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Research Paper

# Uniaxial and biaxial mechanical characterization of a prosthetic mesh at different length scales

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ABSTRACT

This study is aimed at a comprehensive experimental analysis of the mechanical behavior of a prosthetic mesh considering different length scales. Uniaxial and biaxial protocols are developed to evaluate global mechanical phenomena of the dry mesh. Furthermore, procedures for local deformation analysis and evaluation of corresponding homogenized kinematic measures are described. The global mechanical response of the prosthetic mesh is characterized by anisotropy, a nonlinear force response, hysteresis and preconditioning effects. The local deformation analysis allows to identify mesh specific phenomena related to mechanisms at the unit cell level. The global and the local kinematic responses of the mesh are seen to be directly related to clinical observations and help to understand associated complications, such as wrinkle formation, dislocation or erosion. In that sense, this study contributes to the analysis of mechanical biocompatibility of mesh implants and proposes protocols for comprehensive mesh product descriptions.



## 1. Introduction

Driven by improved outcomes when using meshes for hernia repair (Luijendijk et al., 2000) there has been a trend for using meshes in pelvic floor reconstruction. However, the benefit of transvaginal placement of surgical meshes has not been proven. In fact, patients' discomfort, mesh dislocation and erosion are severe complications that have been associated with the application of presently available meshes in pelvic floor repair (US Food and Drug Administration, 2011). There are indications that an improved mechanical biocompatibility of such prosthetic meshes is able to positively influence the host response and a smooth integration of the implant (Abramowitch et al., 2009; Ozog et al., 2011b; Gabriel et al., 2011). The notion of mechanical biocompatibility of implants is not based on generally accepted criteria and evaluation standards. Various aspects contribute to the mechanical interaction between implant and host tissue, such as different mesh deformation mechanisms in different loading conditions and at different length scales, all of which are to be evaluated in context with a physiological reference.

Within the clinical and bioengineering community, several studies on prosthetic meshes before implantation, called *dry meshes*, have been reported. Uniaxial stress (Jones et al., 2009; Shepherd et al., 2012; Hernandez-Gascon et al., 2011; Deeken et al., 2011; Krause et al., 2008) and biaxial stress (Deeken et al., 2011; Hollinsky et al., 2008; Eliason et al., 2011) loading conditions have been applied to evaluate the deformation (stiffness) (Jones et al., 2009; Shepherd et al., 2012; Hollinsky et al., 2008) and rupture behavior (maximum elongation or

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load) (Jones et al., 2009; Krause et al., 2008; Hollinsky et al., 2008; Eliason et al., 2011) of different meshes. Global mesh phenomena, possibly influencing the clinical outcome, such as anisotropy (Deeken et al., 2011; Hernandez-Gascon et al., 2011), preconditioning effects and hysteresis in cyclic loading conditions (Shepherd et al., 2012; Krause et al., 2008; Eliason et al., 2011), have been investigated. These findings are based on the evaluation of global data, such as actuator force and displacement records. An evaluation of local deformation patterns, at the level of the pores (mesoscale), has not been performed so far.

On the other hand, several investigations were presented testing and modeling textiles, using advanced test setups and procedures for local deformation analysis (Lomov et al., 2008; Boisse et al., 2005; Ivanov et al., 2009; Potluri et al., 2006; Takano et al., 2004; Zhu et al., 2007; Harrison et al., 2008). In contrast to the mainly knitted prosthetic meshes, the above studies focus on woven fabrics. Commonly applied testing methods are the “picture frame test” (Lomov et al., 2008; Boisse et al., 2005; Harrison et al., 2008; Peng et al., 2004; Harrison et al., 2012; Cao et al., 2008) or the “bias (45°) extension test” (Lomov et al., 2008; Potluri et al., 2006; Zhu et al., 2007; Harrison et al., 2008; Lam et al., 2003; Harrison et al., 2012; Cao et al., 2008), resulting in shear dominated loading conditions with respect to the warp (0°) and weft (90°) directions, the principal directions of material orthotropy. Moreover, uniaxial (Lam et al., 2003; Ivanov et al., 2009; Takano et al., 2004) and biaxial (Lomov et al., 2008; Boisse et al., 2005) tensile tests, loading the textile in the warp and weft directions, have been reported. Structural stiffnesses in shear and tension as well as failure behavior are of interest. Unlike in the dry mesh studies, the characterization of textiles focuses on mesoscale phenomena, such as the alignment, interaction and slippage of yarns (Harrison et al., 2012; Lam et al., 2003; Cao et al., 2008; Lomov et al., 2008; Boisse et al., 2005; Ivanov et al., 2009; Potluri et al., 2006; Takano et al., 2004; Zhu et al., 2007; Harrison et al., 2008). For this reason, digital image correlation is often used to assess the full planar local deformation gradients from an image sequence of the specimens during deformation. The local deformation analysis is aimed at assessing the homogeneity of the deformation, evaluating the actual yarns strain, which might differ from the globally imposed strain, observing mesoscale mechanisms and non-affine deformation and developing and validating physically based numerical models (Lomov et al., 2008; Boisse et al., 2005; Ivanov et al., 2009; Potluri et al., 2006; Takano et al., 2004; Cao et al., 2008).

