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Characterization of the anisotropic mechanical behavior of human abdominal wall connective tissues

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ABSTRACT

Abdominal wall sheathing tissues are commonly involved in hernia formation. However, there is very limited work studying mechanics of all tissues from the same donor which prevents a complete understanding of the abdominal wall behavior and the differences in these tissues. The aim of this study was to investigate the differences between the mechanical properties of the linea alba and the anterior and posterior rectus sheaths from a macroscopic point of view. Eight full-thickness human anterior abdominal walls of both genders were collected and longitudinal and transverse samples were harvested from the three sheathing connective tissues. The total of 398 uniaxial tensile tests was conducted and the mechanical characteristics of the behavior (tangent rigidities for small and large deformations) were determined. Statistical comparisons highlighted heterogeneity and non-linearity in behavior of the three tissues under both small and large deformations. High anisotropy was observed under small and large deformations with higher stress in the transverse direction. Variabilities in the mechanical properties of the linea alba according to the gender and location were also identified. Finally, data dispersion correlated with microstructure revealed that macroscopic characterization is not sufficient to fully describe behavior. Microstructure consideration is needed. These results provide a better understanding of the mechanical behavior of the abdominal wall sheathing tissues as well as the directions for microstructure-based constitutive model.

1. Introduction

Abdominal wall hernia repair is one of the most common and frequent surgical operations performed in the world (Rutkow, 1997). Abdominal hernia is an abnormal protrusion of the abdominal cavity contents and/or pre-peritoneal fat through a defect or weakness in the abdominal wall. Treatment is commonly performed with sutures or prosthetic meshes. Unfortunately, a weakness of the incised wall can still be observed: incisional hernia recurrence rate after mesh repair surgery is close to 11% (Cassar and Munro, 2002) and the reoperative rate after the second repair goes up to 35% (Flum et al., 2003). Consequently, a repaired wall is less solid than a healthy one.

To reduce complications associated with surgical mesh implants for abdominal hernia cure, research is moving towards the design of meshes mimicking the mechanical physiological behavior of healthy abdominal wall (Hernández-Gascón et al., 2011; Podwojewski et al., 2013). A thorough knowledge of the mechanical behavior of the soft connective tissues constituting abdominal wall is essential. The sheathing parts are the linea alba and the rectus sheaths, which are surrounding the rectus abdominis muscles, ensuring the stability of this system from the mechanical point of view (Axer et al., 2001b; Gräßel et al., 2005).

Despite their preponderant role in hernia occurrence (Cooney et al., 2016), only few studies have been published on the mechanical behavior of soft tissues constituting the abdominal wall and most are limited to determining the ultimate stress and stretch (Hollinsky and Sandberg, 2007; Korenkov et al., 2001; Rath et al., 1997). Linea alba is the most investigated tissue (Cooney et al., 2015, 2016, 2017; Förstemann et al., 2011; Gräßel et al., 2005; Levillain et al., 2016; Rath et al., 1996). Authors show an anisotropic and non-linear behavior. Rath et al. (1996) highlighted a heterogeneity related to the location and Gräßel et al. (2005) a gender dependence. Their results are corroborated by the morphological studies of Askar (1977) and Axer et al. (2001a, 2001b). Hypogastric anterior rectus sheath anisotropy was highlighted by

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Martins et al. (2012) and its non-linearity was shown by Ben Abdelounis et al. (2013). Epigastric anterior rectus sheath and posterior rectus sheath mechanical behavior has never been reported.

Regardless of the number of studies, there is very limited data reported on all abdominal wall sheathing parts from the same individual donor which prevents good understanding of the differences between these soft connective tissues. The aim of the proposed study was to investigate the inter and intra-individual differences between the mechanical properties of the linea alba and the anterior and posterior rectus sheaths from a macroscopic point of view, without assumption on microstructure. Full thickness anterior abdominal wall of eight cadavers of both genders were collected and studied. For every collected tissue, behavior and anisotropy was investigated. Heterogeneity and impact of location were questioned. A statistical analysis was performed to provide a better understanding of the mechanical behavior of the abdominal wall and the disparity of the sheathing tissues properties.

2. Materials and methods

2.1. Population studied

Eight cadavers were studied: 6 men and 2 women. Average age of male donors was 78 years old (SD: 8.3) and average body mass index (BMI) was 23 (SD: 3.0). Female donors were 83 and 94 years old with BMIs 25 and 22, respectively. Considering both male and female donors, average age was 80 (SD: 9.1) and average BMI 23 (SD: 2.7). Bodies were chosen carefully discarding those with abdominal or pelvic surgery or BMI lower than 19. They were embalmed with a solution of water (40%), methanol (40%), glycerin (14%) and phenol (6%). An internal study between fresh and embalmed cadavers, using protocol described in the present article, shown that glycerin does not alter mechanical properties of connective tissues, after a washing procedure with saline, as reported by Richters et al. (1996) and Steinke et al. (2012). The cadavers were dissected and studied at the Anatomical Laboratory of Lille CHRU. Each patient had consented prior to death to his cadaver being used for scientific and/or educational purposes according to the legislation in force.

