An analytical model to assess the load sharing ability of scaffolds used to augment rotator cuff repairs

INTRODUCTION
Several synthetic and natural scaffolds are currently being used as devices to reinforce soft tissues repaired by sutures or suture anchors during the repair of large to massive rotator cuff tears [1]. When used as an augmentation device, these scaffolds are assumed to provide some degree of load sharing in a manner that will decrease the likelihood of tendon re-tear. However, to date no studies have specifically investigated the degree of load sharing provided by a scaffold used for tendon repair augmentation. More generally, the manner in which loads and displacements on a repair construct are distributed amongst the various components of the repair is also not known. Consequently, the relative biomechanical importance of various components of the repair to its overall mechanical function has not been fully appreciated. Hence there is a need for improved understanding of the mechanisms governing tendon repair biomechanics (with or without augmentation scaffold devices). To address this need, a simple quasi-static analytical model of rotator cuff tendon repair is proposed. Here the model and its validation are presented. An illustrative parametric simulation to demonstrate the applicability of the model to predict tendon repair mechanical properties under various simulated conditions is also included.

MATERIALS AND METHODS
Model Formulation: The primary tendon repair (no scaffold) was modeled as two springs in series, namely, the bone-tendon-suture interface (spring#1) and the tendon itself (spring#2) (Figure 1a, 2a). The augmented tendon repair was modeled as five springs in series and parallel with each other (Figure 1b, 2b). The tendon (spring#2) was split into two half springs, spring#2' and spring#2". The bone-scaffold-suture component (spring#3) and the medial tendon-suture interface (spring#4) were in series with each other and together in parallel with the primary tendon repair (spring 1 and 2'). The entire repair model was then placed in series with the other half tendon spring#2".

Repair Construct Mechanical Properties: Ten, 12-mm wide strips of the infraspinatus tendon (IFT) from five pairs of human cadaveric shoulders (50-70 years) were isolated, released and repaired back to bone using double-row transosseous technique (Figure 2a). For the augmented repair, five of ten primary repairs were then augmented with a woven polymer device (12 x 35mm) (Figure 2b) [2]. For mechanical testing, the infraspinatus muscle belly was freeze-clamped and the repair constructs were cycled between 5-100N @ 0.25 Hz and subsequently loaded to failure at 30mm/min. Experimental data from the failure portion of the test were used to develop the model.

Individual Spring Component Mechanical Properties: 1. Spring#1 & #2: Optical markers placed on (i) the bone, (ii) the tendon just medial to the repair sutures, and (iii) the tendon midsubstance were used to determine the displacements of the springs #1 & #2 from the mechanical tests of the primary repair construct (n=5). 2. Spring#3: Isolated, woven polymer scaffold was screwed to a saw bone on one end and sutured with 3 simple stitches to a rod on the other end (n=3). The devices were preloaded to 5N and subsequently loaded to failure at 30mm/min. 3. Spring#4: Three modified Mason Allen sutures were placed in isolated IFT tendons (n=3) and secured over a rod. The muscle was freeze clamped and the interface was cycled for 20 cycles between 5-30N @ 0.25Hz and subsequently loaded to failure at 30mm/min. Properties of spring#3 and #4 were obtained using actuator displacements.

Parameter Estimation and Model Solution: The model parameters were determined by fitting the component-specific load-displacement data up to the first relative maximum load to a single phase non-linear equation (F = F0 + A*x^c) for spring#2, #3 and #4 and to a biphasic non-linear equation (F = F0 + A*x^c + B*x) for spring#1 using SigmaStat. The system of equations developed for the respective spring models were solved in MATLAB and compared to the loads of the experimentally tested repair constructs.

Model Parametric Simulation: The augmented repair model was used to estimate the biomechanical effect of a 50% increase in selected model parameters for springs#1, #3 and #4. A 50% increase in ‘A’ or ‘b’ may be interpreted to represent a biomechanically stronger or stiffer repair technique (spring#1), scaffold material (spring#3) or suture attachment (spring#4).

RESULTS
The root mean square (RMS) error for the primary repair model (14.4N) was 3% of the average experimental, first relative maximum load for primary repairs (415.6±81N, n=5) (Figure 3). The RMS value for the augmented repair model parameters 'A' and 'b' of springs#1, #3 and #4 respectively. A 50% increase in the parameters 'A' and 'b' may be interpreted to represent a biomechanically stronger or stiffer repair technique (spring#1), scaffold material (spring#3) or suture attachment (spring#4).

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REFERENCES