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WAVE PROPAGATION ACROSS THE TENDON-TO-BONE INTERPHASE MODELED AS AN EQUIVALENT INTERFACE WITH SPECIFIC SURFACE PROPERTIES

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ABSTRACT

The integration between soft and hard materials often occurs through functionally graded interphases, which are typically designed as multilayers whose material properties gradually vary in space, in order to reduce mechanical stresses [1]. In the musculoskeletal system in particular, the attachment between tendon and bone occurs through a specific functionally graded interphase called *enthesis* (Fig. 1a), which serves the challenging task of connecting these two highly dissimilar tissues over a very small region ($\sim$ 100 μm) by means of finely tuned gradients in structure, composition and biomechanical properties at different length scales (Fig. 1b) [2]. Nevertheless, this interphase is a frequent site of injury because of physical overloading, systemic diseases or tissue degeneration in the elderly.

Within this context, computational models were developed both to investigate basic anchoring strategies at the microstructural level [4] or to address applied orthopedic strategies at the organ level [5]. Notwithstanding, from a modeling viewpoint, it is highly challenging to bridge the gap between these two scales [6], and current models targeting reattachment procedures should be enriched by including a more detailed description of the microstructure across the tendon-to-bone interphase. Indeed, to adequately capture the biomechanical behavior of an interphase layer, the optimal choice is to consider its exact geometry between the two surrounded tissues [7]. However, this choice can be prohibitive when dealing with complex geometries such as the tendon-to-bone interphase. In particular, the finite size of the interphase, which is small compared to that of the surrounding tissues, may cause computational burden when mesh refinements are required for convergence purposes (*e.g.*, time-domain study). To face this limitation, a possible solution consists in replacing the finite heterogeneous interphase (Fig. 1c) by an equivalent model with specific interface conditions (Fig. 1d). It is commonly accepted that such approach can be satisfactorily addressed by introducing elastic and inertial fields in the equivalent model [8].

In this study, we propose an equivalent model that incorporates specific interface conditions by means of surface kinetic and potential energy densities. On the one hand, the surface kinetic energy is supposed to depend on the surface mass density and the dynamical interactions between the two sides of the surface [9]. On the other hand, the surface potential energy is assumed to be of elastic nature, namely a system of distributed springs inside the surface which confers an elastic rigidity. Furthermore, to account for the gradient in mechanical properties across the interphase [10], we hypothesize that the displacement field can be approximated using a piece-wise affine profile. To investigate the reliability of such equivalent model for diagnostic purposes, the focus here is on the ultrasound wave propagation problem across two dissimilar homogeneous and solid half-spaces (*i.e.*, tendon and

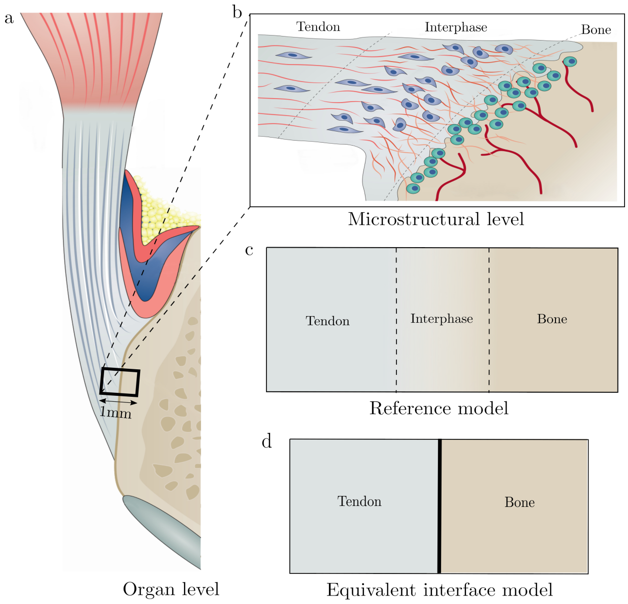

Figure 1. (a) Organ level schematic of the tendon-to-bone attachment at the Achilles tendon insertion site; (b) Microstructural level illustration of the gradients in structure and composition across the interphase (images modified from Ref. [3]); (c) Finite heterogeneous interphase model with varying mechanical properties; and (d) Equivalent interface model with zero thickness.

bone) separated by a finite interphase layer with heterogeneous properties, which are likely to mimic the tendon-to-bone attachment. An elastic plane wave under normal incidence propagates in the first half-space and interacts with the interphase. In this way, our modeling approach is reduced to an incident and a reflected longitudinal bulk wave in the first half-space and a transmitted longitudinal bulk wave in the second half-space. The performance of our equivalent model is evaluated by calculating the frequency-dependent power reflection coefficient (Fig. 2), which is then compared to different models, including (i) the reference model, which consists in a finite heterogeneous interphase with a gradient in mechanical properties (black line), (ii) an abrupt transition corresponding to the case where the surroundings tissues are placed directly in contact without the presence of an interphase (dashed line), and (iii) the equivalent interface model from [8], which is associated with a displacement field with an affine profile (blue line).

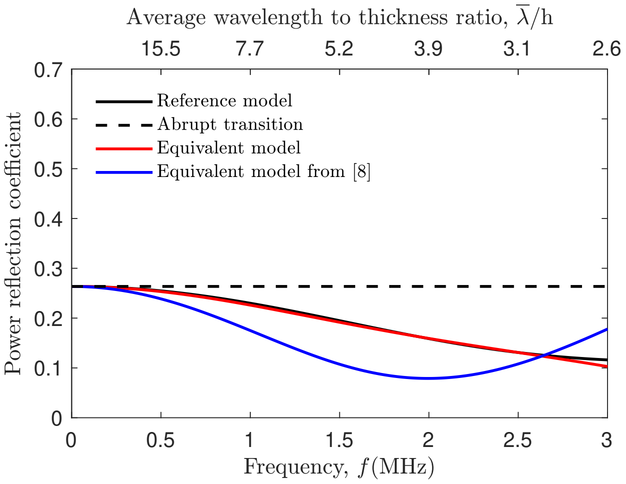

Figure 2. Frequency-dependent power reflection coefficient obtained using: (1) the reference model (black line); (2) an abrupt transition (dashed line); (3) the equivalent interface model (blue line) associated with a displacement field with an affine profile (Ref. [8]); and (4) our equivalent interface model (red line).

As can be observed, our equivalent model with specific interface conditions provides a very accurate approximation of the reference model over a broad frequency range up to around 2.6 MHz (*i.e.*, ratio between the average wavelength to the thickness of the interphase $\bar{\lambda}/h \approx 3$). It thus outperforms the results obtained with the equivalent model from [8], which still remains valid but for a much narrower frequency regime around 0.3 MHz. In contrast, a model that only accounts for an abrupt transition, *i.e.*, commonly used baseline in finite element simulations at the organ scale, totally fails in capturing the complex dynamics of the interphase.

Our numerical results show that the proposed equivalent interface model is suitable for the solution of a complete elastodynamics problem in the frequency domain, since it captures the complex biomechanical behavior of the tendon-to-bone interphase over a broad frequency range. In addition, this model has a much lower computational cost that the reference one, as the interphase must not be incorporated explicitly. To further underline the advantage of such modeling approach, future works should address more complex propagation configurations, such as 2-D problems incorporating both longitudinal and shear waves.

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