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A physically based structural model for a textile prosthetic mesh

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ABSTRACT

This study is aimed at a physically based model formulation for a textile mesh implant to describe its mechanical behavior at a mesoscopic length scale. A structural model of a representative unit cell of the knitted prosthetic mesh is proposed based on the theory of multibody systems. The model geometry and the constitutive laws of the force elements are defined based on physical considerations. The parameters determining the force laws, are adjusted to fit the experimentally observed force response and the macro- and mesoscale kinematics. A comparison between the experimental data and the model response show its excellent descriptive capabilities. The level of non-affine deformations within a unit cell is proposed as a mesoscale criterion to quantify the mechanical biocompatibility of textile mesh implants. This view might help to understand clinical observations and complications associated with a local mismatch of deformation between the implant and the host tissue.

1. Introduction

There is a long history of structural models for textile fabrics, starting with the semi-analytical truss models for plain weaves by Kawabata et al. (1973a,b,c) and followed by a large number of extended models accounting for different mechanisms and using advanced techniques for efficient computation (King et al., 2005; Nadler et al., 2006; Assidi et al., 2011; Boubaker et al., 2007; Grujicic et al., 2009; Carvelli, 2009; Nayfeh and Kress, 1997; Xiao et al., 2011; Antonietti et al., 2011).

The basic idea behind structural models is to use a simplified but physically motivated mesoscale structure in order to capture more complex mechanical phenomena at the macroscale. Ideally, the mechanical properties of the mesoscale elements are directly measured in corresponding experiments (King et al., 2005) or deduced from manufacturer specifications (Nadler et al., 2006; Assidi et al., 2011; Boubaker et al., 2007; Grujicic et al., 2009; Carvelli, 2009; Nayfeh and Kress, 1997; Xiao et al., 2011). Macroscale phenomena simulated by such models include geometric nonlinearity (King et al., 2005; Nadler et al., 2006; Boubaker et al., 2007; Nayfeh and Kress, 1997), large Poisson ratios (Assidi et al., 2011) or anisotropy (Assidi et al., 2011; King et al., 2005; Nadler et al., 2006). The major challenge is the abstraction process, which has to be based on a thorough identification of the critical structures underlying the specific deformation mechanisms and structural features of interest. Weaves represent the simplest fabric structure and are therefore examined most frequently (King et al., 2005; Nadler et al., 2006; Assidi et al., 2011; Boubaker et al., 2007; Grujicic et al., 2009; Carvelli, 2009; Nayfeh and Kress, 1997; Xiao et al., 2011). Respective structural models focus on yarn-yarn interactions, such as crimp interchange in tension or shear-locking (King et al., 2005; Nadler et al., 2006; Assidi et al., 2011; Boubaker et al., 2007; Grujicic et al., 2009; Carvelli, 2009; Nayfeh and Kress, 1997; Xiao et al., 2011). There are only few structural models for knitted textiles, e.g. Antonietti et al. (2011).

One major objective of structural models is understanding and quantifying the impact of mesoscale properties on the mechanical properties at the macroscale in order to deduce criteria for fabric design and optimization (King et al., 2005; Nadler et al., 2006; Assidi et al., 2011; Boubaker et al., 2007; Grujicic et al., 2009; Carvelli, 2009; Nayfeh and Kress, 1997; Xiao et al., 2011; Antonietti et al., 2011). Multiscale approaches are also aimed at determining corresponding constitutive model formulations to be implemented in finite element codes (King et al., 2005; Nadler et al., 2006; Antonietti et al., 2011; Grujicic et al., 2009). To this end, the incremental deformation gradient is applied on a structural unit cell model as kinematic boundary conditions. The model is solved according to minimum energy principles and the homogenized reaction forces at the boundaries lead to the incremental stress tensor.

Due to their complex interlooping structure and the associated challenges in finding an appropriate abstraction, knitted fabrics are more frequently modeled at the microscale with an explicit representation of each filament (Duhovic and Bhattacharyya, 2006; Hart

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et al., 1985; DeJong and Postle, 1978). Such detailed models are associated with lesser model assumptions, as the geometry and the assigned material properties for the filaments are based on real measured data. These models can be used to perform virtual experiments with perfectly controlled boundary conditions. However, such models are computationally expensive and require the solution of multi-contact problems, which often lack numerical convergence or require non-physical assumptions on the friction behavior and the inter-penetration of filaments (Duhovic and Bhattacharyya, 2006). Another challenge is the definition of a representative initial configuration, which might be found by an elaborate simulation of the manufacturing process and the corresponding solution of the unloaded equilibrium state (Glaessgen et al., 1996; DeJong and Postle, 1978).

In this study, a structural model of a representative unit cell of a knitted prosthetic mesh is proposed based on the theory of multibody systems. Its geometrical structure and the constitutive laws of the force elements (connecting the massless rigid bodies) are based on mechanical measurements and considerations. The model is aimed at capturing experimentally observed physical effects, such as the non-linear force-strain relationship and anisotropy and thus at providing insight into the underlying mesoscale mechanisms. It will be shown that such a structural model has excellent descriptive capabilities with respect to force response and meso- and macroscale kinematics. Moreover, preconditioning will be rationalized as a change of the mesoscale structure and thus of the material. The model will be shown to represent a valuable tool to assess mesoscale aspects of the mechanical biocompatibility of textile mesh implants and thus to understand clinical observations and associated complications, in particular with respect to pelvic floor reconstruction.

