Mechanics of Materials 44 (2012) 83–92

Contents lists available at SciVerse ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Bi-material attachment through a compliant interfacial system at the tendon-to-bone insertion site

Y.X. Liu [a], S. Thomopoulos [b], V. Birman [c], J.-S. Li [d], G.M. Genin [a,*]

[a] Department of Mechanical Engineering and Materials Science, Washington University, St. Louis, MO 63130, USA
[b] Department of Orthopaedic Surgery, Washington University School of Medicine, St. Louis, MO 63110, USA
[c] Engineering Education Center, Missouri University of Science and Technology, One University Blvd., St. Louis, MO 63121, USA
[d] Department of Electrical and Systems Engineering, Washington University, St. Louis, MO 63130, USA

ARTICLE INFO

Article history:
Received 12 January 2011
Received in revised form 31 July 2011
Available online 31 August 2011

Keywords:
Stress concentrations
Material optimization
Tendon-to-bone attachment
Enthesis

ABSTRACT

The attachment of tendon to bone, one of the greatest interfacial material mismatches in nature, presents an anomaly from the perspective of interfacial engineering. Deleterious stress concentrations arising at bi-material interfaces can be reduced in engineering practice by smooth interpolation of composition, microstructure, and mechanical properties. However, following normal development, the rotator cuff tendon-to-bone "insertion site" presents an interfacial zone that is more compliant than either tendon or bone. This compliant zone is not regenerated following healing, and its absence may account for the poor outcomes observed following both natural and post-surgical healing of insertion sites such as those at the rotator cuff of the shoulder. Here, we present results of numerical simulations which provide a rationale for such a seemingly illogical yet effective interfacial system. Through numerical optimization of a mathematical model of an insertion site, we show that stress concentrations can be reduced by a biomimetic grading of material properties. Our results suggest a new approach to functional grading for minimization of stress concentrations at interfaces.

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1. Introduction

Connecting dissimilar materials is a fundamental challenge because of stress concentrations that can arise at their interface (Williams, 1952). Interfacial stress concentrations can contribute to material failures at levels of mechanical loads that are too small to cause failure in either material individually (Hutchinson and Suo, 1992). "Functionally graded" material systems that interpolate spatially between properties of two materials are often considered to reduce stress concentrations in engineering and medical applications, ranging from semiconductor thin films to prosthetic joints and limbs (Birman and Byrd, 2007; Suresh and Mortensen, 1998; Tersoff and LeGoues, 1994).

In nature, a graded material exists between the unmineralized ("soft") and mineralized ("hard") tissues (Thomopoulos et al., 2003; Stouffer et al., 1985), for example, at the shoulder's rotator cuff tendon-to-bone attachment (Fig. 1). Here, tendon attaches to bone through a fibrocartilaginous transition zone ("insertion site") that presents a continuous spatial grading in mineralization and organization of the underlying collagen fibers (Wopenka et al., 2008). Although data and models are sparse, current data suggest that this attachment mechanism might exist in other tensile connections such as ligaments (Moffat et al., 2008) and menisci (Villegas et al., 2007), but not in compressive osteochondral connections (Ferguson et al., 2003). Whereas engineering practice would be to interpolate between the mechanical properties of tendon and bone,

* Corresponding author. Address: Department of Mechanical Engineering and Materials Science, Campus Box 1185, Washington University in St. Louis, St. Louis, MO 63130, USA. Tel.: +1 314 935 5660; fax: +1 314 935 4014.

E-mail address: genin@wustl.edu (G.M. Genin).

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doi:10.1016/j.mechmat.2011.08.005

