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Research Paper

A constitutive description of the anisotropic response of the fascia lata

F.Q. Pancheri[a], C.M. Eng[b,c], D.E. Lieberman[b,c], A.A. Biewener[b], L. Dorfmann[d,*]

[a]Department of Mechanical Engineering, Tufts University, Medford, MA, United States
[b]Department of Human Evolutionary Biology, Harvard University, Cambridge, MA, United States
[c]Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA, United States
[d]Department of Civil and Environmental Engineering, Tufts University, Medford, MA, United States

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ABSTRACT

In this paper we propose a constitutive model to analyze in-plane extension of goat fascia lata. We first perform a histological analysis of the fascia that shows a well-organized bi-layered arrangement of undulated collagen fascicles oriented along two well defined directions. To develop a model consistent with the tissue structure we identify the absolute and relative thickness of each layer and the orientation of the preferred directions. New data are presented showing the mechanical response in uniaxial and planar biaxial extension. The paper proposes a constitutive relation to describe the mechanical response. We provide a summary of the main ingredients of the nonlinear theory of elasticity and introduce a suitable strain-energy function to describe the anisotropic response of the fascia. We validate the model by showing good fit of the numerical results and the experimental data. Comments are included about differences and analogies between goat fascia lata and the human iliotibial band.

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1. Introduction

A detailed description of the human fascial system is given by Stecco et al. (2011). They specify that from all connective tissue of the body only those characterized by well-defined fibrous layers are correctly called 'fascia'. Stecco et al. (2011) differentiate between three fundamental fibrous connective layers: (i) the superficial fascia, (ii) the deep fascia and (iii) the epimysium. We refer to Stecco et al. (2011) and to the cited references for a complete list of functional details.

Deep fascia encloses many muscles and connects them to each other and to bones. There is growing evidence that fascia can influence limb stability, force transmission, and elastic energy storage during locomotion (Bennett, 1989; Garfin et al., 1981; Maas and Huijing, 2005; Maas et al., 2005a, 2005b). However, quantifying the role of fascia during active movement presents challenges. First, its sheet-like structure contains multiple layers of well-organized collagen fibers making the tissue highly anisotropic. These are interconnected by a surrounding matrix that contains disorganized collagen fibers. Second, deep fascia has multiple connections to muscles and bones that generate complex non-homogeneous states of strain. The complex structure and loading environment of fascia may help explain why many current musculoskeletal

*Corresponding author.
E-mail address: Luis.Dorfmann@tufts.edu (L. Dorfmann).
URL: http://ase.tufts.edu/msml/ (L. Dorfmann).

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models ignore its role in simulations of muscle function (see Lee et al., 2010; Tang et al., 2009). In an effort to address this deficiency, we describe here the mechanical properties of an example of a deep fascial structure, the fascia lata in the goat hindlimb, using structurally driven assumptions to capture and reproduce its anisotropic response measured during strain-controlled uniaxial and biaxial tension tests.

Our results have implications for modeling the function of the human iliotibial band (ITB), which is a thickening of the lateral portion of the fascia lata in humans (Gray et al., 1995; Birnbaum et al., 2004). The ITB's role in human locomotion is not well understood, in part because it is difficult to experimentally test ITB function. For example, age dependent mechanical properties of the iliotibial band were investigated by Hammer et al. (2012) and Steinke et al. (2012). These authors report Young's modulus and ultimate stress of specimens characterized by one set of parallel fibers oriented in the longitudinal direction of the ITB. The data are limited to simple tension, i.e. the properties in the transverse direction were not investigated. Steinke et al. (2012) emphasize the importance of accurate material properties in a numerical simulation of ligaments and acknowledge the difficulty in obtaining reliable data due to the non-parallel fiber alignment within the tissue. In this paper, in order to better understand the *nonlinear behavior* of connective tissues and to provide accurate data of the mechanical response, we focus on planar biaxial extension of fascia lata. The methodological protocol can be adapted to the dimensions of the ITB and used to test hypotheses of ITB functions.

