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Research Paper

The concentration of stress at the rotator cuff tendon-to-bone attachment site is conserved across species

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ABSTRACT

The tendon-to-bone attachment site integrates two distinct tissues via a gradual transition in composition, mechanical properties, and structure. Outcomes of surgical repair are poor, in part because surgical repair does not recreate the natural attachment, and in part because the mechanical features that are most critical to mechanical and physiological functions have not been identified. We employed allometric analysis to resolve a paradox about how the architecture of the rotator cuff contributes to load transfer: whereas published data suggest that the mean muscle stresses expected at the tendon-to-bone attachment are conserved across species, data also show that the relative dimensions of key anatomical features vary dramatically, suggesting that the amplification of stresses at the interface between tendon and bone should also vary widely. However, a mechanical model that enabled a sensitivity analysis revealed that the degree of stress concentration was in fact highly conserved across species: the factors that most affected stress amplification were most highly conserved across species, while those that had a lower effect showed broad variation across a range of relative insensitivity. Results highlight how micromechanical factors can influence structure–function relationships and cross-species scaling over several orders of magnitude in animal size, and provide guidance on physiological features to emphasize in surgical and tissue engineered repair of the rotator cuff.

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1. Introduction

The tendon-to-bone attachment connects two very different materials: compliant tendon and stiff bone. As an interface between such dissimilar materials, it is prone to stress concentrations and increased risk of failure (Munz and Yang, 1992; Thomopoulos et al., 2012). In healthy tissue, the attachment site exhibits a number of structures which serve to attenuate stress concentration (Thomopoulos et al., 2003b; Liu et al., 2011; Schwartz et al., 2012). However, after healing or surgical repair, these structures are not recovered in adults. Post-surgical failures, which can occur in 94% of elderly patients with massive tears (Galatz et al., 2004; Cummins and Murrell, 2003; Zumstein et al., 2008; Thomopoulos et al., 2010), tend to occur at the interface and constitute a major clinical challenge in orthopedic surgery (Paxton et al., 2013). These high failure rates point to the importance of identifying and reconstituting the interfacial structures most important to maintaining the structural integrity of the attachment. Understanding the mechanisms of load transfer at the tendon-to-bone attachment and characterizing this transitional tissue may uncover strategies to create stronger and more resilient interfaces in both engineering and medical applications.

The focus in this study is a gradient region from tendon to bone showing gradual increases in mineral content and collagen misalignment (Qu et al., 2013; Thomopoulos et al., 2006; Wopenka et al., 2008; Schwartz et al., 2012). With the goal of providing guidance for surgical repair and healing strategies, we quantified how anatomic features of the attachment site, including relative dimensions and anisotropy, affect load tendon-to-bone transfer across species ranging in size from 30 g mice to 45 kg pigs.

The efficient binding of dissimilar materials has been studied widely, as have engineered material systems that exhibit analogous spatial gradations in material properties, termed functional grading (Liu et al., 2011; Birman, 2014; Apalak, 2014). The mechanics of load transfer at isotropic functionally graded interfaces is well understood (Birman et al., 2013; Byrd and Birman, 2007). However, the tendon to-bone attachment exhibits a 10 fold change in tissue anisotropy between strongly anisotropic tendon and nearly isotropic bone. This latter effect has not been well studied, and results from the existing mechanics literature cannot provide guidance for the problem of interest (Birman et al., 2013; Byrd and Birman, 2007; Genin and Birman, 2009). We therefore approached our problem with an anisotropic generalization of an approach that has been applied previously to study isotropic attachments.

The cross-species approach we adopted falls under the rubric of allometry (cf. Huxley et al., 1932; Thompson et al., 1915; Huxley and Teissier, 1936). The allometric scaling of rotator cuff anatomy with body size was pursued both to gain insight into the sizing and mechanical function of the tendon-to-bone attachment site and to address the challenge of relating research on small animal models to human health. A specific question of interest is whether experiments on the mineral gradient at the tendon-to-bone attachment of the rat can inform human surgeries through the principle of similarity (Schmidt-Nielsen, 1984; Wopenka et al., 2008). We studied the scaling via the Huxley and Teissier (1936) power-law expression for the relationship between the size of a body part and the size of the body as a whole:

$$Y = bM^{\alpha} \quad (1)$$

where Y is a biological variable, M is a measure of body size, and α and b are fitting parameters (Gayon, 2000). This has proven effective in describing scaling of morphological traits (e.g., brain versus body size among adult humans), physiological traits (e.g., metabolic rate versus body size among mammals) and ecological traits (e.g., wing size versus flight performance in birds) (West and Brown, 2005; Smith, 1984; Huxley et al., 1932; Gould, 1966, 1977; Klingenberg and McIntyre, 1998). The range of animals considered stretched from small rodents to pigs, with the mass of pigs approaching the lower end of the normal range for humans.

The current study follows recent investigations of the scaling of the supraspinatus muscle and the force it applies in relation to the geometry of the insertion into the humeral head (Mathewson et al., 2013; Deymier-Black et al., 2015). Volume and physiological cross-sectional area (PCSA) of the muscle scale geometrically across species, and the area of attachment at the humeral head scales to maintain constant nominal stress at the interface. However, paradoxically, the microscale mineral gradient length changes minimally across species: given that the mean muscle stresses are conserved across species, why would this factor, known to affect the amplification of stress at the bi-material interface, show such broad variation? The answer that emerged from a simple model is that cross-species variation was substantial only in a range of parameters for which the effect on stress amplification was relatively low: the design of the rotator cuff attachment and cross-species variation appear intertwined in a way that conserves stress concentrations across species.

In the current study, we first adapted a mathematical idealization of the rotator cuff attachment site to identify the effects of anisotropy on load transfer. Special attention was devoted to finding a smooth spatial scaling of material properties between tendon and bone that did not violate thermodynamic bounds at any point between the two tissues. Then, the concept of allometry was employed to test the hypothesis that, despite the unusual scaling of the size of the mineral gradient, stress concentration is conserved across species.

2. Methods

2.1. Stress analyses

The mechanical consequences of mineral gradation allometry were studied through an adaptation of a previously published idealized mathematical model of the rotator cuff attachment site (Fig. 1b) (Liu et al., 2012). The mathematical model is an axisymmetric, orthotropic linear elastic idealization of the anatomy of the rotator cuff viewed in the sagittal plane (Fig. 1a). In this model, the tendon-to-bone attachment was idealized as three concentric layers including: (1) a central core of bone with a radius of R_b, (2) a graded