Journal of Biomechanics 41 (2008) 1–10

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Micromechanical modeling of the epimysium of the skeletal muscles

Yingxin Gao[a], Anthony M. Waas[b,*], John A. Faulkner[c],
Tatiana Y. Kostrominova[c,d], Alan S. Wineman[a]

[a]Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA
[b]Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA
[c]Department of Molecular and Integrative Physiology, BSRB, University of Michigan, Ann Arbor, MI 48109-2007, USA
[d]Department of Anatomy and Cell Biology, Indiana University School of Medicine-Northwest, Gary, IN 46409-1008, USA

Accepted 7 August 2007

Abstract

A micromechanical model has been developed to investigate the mechanical properties of the epimysium. In the present model, the collagen fibers in the epimysium are embedded randomly in the ground substance. Two parallel wavy collagen fibers and the surrounding ground substance are used as the repeat unit (unit cell), and the epimysium is considered as an aggregate of unit cells. Each unit cell is distributed in the epimysium with some different angle to the muscle fiber direction. The model allows the progressive straightening of the collagen fiber as well as the effects of fiber reorientation. The predictions of the model compare favorably against experiment. The effects of the collagen fiber volume fraction, collagen fiber waviness at the rest length and the mechanical properties of the collagen fibers and the ground substance are analyzed. This model allows the analysis of mechanical behavior of most soft tissues if appropriate experimental data are available.

Keywords: Epimysium; Collagen fiber; Ground substance; Waviness; Reorientation; Mechanical properties; Unit cell

1. Introduction

Skeletal muscle is composed of muscle fibers and an extracellular matrix (ECM). The ECM is associated with different levels of structure: (a) the epimysium that encompasses the whole muscle; (b) the perimysium that binds groups of muscle fibers into bundles and (c) an endomysium that surrounds the individual muscle fibers (Sane, 1994). The overall mechanical properties of the entire skeletal muscle are determined by the properties of muscle fibers, the surrounding ECM and the interactions between these two components (Purslow and Trotter, 1994; Trotter et al., 1995).

A relaxed muscle can be stretched, and this is referred to as the passive elasticity of the muscle. The ECM has been considered as an important contributor to passive elasticity (Hill, 1950; Ramsey and Street, 1940). Many investigators have reported that the ECM does not contribute to the passive elasticity of muscle fibers at and near the rest length, but does at higher extensions (Casella, 1950; Podolsky, 1964). This behavior was suggested to be associated with the nonlinear stress–strain relationship of the ECM (Purslow and Duance, 1990), which is characterized by an increasing stiffness at higher extensions beyond the resting length.

Collagen fibers are the major contributors to the mechanical strength of soft tissues. The arrangement and orientation of the collagen fibers determine the mechanical behavior of soft tissues. In the tendon and the ligament, the collagen fibers are wavy and nearly parallel to one another. This arrangement results in a high stiffness in the direction of the collagen fibers and high compliance in directions transverse to the collagen fibers. The wavy pattern of the collagen fibers leads to a low modulus at or near the resting length (Fung, 1984; Viidik, 1979), which corresponds to progressive straightening of the collagen fibers (Viidik, 1980). In other soft tissues, such as blood vessel walls and

---

*Corresponding author. Tel.: +1 734 764 8227.
E-mail address: dcw@umich.edu (A.M. Waas).

0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.08.008

the ECM of skeletal muscles, the collagen fibers have been reported to be arranged in a much more complicated manner (Bigi et al., 1981; Purslow, 1989; Rowe, 1974). Many studies demonstrated that on extension of these tissues, the collagen fibers are substantially reoriented (Bigi et al., 1985; Purslow, 1989). Thus, for these tissues, the nonlinear mechanical properties result from not only the progressive straightening of the fibers, but also from the reorientation of the fibers. Consequently, the interaction of the collagen fibers with the surrounding ground substance during the reorientation process needs to be properly captured.

