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Technical Note

Material model calibration from planar tension tests on porcine *linea alba*

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ABSTRACT

The purpose of this study was to determine biomechanical properties of *linea alba* subjected to transverse planar tension and to compare its behavior at different locations of the abdominal wall. Samples of *linea alba* from five different porcine abdominal walls were tested in planar tension. During these tests, strain maps were measured for the first time ever using the stereo-digital image correlation (S-DIC) technique. The strain maps were used to derive the properties of different hyperelastic material models. It was shown that the Ogden model and the Holzapfel–Gasser–Ogden model are appropriate to reproduce the response in planar tension. The *linea alba* located above the umbilicus was significantly more compliant than below the umbilicus. This difference which is reported for the first time here is consistent with the tissue microstructure and it is discussed within the perspective of clinically-relevant numerical simulations.

1. Introduction

Abdominal wall (AW) is a complex musculo-aponeurotic structure made of 2 symmetrical parts that join in the sagittal plane along a mid-line named *linea alba*, as explained by Podwojewski et al. (2013) and López-Cano et al. (2013). It is the most common site for laparotomy incision (World Health Organization, 2003) and it plays a key role in AW biomechanics during and after closure of incisions or hernia defects (van't Riet et al., 2002). From an anatomic point of view, *linea alba* is a midline raphe formed by interweaving of anterolateral abdominal muscle aponeuroses, as described by Gray (1918) and Dyce et al. (2009) for respectively human and porcine anatomy. Porcine tissue have a similarly sized heart and body length to humans but it is unknown if they share histological similarities (Cooney et al., 2014). As commonly described, the width of *linea alba* varies significantly from cranial to caudal. Typical porcine *linea alba* was observed to have an average width of 20±5 mm (Cooney et al., 2014).

The mechanical properties of *linea alba* were characterized by different authors (Rath et al., 1996; Grässel et al., 2005; Förstemann et al., 2011; Martins et al., 2012; Podwojewski

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et al., 2013; Tran et al., 2014; Cooney et al., 2014). These authors characterized linear elastic or hyperelastic properties to model the AW biomechanical behavior. Cooney et al. (2014) applied uniaxial and equibiaxial tension tests to identify the mechanical properties of the tissue.

The main goal of the present study is to characterize the mechanical behavior of the *linea alba* in the situation of a laparotomy closure. A tensile test, with 100% of the deformation in the transverse direction, is applied to obtain the mechanical properties. This test was chosen because it is globally similar to the loading applied to the *linea alba* during a laparotomy closure by suture.

Additionally, experimental studies may yield material properties that can be input in finite element models, as performed for instance by Hernández-Gascón et al. (2013) and Cooney et al. (2014). Finite-element model of midline laparotomy closure requiring knowledge of such material properties is currently under development (Nováček and Turquier, 2013). An accurate characterization of the biomechanical properties of *linea alba* is therefore an essential issue for the validity of the models.

In this work, we present an in vitro mechanical characterization of *linea alba* using the planar tension tests. The purpose is to compare the biomechanical properties at different locations of the abdominal wall (supraumbilical and infraumbilical zones). Samples *of linea alba* were harvested from five porcine abdominal walls. Full-field deformation measurements were performed, for the first time ever, by stereo digital image correlation (S-DIC). Finally, an inverse approach was used to derive the parameters of different material models from the response of the tissue to each test.

2. Materials and methods

2.1. Preparation and dimensions of the specimens

Anterolateral AWs of five female pigs, aged 4–5 months and weighing about 45 kg, were used for the current study. The AWs were removed from the animals less than 30 min after euthanasia at the VetAgro Sup—Veterinary Campus of Lyon (Marcy l'Etoile, France), and then kept frozen at $-20\,^{\circ}$C until testing. The AWs were cut along xiphoid process and costal margins and along pubic bones and iliac crests. Lateral incisions were done between iliac spines and the lower part of the rib cage. All the layers were preserved: muscles, aponeuroses, adipose tissue, skin and peritoneum. In a second phase, AWs were thawed at room temperature 16 h in order to cut out samples.

After dissecting skin and adipose tissue on the ventral side and peritoneum on the dorsal side, 80 to 100 mm long rectangular samples were cut for the tensile tests. Thirty samples of *linea alba* were obtained from five different porcine abdominal walls. The *linea alba* tissue was divided in the supraumbilical and infraumbilical zones (above and below umbilicus, respectively). For each abdominal wall six samples were considered. Additionally, for each zone three different samples were obtained, see Fig. 1a. With respect to the umbilicus, samples 1 and 6 are the most distant and samples 3 and 4 are the closest, see Fig. 1a. Before the test, the samples dimensions were measured with a digital caliper. Considering the size of the samples and the relative flatness of the surface, caliper seems to be an adequate technique of thickness measurement (O'Leary et al., 2013; Lee and Langdon, 1996).

The sample height is denoted as H_0. For the supraumbilical and infraumbilical zones the reported H_0 was 24.5 ± 5.37 mm. Only the middle part of the sample is *linea alba* tissue, the remainder of the sample is composed of rectus abdominis muscle (RM) and rectus sheaths (RS), see Fig. 1b. The width and the thickness of the *linea alba* are denoted as W_0 and t_0, respectively, see Fig. 1b.

2.2. Multiphoton imaging

Before the mechanical tests, collagen and elastin fibers were imaged using two photon excitation microscopy in a $500 \times 500 \times 150\,\mu m^3$ volume (150 μm being the depth) located in the middle part of the samples (*linea alba*). The confocal microscope was Nikon A1R MP PLUS® (ivtv.ec-lyon.fr). The tissue was excited with an 800 nm laser. The second harmonic generation (SHG) signal of the collagen fibers was collected through a 380–420 nm bandpass filter using a $20\times$ objectives. The autofluorescence signal was also collected and subtracted to the SHG signal in order to image the elastin fibers.

2.3. Planar tension tests

During the experimental tensile test, only the middle tissue (i. e. *linea alba*), was subjected to tension. The *RM* and *RS* tissues were pressed by hydraulic clamps with 3 bars of pressure. Consequently, no sliding of the specimens was reported. In the geometrical definition of the samples, H_0 is larger than W_0. The assumption of planar tension was satisfied in the experimental protocol (the height remained constant during the tensile test). In the tensile test the axial direction corresponded to the width (direction 2 in the global coordinate system, see Fig. 1c). The transversal direction corresponded to the height of the specimen (direction 1). Finally, the out-of-plane dimension corresponded to the thickness (direction 3). Only the transverse direction was characterized with this experimental protocol.

The planar tension test was performed in an Instron machine (3343—Series 3300 Load Frames). The testing machine was instrumented with a load cell (2519 Instron Series) to measure the axial force resulting of an imposed displacement, see Fig. 1c. The vertical displacement was imposed to the movable clamp while the bottom clamp remained static, see Fig. 1c. The test was performed at 0.2 mm/s cross-head velocity. The test lasted less than 10 min ($7 \leftrightarrow 10$ min). No significant dehydration effects were observed during the tests (Martins et al., 2012).

2.4. Measurement of strain maps by 3D-S-DIC

A non-contacting full-field measurement technique, called Stereo-Digital Image Correlation (S-DIC), was used to measure local displacements in the soft tissue (Sutton et al., 2009). The S-DIC system (GOM, 5M LT) was composed of two 8-bit CCD cameras equipped with 50 mm lenses with a resolution of 1624×1236 pixel. Even for tensile tests a single camera is very sensitive to parasitic out of plane motions, even tiny, whereas