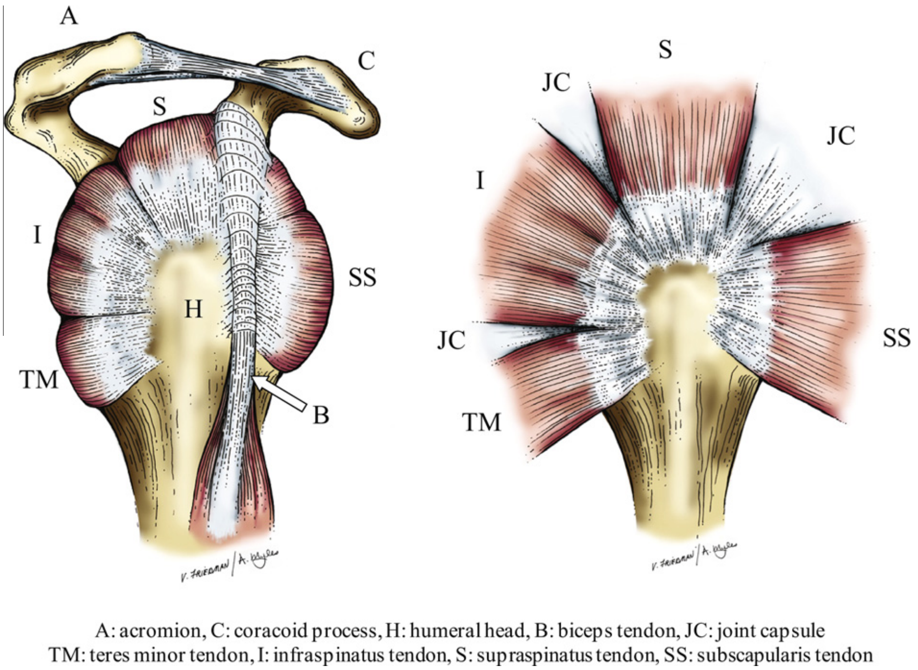

Fig. 1. The rotator cuff as viewed from the side (i.e., the lateral view). Tendons are shown in white, muscles in red, and bones in tan. The rotator cuff tendons (TM, I, S, and SS) wrap around the spherical humeral head (H) (left panel). Removing the overlying structures (A, B, C) and unwrapping the rotator cuff tendons reveals the axisymmetric geometry of the tendons and their bony insertions (right panel).

recent experimental evidence indicates that grading at the rotator cuff insertion site produces a soft tissue region that is more compliant than either tendon or bone (Genin et al., 2009).

The interface between tendon and bone develops following birth, and matures only after weight-bearing and increased muscle loading (Das et al., 2011; Thomopoulos et al., 2007, 2010). In contrast to the developmental process, a functionally graded transition is not regenerated at the healing tendon-to-bone insertion. Rather, scar tissue fills the repair site, resulting in an abrupt interface that lacks a compliant band between the tendon and the bone (Thomopoulos et al., 2003). Surgical repair of tendon-to-bone attachment at the rotator cuff is therefore prone to re-injury, with failure rates up to 94% for rotator cuff reattachment (Galatz et al., 2004). Understanding the counter-intuitive biophysics of the natural attachment (i.e., a compliant zone at the interface between the disparate materials) is important for medical practice and for biomimetic design.

The hypothesis that the grading found at the insertion site reduces stress concentrations has been suggested (Benjamin et al., 2002; Thomopoulos et al., 2006), but evidence that this unusual attachment scheme actually reduces stresses has not been reported. Here, we show through numerical optimization of a mathematical model of a rotator cuff insertion site that a qualitatively biomimetic material grading can reduce or even eliminate stress concentrations in a model of the rotator cuff insertion site. Fields in the vicinity of an interface are shown to depend strongly upon the local material grading. Taken in the context of hierarchical structural adaptation to mitigate stress concentrations in biological systems, results have implications for the design of engineering interfaces, surgical techniques, and surgical grafts that guide tissue development following insertion site repair.

2. Mathematical model and optimization methods

The effects of material stiffness grading on the stress field at the attachment of tendon to bone were assessed by studying an idealization of the rotator cuff insertion site (Fig. 1). The mathematical model involved axisymmetric linear elasticity (Fig. 2), and in all cases studied involved an isotropic bone core within a cylindrically orthotropic

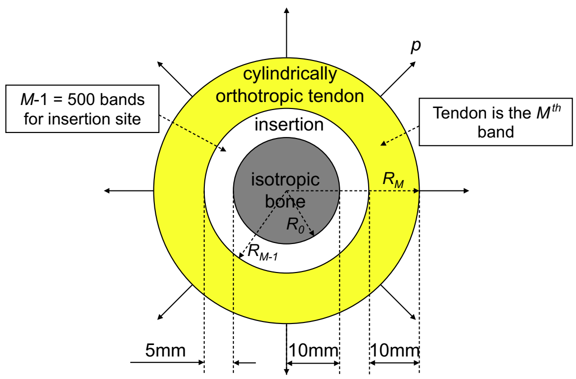

Fig. 2. Mathematical model of an axisymmetric insertion site stressed by an equibiaxial loading, p. Dimensions are representative of an adult human humeral head.

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