Various models have been proposed to describe the nonlinear stress–strain behavior of parallel-fibered collagenous tissue (Diamant et al., 1972; Comninou and Yannas, 1976; Kwan and Woo, 1989). Woo et al. (1993) presented a comprehensive survey of developments in mathematical modeling of ligaments and tendon. For tissues with more randomly oriented fibers, several investigators developed models that attributed the 'toe' region to the sequential straightening of the collagen fibers (Liao, 1979, 1983; Belkoff and Haut , 1991). In these models the collagen fibers were spatially arranged by a distribution function. Based on the model developed by Liao (1979, 1983) and Decraemer et al. (1980), in which a strain energy function was incorporated, Belkoff and Haut(1991) proposed a microstructural model for soft biological tissues. In the model, a recruitment function $R(x)$, which is a normal Gaussian distribution function, was introduced to describe the straightening of the collagen fibers. The results indicated a good fit with experimental observations. However, the model did not consider the reorientation of the collagen fiber. Later, Hurschler et al. (1997, 2003) developed a probabilistic microstructural model to predict the stress–strain relationship of fibrous connective tissue. The models successfully captured the progressive straightening of the wavy collagen fibers and predicted the nonlinear stress–strain relationship of the tissue by using a 3-parameter Weibull probability distribution function (PDF) to represent the fiber recruitment. However, the models assumed that the collagen fiber could not bear any load until it became straight and after that, the collagen fibers deformed in a linear manner. In addition, the models only considered the contribution of straightening of the collagen fibers to the toe-region without the effect of stretch induced reorientation of collagen fibers. No interaction between the collagen fibers and ground substance was included in the models.

A composite micromechanical model for connective tissue was proposed by Ault and Hoffman (1992a, b). The model viewed the tissue as an aggregation of subunits, which were modeled as a composite of unidirectional fibers in a surrounding ground substance. The models used the theorem of least work and minimum potential energy to predict the upper and lower bounds, and utilized the composite cylinder (CCM) model (Hashin and Rosen, 1964) to calculate the mechanical properties of each subunit based on component material properties and geometric configurations. The models successfully predicted increased axial stiffness with increasing stretch due to fiber reorientation, but the effect due to the waviness of individual fibers was not considered as each collagen fiber was considered as a multiple of independent straight segments. Another composite model proposed by Wren and Carter (1998) took into account the fiber orientation and the waviness of the collagen fibers, but this model also assumed that before the collagen fibers were taut, there was no tensile stress, which was found to be incorrect mechanically.

A one-dimensional geometric model, reported by Purslow (1989), was based on the assumption that the muscle fiber contracts and lengthens at constant volume (Ervasti and Campbell, 1963). This model assumes that two groups of collagen fibers are lying at an orientation of $\pm\theta$ to the muscle fiber direction and the modulus of the collagen fiber and ground substance are calculated by the rule of mixtures, in which no bending effects are considered.

In the present paper, a nonlinear mechanical model for the epimysium is introduced that incorporates both the progressive straightening and the reorientation of the collagen fibers. In addition, contributions from the collagen fibers, ground substance and the interaction between them are considered in the model. Some of the model parameters are based on published clinical data and some of them are obtained from the authors's experimental data (details are given in Section 2.3). The utility of the model to describe the mechanical response of other fibrous soft tissues such as cartilage, tendon and blood vessel walls is evident, because of the manner in which the model has been formulated. The model predicts the experimental results, since the effects of the fiber volume fraction, the waviness of the collagen fibers, and the mechanical properties of the collagen fiber and the ground substance on the mechanical behavior of the epimysium are each captured successfully.

2. Method

In the model developed in this paper, the epimysium is considered to be macroscopically homogeneous (Fig. 1). The assumption is made that all the collagen fibers have the same sinusoidal shape. Two parallel wavy collagen fibers and the surrounding ground substance are used as the repeat unit (unit cell), as shown in Fig. 2, and the epimysium is considered as an aggregate of unit cells. Each unit cell is distributed in the epimysium with a different angle to the muscle fiber direction. The distribution functions for the angles of the unit cell, as a function of the stretch ratio, are taken from the literature (Purslow and Trotter, 1994). The interactions between the unit cells were neglected in this model for simplification.

2.1. Unit cell

As shown in Fig. 2, the unit cell is composed of two wavy collagen fibers parallel to each other embedded in the ground substance. It is assumed that there is no slip between the collagen fibers and the ground substance. The initial shape of the center line of a collagen fiber is assumed