SEARCHING A SAFETY FACTOR IN THE FAILURE OF THE SUPRASPINATUS TENDON (ROTATOR CUFF)

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The injuries of the rotator cuff are a frequent pathology within the group of mechanical problems of the shoulder and almost as common in general consultation as the lumbar pain. As a result of aging, the collagen in of the rotator cuff tendons is debilitated [1] and the incidence of the tendon structural fault increases with age [2]. This increase is in percentage of people affected and in size of the failure [3]. Whereas the incidence of rotator cuff injuries in persons less than 40 years old is near zero, it is considered that 30% of the people over 60 years old present/display some degree of rupture of the rotator cuff [4, 5, 6]. The massive injuries are very common; correspond at least to 25% of the ruptures of the rotator cuff [7, 8].

Estimation of the magnitude of the injury and the safety margin of the supraspinatus tendon before total failure is based on the knowledge of the geometry and mechanical properties of the tendon. Calculation of the mechanical stress induced on the tendon is then achievable. Finite element analysis (FEA) is a very useful and efficient approach for calculation of mechanical stresses in objects of complex geometry.

The objectives of this study are to determine the critical tear dimension that causes the induced mechanical stress to exceed the tendon's failure strength, to develop a FEA model of the mechanical stresses of the failure of the supraspinatus tendon and to find a safety margin in the failure of the supraspinatus tendon.

MATERIALS AND METHODS

Experimental part:

To estimate the stress state of a structure, it is necessary to define the geometry and the material characteristics. As the tendon fibers approach the insertion into the bone, they pass above the humeral head assuming its spherical shape. This implies that the tendon will suffer deformations in both longitudinal and transversal directions in some movement ranges. The transversal stresses could be significant and the possibility of tendon failure because transversal overload should be considered.

A total of 14 human supraspinatus tendons were subjected to tensile stress test, with 7 loaded longitudinally and 7 loaded transversally to the fibers. All tendons were collected from bodies less than 12 h postmortem, and loaded in the following 48 h. between collection and testing; tendons were kept in a refrigerator at –5˚C.

For the longitudinal tension tests, tendons were collected with their insertion in the bone, and the proximal incision was made towards the muscle-tendon transition. The test pieces were at least 6 cm-long, including the hard tissue (bone) of the insertion. The part of the bone that stood out of the insertion was set in the upper clamp and the proximal part of the tendon was fixed to the lower clamp. All the tensile strength tests were realized with a machine Instron 5500 and a rupture speed of 10 mm/min.

Finite Element Analysis Model:

As a first step, the higher complexity of the orthotropic tendon was simplified to an isotropic model. The mechanical properties found in the longitudinal tension tests were used. The geometry of the tendon was assumed as a part of a hollow cylindrical shape, see fig 1.

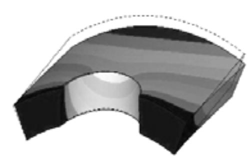

Fig 1. Tendon as a hollow cylindrical shape (in this case with a failure)

The geometric values used in the model were an inner diameter of 48 mm (diameter of the humeral head), a traverse area of $9.9*10^{-5}$ m^2 (*tendon's traverse area), and a thickness of 4.26 mm (*tendon's thickness). The materials properties used were a * tendon's Young Modulus of 18.46 MPa. and a *tendon's ultimate stress of 4.45 MPa. (*From the experimental part).

Three restrictions of movement were assumed: First, at the insertion in the bone, total restriction of movement was established. Just as it can be seen in reality when the tendon fibers enter to the bone increasing its rigidity and changing their properties to those of the bone. Second, in the most external area of insertion, a partial restriction was assumed. Movement was allowed only in the normal direction to the bone surface. This restriction was intended to represent a transition state between bone and tendon. All other parts of the tendon were free of restrictions.