In this study, we propose test protocols and analysis procedures to perform a comprehensive mechanical characterization of a prosthetic mesh, a knitted fabric, and to quantify the underlying deformation mechanisms at the level of one unit cell. The prosthetic mesh is characterized in uniaxial stress and uniaxial strain (biaxial stress) loading conditions, applied in the two principal directions of material orthotropy and two off-axis directions. Procedures for local deformation analysis and the evaluation of corresponding homogenized kinematic measures are described. It will be shown that the local deformation analysis helps to interpret the global outcome, which differs significantly from what is expected for general continua or biological tissue. Besides providing essential information for the development of appropriate constitutive model formulations for textile mesh implants, the present findings will be discussed in terms of mechanical biocompatibility of this type of prosthetic mesh.

## 2. Material and methods

### 2.1. Material

In this study the commercially available prosthetic mesh Gynemesh M, knitted from non-resorbable polypropylene fibers, was characterized (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 (Ozog et al., 2011a,b; Cobb et al., 2005; Junge et al., 2005). Resorption of the polyglecaprone component takes place within 90–120 days after implantation. Here, the mesh was used in its resorbed state, containing only polypropylene fibers. All materials tested came from the same production lot and were provided by the manufacturer.

For the experimental analysis, a material coordinate system $(\mathbf{e_x}, \mathbf{e_y}, \mathbf{e_z})$ was introduced (Fig. 1). The mesh was regarded as a two-dimensional and periodic structure. The out-of-plane direction $(\mathbf{e_z})$ was not considered. The in-plane material properties of the mesh are orthotropic (Ozog et al., 2011a). A material coordinate system $(\mathbf{e_x}, \mathbf{e_y}, \mathbf{e_z})$ was introduced (Fig. 1): the direction of the blue (dark) lines, which serve for orientation only, is the stiffest material direction, called $\mathbf{e_y}$, the orthogonal direction is the most compliant direction, called $\mathbf{e_x}$, and $\mathbf{e_z} = (0,0,1)^T$ is the out-of-plane direction. One unit cell, a representative pattern of the periodic mesh structure, is marked by the dashed rectangle in Fig. 1. Tests were conducted in four material directions defined with respect to an inertial machine coordinate system $(\mathbf{e_1}, \mathbf{e_2}, \mathbf{e_3})$ (Fig. 2): The direction of load application was called $\mathbf{e_2}$, the transverse direction $\mathbf{e_1}$, the out-of-plane direction $\mathbf{e_3} = (0,0,1)^T$. The angle $\alpha$ was introduced between $\mathbf{e_1}$ and $\mathbf{e_x}$, characterizing the loaded material directions: the two principal directions of material orthotropy $\alpha = 0°, \alpha = 90°$ and two off-axis directions $\alpha = 33.5°, \alpha = 56.5°$, which were chosen with respect to the knitting pattern of the mesh (Fig. 2b). In the following sections, specimens are referred to by the corresponding loaded material direction ($\alpha$), e.g. the 0°-material direction, meaning specimens loaded in the 0° material direction.

### 2.2. Loading conditions

Two types of uniaxial tensile tests, called *uniaxial strain* and *uniaxial stress*, were performed. The case of uniaxial strain is characterized by only one non-vanishing in-plane principal strain direction, $E_{22}$, and a constrained transverse contraction, $E_{11} = 0$. The corresponding state of stress is biaxial, $T_{11} \neq 0, T_{22} \neq 0$. It is realized by a specimen geometry with a high aspect ratio $w/l$ (width/length).