Most published data on the fascia lata have been limited to uniaxial tension with either the applied stretch increasing monotonically or in the form of periodic loading, unloading and reloading up to different, but fixed, stretches (Gratz, 1931; Butler et al., 1984; Bennett, 1989). Gratz (1931), using fresh human specimens of fascia lata, identifies the maximum 'safe stress' in simple tension as 14.5 MPa corresponding to a strain of 3.5% and the ultimate strength as 54 MPa for 9% strain. The concept of 'safe stress' is used by Gratz (1931) to define the maximum allowable stress in simple tension to avoid irreversible damage of the tissue structure. Values of the tissue strength have also been reported by Butler et al. (1984) and Hinton et al. (1992).

Many biological tissues are anisotropic, requiring a wide range of experimental data to obtain appropriate representations of their behaviors (Holzapfel and Ogden, 2009). The early experimental papers by Lanir and Fung (1974) and Humphrey et al. (1986) have motivated the use of biaxial testing to characterize soft tissues. Jor et al. (2011a), for example, used multi-axial planar extension to characterize the collagen fiber distribution in porcine skin. Corresponding material parameters and a modeling framework, including constitutive relation involving a probability density function, are given by Jor et al. (2011b). These studies show that planar biaxial tension can generate deformations that more closely resemble the *in vivo* state of strain compared to uniaxial tension.

While authors agree that fascia is a multi-layered collagenous tissue, descriptions of fascia lata's structure vary because of its layered arrangement and, possibly, because of variation between different species in which it has been studied. For example, Butler et al. (1984) described human fascia lata as a bi-layered tissue with weak interaction between layers. Based on analysis of fascia lata from a number of different mammals, Bennett (1989) distinguished three distinct layers: a thin outermost layer rich in randomly oriented collagen fibers and two inner layers each containing parallel fascicles of collagen fibers oriented along a clear direction. Bennett (1989) reported that the two families of fibers each contained in one of the layers, enclose an angle of 70–85°. More recently, Stecco et al. (2009) proposed that deep fascia has either completely independent layers or some regions within layers that are loosely connected by bundles of collagen fibers present in low quantities. These varied descriptions of fascial structure highlight the importance of combining tissue-specific structural investigations and accurate experimental data to formulate a constitutive model.

Constitutive models (mathematical models of material behavior) of biological tissues have improved over the years by making justified revisions based on the structure of the

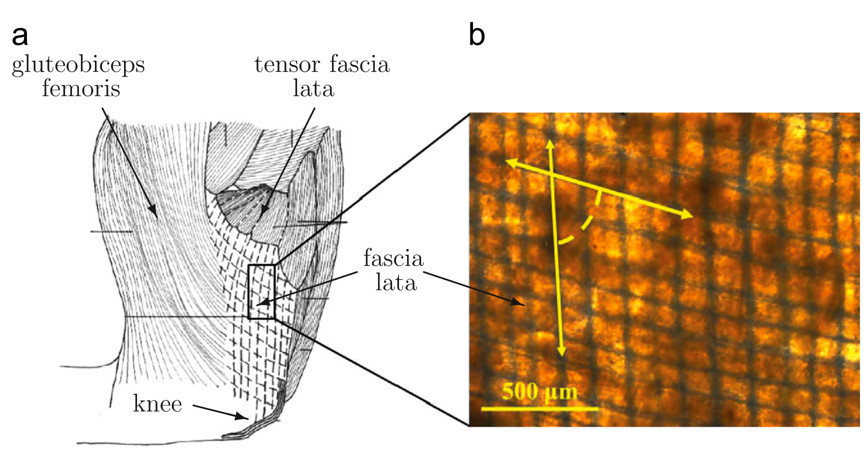

Fig. 1 – Image (a) shows the location of facia lata and major muscle groups in hindlimbs of adult goats (Bennett, 1989, reproduced with permission of the copyright owner, Wiley, UK). Image (b), light microscopy, is used to determine the structural arrangement of the preferred directions. From the analysis of multiple samples we found that the angle between the longitudinally and transversely oriented collagen fibers is between 67° and 80°.

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