2.2. Tissue collection and preparation of samples

Complete linea alba and anterior and posterior rectus sheaths were collected. Linea alba and anterior rectus sheath were carefully trimmed and larger bits of skin, fat and superficialis fascia were removed (Fig. 1-A). After removal of rectus abdominis muscle, posterior rectus sheaths were cleared from peritoneum and transversalis fascia and collected

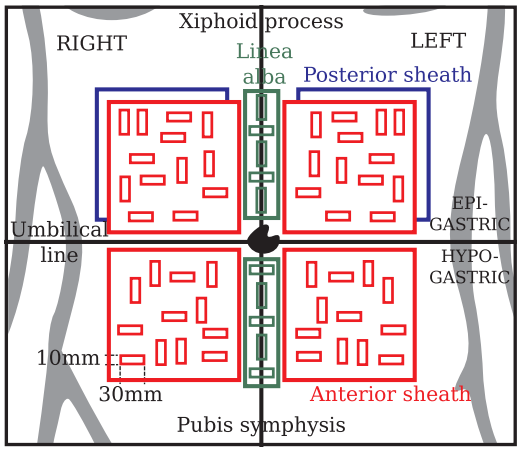

Fig. 2. Definition of the four anatomical areas, above and below the umbilical line (epigastric and hypogastric) and the left and right hand-sides of the linea alba, and random sampling of specimens.

entirely above the arcuate line (Fig. 1-B). The structure below the arcuate line is not considered as sheathing tissue (Hollinsky and Sandberg, 2007), it is transversalis fascia (Wolloscheck et al., 2004). These tissues were divided into anatomical segments for inter-individual and intra-individual comparison. Four areas were defined: above and below the umbilical line (treated as the arcuate line) and the left and right hand-sides of the linea alba (Fig. 2). Samples were frozen for conservation in saline at −20 °C according to the protocol developed by Rubod et al. (2007), preserving position and orientation.

Tissues were thawed nine hours before the tests in saline at room temperature. In this study, we focused on macroscopic behavior. For each defined area, several specimens were punched in two orientations : longitudinal and transverse according to cranio-caudal axis (Fig. 2), in agreement with literature (Cooney et al., 2015, 2016; Förstemann et al., 2011; Gräßel et al., 2005; Hollinsky and Sandberg, 2007; Levillain et al., 2016; Rath et al., 1996, 1997). Dog-bone shaped specimens were avoided because of the low availability of intact tissue and in order to not damage sample fibers (Cooney et al., 2016). In order to circumvent the classical expected shape and sample size limit, the representative size of the sample was determined with an iterating process developed in Morch et al. (2017). Dimensions of connective tissue were downsized until a change in mechanical properties was detected. During downsizing, mechanical properties appeared to be constant (Fig. 3), except for extremes dimensions. We opted for a specimen, with the widest

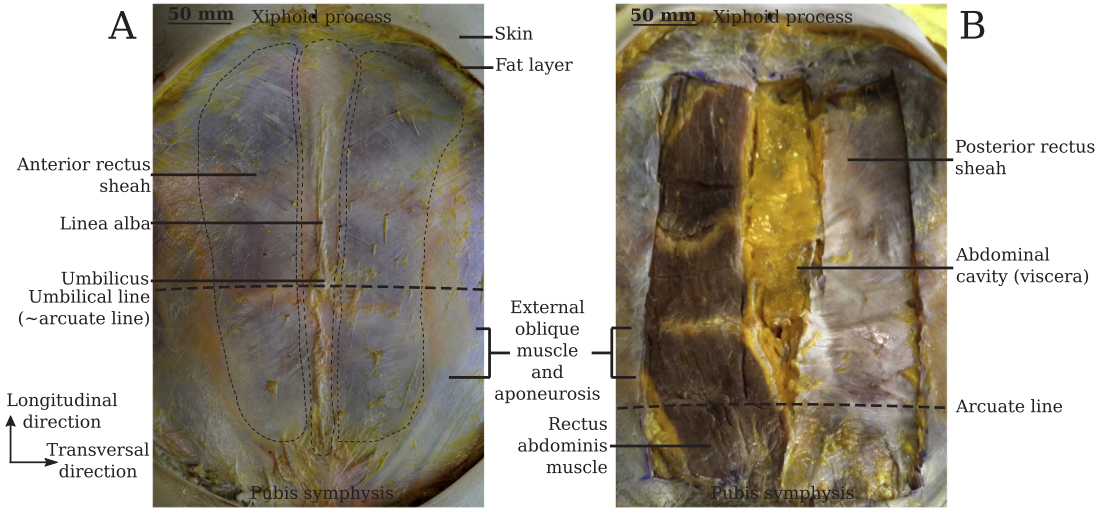

Fig. 1. Identification of the tissues: anterior rectus sheath and linea alba, being skin and fat removed-(A); and posterior rectus sheath with rectus abdominis muscle removed-(B).