Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Full-thickness tears of the supraspinatus tendon: A three-dimensional finite element analysis

C. Quental [a,*], J. Folgado [a], J. Monteiro [b], M. Sarmento [b]

[a] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[b] Faculty of Medicine, Universidade de Lisboa, Lisbon, Portugal

ARTICLE INFO

Article history:
Accepted 11 November 2016

Keywords:
Rotator cuff
Supraspinatus
Full-thickness tear
Finite element method
Hyperelastic

ABSTRACT

Knowledge regarding the likelihood of propagation of supraspinatus tears is important to allow an early identification of patients for whom a conservative treatment is more likely to fail, and consequently, to improve their clinical outcome. The aim of this study was to investigate the potential for propagation of posterior, central, and anterior full-thickness tears of different sizes using the finite element method. A three-dimensional finite element model of the supraspinatus tendon was generated from the Visible Human Project data. The mechanical behaviour of the tendon was fitted from experimental data using a transversely isotropic hyperelastic constitutive model. The full-thickness tears were simulated at the supraspinatus tendon insertion by decreasing the interface area. Tear sizes from 10% to 90%, in 10% increments, of the anteroposterior length of the supraspinatus footprint were considered in the posterior, central, and anterior regions of the tendon. For each tear, three finite element analyses were performed for a supraspinatus force of 100 N, 200 N, and 400 N. Considering a correlation between tendon strain and the risk of tear propagation, the simulated tears were compared qualitatively and quantitatively by evaluating the volume of tendon for which a maximum strain criterion was not satisfied. The finite element analyses showed a significant impact of tear size and location not only on the magnitude, but also on the patterns of the maximum principal strains. The mechanical outcome of the anterior full-thickness tears was consistently, and significantly, more severe than that of the central or posterior full-thickness tears, which suggests that the anterior tears are at greater risk of propagating than the central or posterior tears.

1. Introduction

The supraspinatus is one of the four muscles that form the musculotendinous complex known as rotator cuff (RC), which gives stability to the glenohumeral joint and protects it from dislocating forces (Wilk et al., 2009; Moore et al., 2009). Due to its anatomic position and its particularly complex loading environment, the tendon of the supraspinatus is the most frequently damaged soft tissue in the shoulder (Lake et al., 2009; Martin et al., 2015; Palastanga et al., 2002). Partial- and full-thickness tears of the supraspinatus tendon are among the most common causes of shoulder disorders (Andarawis-Puri et al., 2009; Engelhardt et al., 2016; Thunes et al., 2015).

Tears of the supraspinatus tendon usually begin at the insertion site on the humeral head as partial-thickness tears. In a significant percentage of patients, the initial tears progress over time to full-thickness tears, and ultimately extend to adjacent tendons (Engelhardt et al., 2016; Huang et al., 2005; Thunes et al., 2015). Symptoms of a supraspinatus tear may include pain and loss of shoulder strength and mobility (Miller et al., 2014; Pandey and Willems, 2015; Seida et al., 2010), but, interestingly, the majority of supraspinatus tears is asymptomatic (Itoi, 2013; Minagawa et al., 2013). The management of tears in symptomatic patients includes both conservative and operative treatments, but there is still little consensus in the best management approach (Hardy and Sanghavi, 2009; Tanaka et al., 2010). Generally, a surgical intervention is only recommended for patients who responded poorly to an initial conservative treatment (Seida et al., 2010; Thunes et al., 2015; Whiting and Zernicke, 2008). However, for some patients the delay in the surgical intervention results in larger, more difficult to

* Correspondence to: IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1 1049-001 Lisboa. Fax: +351218417915.
E-mail addresses: carlos.quental@tecnico.ulisboa.pt (C. Quental), jfolgado@tecnico.ulisboa.pt (J. Folgado), jac.monteiro@chln.min-saude.pt (J. Monteiro), marco.sarmento@chln.min-saude.pt (M. Sarmento).

http://dx.doi.org/10.1016/j.jbiomech.2016.11.049
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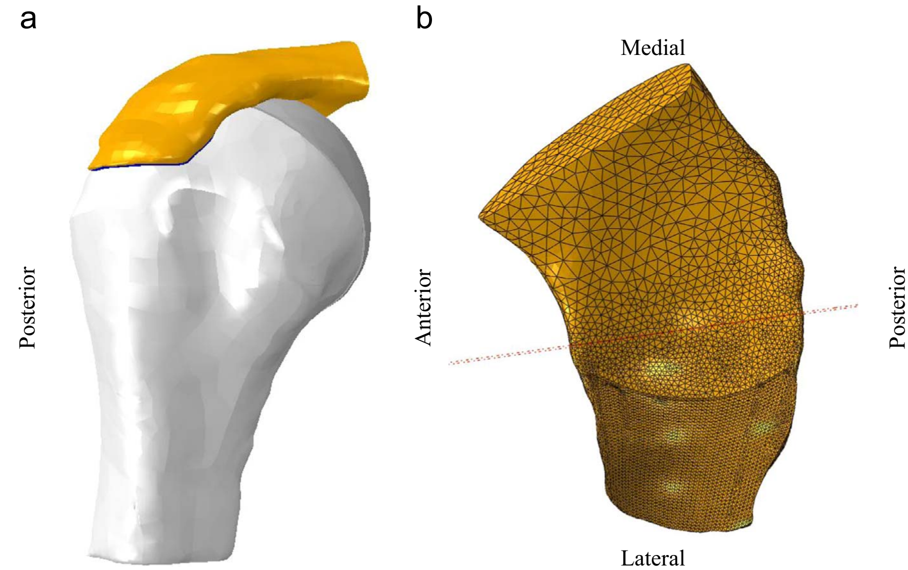