2. Materials, methods and calculation procedure

2.1. Material properties

The commercially available prosthetic mesh Gynemesh M, knitted from non-resorbable polypropylene fibers, is investigated here (Fig. 1). Gynemesh M is a so-called light-weight hybrid construct, containing polypropylene and polyglecaprone fibers (weight prior to resorption: 56 g/m^2, after resorption: 32 g/m^2, Ethicon Inc., Somerville, NJ, United States) (Klosterhalfen et al., 2005). The polyglecaprone fibers are added to improve the surgical handling properties of the material as well as because of the anti-inflammatory properties (Cobb et al., 2005; Junge et al., 2005). Resorption of the polyglecaprone component takes place within 90–120 days after implantation. For the present modeling approach, the mesh is used in its resorbed state, containing only polypropylene fibers.

Gynemesh M is a knitted fabric. It consists of strands of stitches knitted from the polypropylene filaments. An additional continuous filament meanders through each strand and connects it to an adjacent strand at nodal points, forming the closed pores. Some filaments and the corresponding strands are colored in blue, which is for orientation purposes only.

2.2. Representative unit cell model

Gynemesh M is assumed to consist of periodically arranged, identical "pores". Therefore, a representative pattern of the mesh, a unit cell, is modeled. A half pore is found to be the smallest periodic pattern of Gynemesh M. Periodicity is preserved also in all deformed configurations. For modeling reasons, the unit cell is chosen, such that, the most complex part, the node, is located in the middle of the unit cell (Fig. 1 (a) and (b)).

2.3. Experimental data

An experimental study was conducted, characterizing Gynemesh M in uniaxial strain and uniaxial stress loading conditions and four loading directions, i.e. the two principal directions of material orthotropy and two off axis directions (33.5°, 56.5°) (Röhrnbauer and Mazza, 2014). A cyclic test protocol was applied, stretching the specimens at a strain rate of 0.005 s^{-1} up to a load case specific maximum force per unit cell (1.6 N per unit cell for uniaxial strain, 0.6 N per unit cell for uniaxial stress) and back. The first ten cycles were referred to as preconditioning, the subsequent three cycles as the actual test. The start of the two procedures, preconditioning and cyclic test, was defined by a preforce of 0.016 N per unit cell for uniaxial strain, 0.006 N per unit cell for uniaxial stress. The value was chosen small compared to the maximum force applied (factor 0.01) and large enough to compensate the noise of the load cell. As described in Röhrnbauer and Mazza (2014), after the preconditioning cycles, the specimens were sagging between the clamps. The introduction of a preforce shifted the start of the test to the beginning of the recruitment of the structure, and led to the definition of a new reference configuration. This resulted in an apparently stiffer initial force response as the filaments were already aligned and explains the different levels of deformation reached for virgin and preconditioned meshes. A non-linear force response, anisotropy, hysteresis and inelastic preconditioning effects were observed. The present structural model is intended to capture geometry based effects, such as the geometric nonlinearity and anisotropy. Dissipative effects (hysteresis) are not included in the model. The experimental findings are given as data arrays of averaged two-dimensional unit cell deformation. Deformation history is represented as a sequence of two line elements $\vec{g}_1(t)$ and $\vec{g}_2(t)$ (current configuration, $\vec{G}_1$ and $\vec{G}_2$ corresponding to the reference configuration) and corresponding force values. These data are used to fit the parameters of the model and to verify its predictive capabilities.

For each configuration (material direction and loading condition), one additional experiment was performed, where the

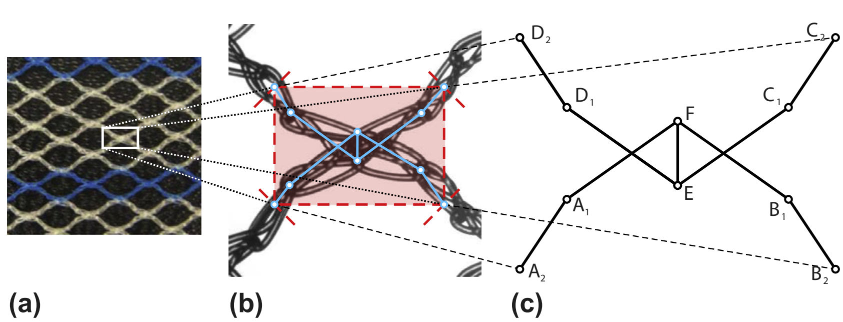

Fig. 1. Identification of a unit cell of Gynemesh M. (a) Close-up of the mesh, a unit cell is marked within the white rectangle. (b) Microscope image of a unit cell overlaid by an abstracted system of ten bodies connected by line elements. (c) The abstracted unit cell geometry represents the geometry of the multibody system.