As boundary condition, a longitudinal working stress (1.18 MPa) was placed in the most proximal portion of the tendon. This stress was found using the maximum force of 117 N, experimentally registered in complete abduction and with neutral rotation [9] and an *area of $9.9*10^{-5}$ m^2 (*from the experimental part). This stress was assumed as the average working stress on the Rotator Cuff for an average person.

RESULTS:

The means and standard deviations (mean±sd) of the most relevant geometric variables for this study were the thickness of tendon (mm), 4.26±0.74, the width of tendon (mm), 23.2±2.5, and the transversal area (m^2), $9.9*10^{-5}\pm2.5*10^{-5}$.

The mechanical properties for large deformations were calculated for each every specimen. Elasticity modulus (mean±sd) in the direction was found to be 18.5 ± 10 MPa (longitudinal) and 2.48 ± 0.63 MPa (transversal). Failure stress (mean±sd) was 4.50 ± 0.75 MPa (longitudinal) and 3.02 ± 0.89 MPa (transversal).

A finite element model for 5 failure widths including one with a zero area of failure (healthy tendon) was constructed and executed. The mean stresses at the insertion were registered. As result, mean longitudinal stress were given by the FEA model for all failure widths studied (from 0 to 8 mm), those can be analyzed and related with failure transversal radius. The best regression fit describes the relationship between the variables was:

$$\sigma_L = 0.108*R^2 - 0.0848*R + 1.6763 \quad (1)$$

Where: σ_L is the mean longitudinal stress at the insertion, in MPa.
R is the transversal failure radius, in mm.

Given the trend of the induced longitudinal stress to increase with failure width, the critical failure transversal radius that induces a longitudinal stress equal to the ultimate longitudinal stress (4.5 MPa) can be calculated. This critical failure radius is 5.6 mm, which results in a critical failure width of 11.2 mm.

Finally, a new functionality concept was implemented as safety margin. Functionality of the rotator cuff was defined in the following way: 100% when the longitudinal mean stress is the 1.68 MPa (evaluating stress in the equation 1 with R=0) and 0% when longitudinal mean stress is equal to the ultimate longitudinal stress (4.5 MPa). Accordingly:

$$F = 160 - 35*\sigma_L \quad (2)$$

Where: F is the rotator cuff functionality, %;
σ_L is the mean longitudinal stress at the insertion, in MPa.

Therefore, the rotator cuff presents a functionality of 60% when the induced longitudinal stress at the insertion will be 2.86 MPa and failure transversal radius is 3.7 mm.

CONCLUSIONS:

According to this study, the critical tear dimension (critical failure width) that causes the induced mechanical stress to exceed the tendon's failure strength is equal to 11.2 mm. A FEA model of the mechanical stresses of the failure of the supraspinatus tendon was developed and a term of functionality was defined. According to this functionality, a safety margin could be proposed. If a functionality of 60% is considered a good margin of safety, then the failure width should be less than 7.4 mm (failure transversal radius is 3.7 mm).

The main contribution of this study is a relationship between failure diameter and functionality. The results of this study indicate that there is a minimal residual width that must be left when repairing massive injuries of the rotator cuff. The limit width of 7.4 mm of cross-sectional defect associates the point where the tendon would have a functionality of 60 %. It must be said again that tendons used in the experimental study were 23 mm wide approx. A regular supraspinatus and infraspinatus tendon at the place of the insertion in the bigger tuberosity is 60 mm, so the minimal residual width would be 19 mm, as a first approach. This aspect remains uncertain and current studies intend to further validate this hypothesis.

Most of the complete ruptures of the rotator cuff are located in the supraspinatus, or there and in the infraspinatus [10], nevertheless the massive ruptures frequently include subscapularis [11]. If the definition of Gerber's massive rupture is accepted [2], all these injuries should be at least 5 cm in width in the place of the insertion. The results of this study suggest that the massive injuries must be repaired to at least small injuries (1cm) in those cases when the defect could not or must not be hermetically sealed.

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