Fig. 1. Three-dimensional finite element model: (a) 3D geometry of the humerus, cartilage, fibrocartilage, and supraspinatus tendon, and (b) inferior view of the finite element mesh of the supraspinatus tendon. The humerus, cartilage, fibrocartilage, and tendon are shown in white, grey, blue, and orange, respectively. The red dashed line in (b) represents the plane that delimits the region refined near the insertion site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

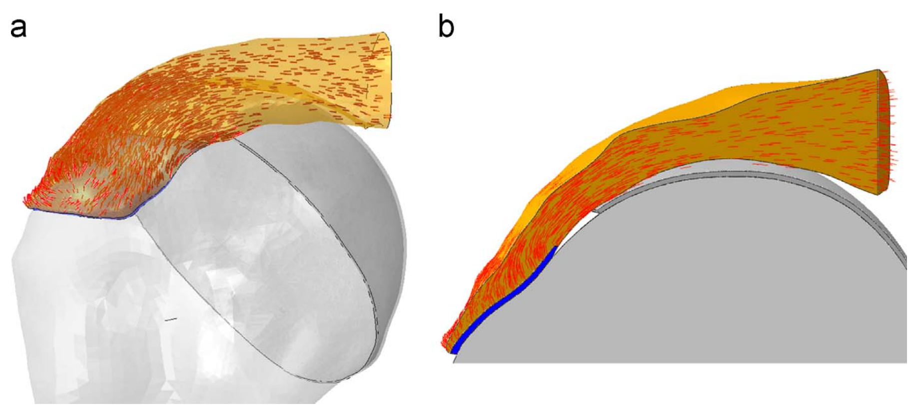

Fig. 2. Fibre directions estimated for the supraspinatus tendon: (a) 3D view, and (b) a 2D cross-sectional view. The humerus, cartilage, fibrocartilage, and tendon are shown in white, grey, blue, and orange, respectively. The tendon fibre directions, represented by red lines, are only displayed for a selected percentage of tendon elements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Description of the 3D meshes of the finite element model.

Part	Nodes	Elements
Cartilage	115,945	59,195
Fibrocartilage	50,355	29,817
Tendon	139,552	94,190
Total	305,852	183,202

Table 2
Material parameters considered for the cartilage, fibrocartilage, and tendon.

Part	Young's modulus (MPa)	Poisson's ratio	C_{10} (MPa)	k_1 (MPa)	k_2	κ
Cartilage (Favre et al., 2012)	10	0.400	–	–	–	–
Fibrocartilage (Sano et al., 2006)	572	0.432	–	–	–	–
Tendon (Kadlowec et al., 2009; Lake et al., 2009, 2010)	–	–	1.901	0.590	89.680	0.139

manage tears, which have poorer clinical outcomes (Andarawis-Puri et al., 2009; Miller et al., 2014). Considering that an early identification of these patients would benefit their clinical outcome, it is important to gain further insight into the likelihood of propagation of the different supraspinatus tears (Thunes et al., 2015). The tear size and location are potentially significant factors (Frisch et al., 2014; Miller et al., 2014).

In vitro experiments have been performed to evaluate the behaviour of partial- and full-thickness tears of the supraspinatus tendon (Andarawis-Puri et al., 2009; Bey et al., 2002; Frisch et al., 2014; Miller et al., 2014; Reilly et al., 2003b). Changes in strain in response to external loading have shown that tears propagate toward regions of highest strain, which are located directly around the tears. Computational analysis using the finite element method have also been performed (Engelhardt et al., 2016; Sano et al., 2006; Thunes et al., 2015). Using a two-dimensional model, Sano et al. (2006) observed a high stress concentration around the partial-thickness tears simulated. Similar results were also observed by Thunes et al. (2015) for full-thickness tears positioned in the posterior, central, and anterior

Please cite this article as: Quental, C., et al., Full-thickness tears of the supraspinatus tendon: A three-dimensional finite element analysis. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.11.049