max. Principal Strain	8.01x10^{-1}	4.21x10^{-1}	47.44
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	75.83	33.48
Max. Principal Strain	6.85x10^{-1}	4.57x10^{-1}	33.28

Table 4. Maximal principal stress and strain in the tear region for a 1 mm thick layer of new tissue with 100% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	**With New Tissue**	**Reduction (%)**
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	88.2	35.15
Max. Principal Strain	8.24x10^{-1}	5.44x10^{-1}	33.98
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	78.2	42.43
Max. Principal Strain	8.01x10^{-1}	4.65x10^{-1}	41.95
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	81.6	28.42
Max. Principal Strain	6.85x10^{-1}	4.90x10^{-1}	28.47

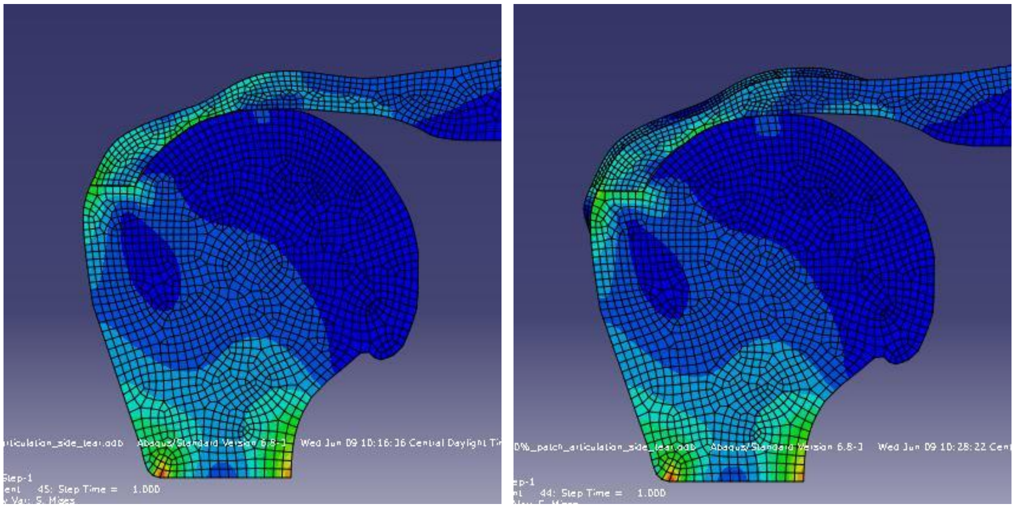
Table 5. Maximal principal stress and strain in the tear region for a 1 mm thick layer of new tissue with 85% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	**With New Tissue**	**Reduction (%)**
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	92.4	32.06
Max. Principal Strain	8.24x10^{-1}	5.70x10^{-1}	30.83
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	82.6	39.26
Max. Principal Strain	8.01x10^{-1}	4.90x10^{-1}	38.83
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	84.6	25.79
Max. Principal Strain	6.85x10^{-1}	5.08x10^{-1}	25.84

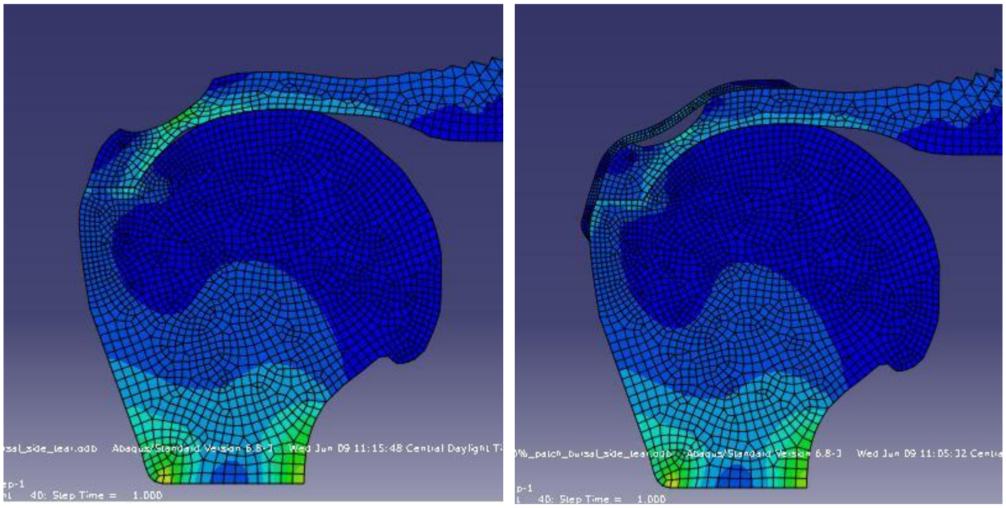
Table 6. Maximal principal stress and strain in the tear region for a 1 mm thick layer of new tissue with 70% of the Young's modulus of the supraspinatus tendon.

	Without New Tissue	**With New Tissue**	**Reduction (%)**
	Articular-Sided Tear		
Max. Principal Stress (MPa)	136	96.9	28.75
Max. Principal Strain	8.24x10^{-1}	5.97x10^{-1}	27.55
	Bursal-Sided Tear		
Max. Principal Stress (MPa)	136	87.4	35.74
Max. Principal Strain	8.01x10^{-1}	5.20x10^{-1}	35.08
	Intra-Tendinous Tear		
Max. Principal Stress (MPa)	114	88.4	22.46
Max. Principal Strain	6.85x10^{-1}	5.30x10^{-1}	22.63

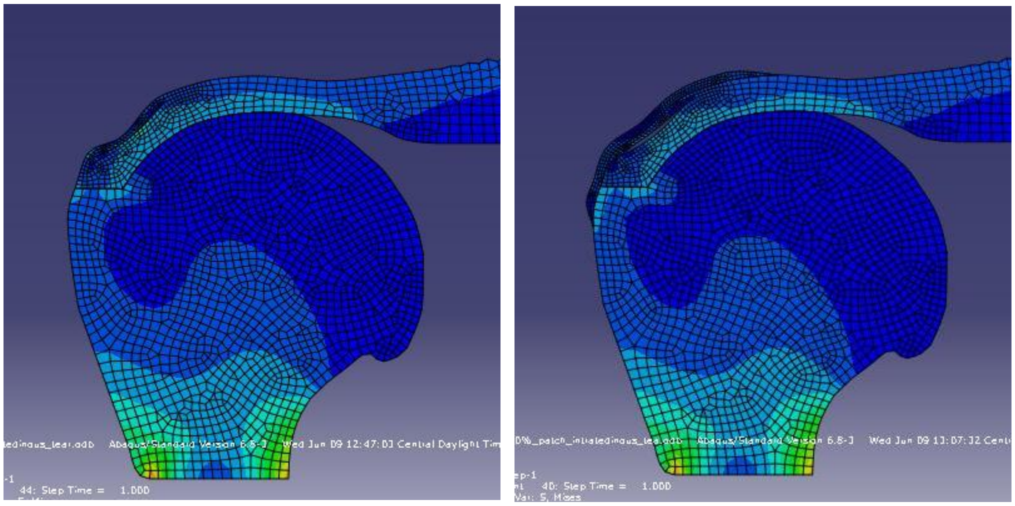
Figure 2. Principal stress and principal strain in the supraspinatus tendon and the maximal values in the region of the tear under each condition with and without the scaffold-induced new tissue.



Articular-sided tear: **Left** without new tissue; **Right** with new tissue.



Bursal-sided tear: **Left** without new tissue; **Right** with new tissue.



Intra-tendinous tear: **Left** without new tissue; **Right** with new tissue.