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Mechanical properties of the abdominal wall and biomaterials utilized for hernia repair

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ABSTRACT

Abdominal wall hernias are one of the most common and long-standing surgical applications for biomaterials engineering. Yet, despite over 50 years of standard use of hernia repair materials, revision surgery is still required in nearly one third of patients due to hernia recurrence. To date, hernia mesh designs have focused on maximizing tensile strength to prevent structural failure of the implant. However, most recurrences occur at the biomaterial-tissue interface. There is a fundamental gap in understanding the degree to which a mechanical mismatch between hernia repair materials and host tissue contributes to failure at this interface. This review summarizes the current literature related to the anatomy and mechanics of both human and animal abdominal wall tissues, as well as the mechanical properties of many commonly-utilized hernia repair materials. The studies reviewed here reported greater compliance of the linea alba, larger strains for the intact abdominal wall, and greater stiffness for the rectus sheath and umbilical fascia when the tissues were loaded in the longitudinal direction compared to transverse. Additionally, greater stresses were observed in the linea alba when loaded in the transverse direction compared to longitudinal. Given these trends, a few recommendations can be made regarding orientation of mesh. The most compliant axis of the biomaterial should be oriented in the cranio-caudal (longitudinal) direction, and the strongest axis of the biomaterial should be oriented in the medial-lateral (transverse) direction. The human abdominal wall is also anisotropic, with anisotropy ratios as high as 8–9 reported for the human linea alba. Current biomaterial designs exhibit anisotropy ratios in the range of 1–3, and it is unclear whether an ideal ratio exists for optimal match between mesh and tissue. This is likely dependent on implantation location as the linea alba, rectus sheath, and other tissues of the abdominal wall exhibit different characteristics. Given the number of unknowns yet to be addressed by studies of the human abdominal wall, it is unlikely that any single biomaterial design currently encompasses all of the ideal features identified. More data on the mechanical properties of the abdominal wall will be needed to establish a full set of guidelines for ideal mesh mechanics including strength, compliance, anisotropy, nonlinearity and hysteresis.

1. Introduction

Hernias are a debilitating and common condition, affecting over 1 million Americans each year (Poulose et al., 2012). Surgical repair of ventral hernias comes at a tremendous cost of over \$3.2 billion/year and comprises more than 350,000 surgeries annually in the United States alone making this one of the most common procedures in all of general surgery (Poulose et al., 2012; Rutkow, 2003). The introduction of mesh materials to reinforce hernia repairs has improved surgical outcomes. However, pain, infection, and recurrence are still common (Burger et al., 2004; Klosterhalfen et al., 2002; Klosterhalfen and Klinge, 2013; Cavallo et al., 2015). Hernia recurrence alone leads to revision surgery in nearly one in three patients, at a substantial cost to the patient in the form of pain, disability, time off work, and procedural costs (Poulose et al., 2012; Burger et al., 2004).

Thus far, hernia mesh designs have focused primarily on maximizing tensile strength to prevent structural failure of the implant. However, the vast majority of hernia recurrences occur at the implant-tissue interface rather than from mechanical failure of the mesh material. Factors affecting integration at the interface such as insufficient mesh-defect overlap (Langer et al., 2001; Cobb et al., 2009; Zuvela et al., 2014; Petro et al., 2015), failure to close the anterior myofascial layer (Langer et al., 2001; Cobb et al., 2009; Zuvela et al., 2014; Petro et al., 2015), migration/damage from fixation devices (Petro et al.,

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2015; Lerdsirisopon et al., 2011), contracture of the wound (Klosterhalfen et al., 2002; Klinge et al., 1998), poor tissue ingrowth (Klosterhalfen et al., 2002; Klosterhalfen and Klinge, 2013; Cavallo et al., 2015), or sustained inflammatory response (Klosterhalfen et al., 2002; Klosterhalfen and Klinge, 2013; Cavallo et al., 2015; Klinge et al., 1999) have all been reported to contribute to the high incidence of hernia recurrence. Surprisingly, the degree to which mechanical mismatch between biomaterial and host tissue contributes to failure has not been evaluated, even though the primary purpose for utilizing biomaterials in hernia repair is mechanical support and integration with the native tissue. As a first step towards properly matching the mechanics of these structures, the full mechanical properties of abdominal tissues and biomaterials used in hernia repair need to be quantitatively described and compared. This review paper will address this topic, summarizing the current literature related to the anatomy and mechanics of both human and animal abdominal wall tissues, as well as the mechanical properties of many commonly-utilized hernia repair materials.

2. Human abdominal wall

2.1. Anatomy and structure of the human abdominal wall

The human abdominal wall is a complex composite structure composed of various layers which vary depending on specific anatomical location (e.g., medial/lateral, above/below the arcuate line). The central abdominal wall is composed, from superficial to deep, of the following layers: skin, subcutaneous fat, anterior rectus sheath, rectus abdominis muscle or linea alba (depending on location), posterior rectus sheath (if above the arcuate line), preperitoneal fat, and peritoneum ((Kalaba et al., 2016); Fig. 1). In locations lateral to the central line, the rectus abdominis is replaced by a muscle layer composed of the external oblique, internal oblique, and transversalis abdominis muscles. Several collagenous connective tissues (e.g., fascias, sheaths, linea alba) integrate the various layers into a functioning composite structure.

Some of the primary roles of the abdominal wall are mechanical in nature: provide a mechanical barrier to protect internal organs, support the intra-abdominal pressures (IAPs) that develop within the abdominal cavity, and provide/facilitate motion and mobility of the torso. Hernias represent a breakdown or disruption in the continuity of the abdominal wall, which (among other complicating issues) impair the mechanical function of this composite tissue. To fully address such clinical issues, it is first necessary to understand how the healthy intact abdominal wall performs its mechanical function. Namely, what are the mechanical properties of each of the different layers of the abdominal wall and how do they function together to provide necessary mechanical support and strength? Answers to such questions are challenging due to (1) the heterogeneous anatomical configuration of the abdominal wall, where specific layers of the composite tissue vary by location, (2) experimental difficulties in quantifying the mechanics of the composite structure, individual layers, and their connections/interactions, and (3) the complex *in vivo* loading environment of the abdomen where the abdominal wall regularly supports multiaxial physiologic loads during normal function.

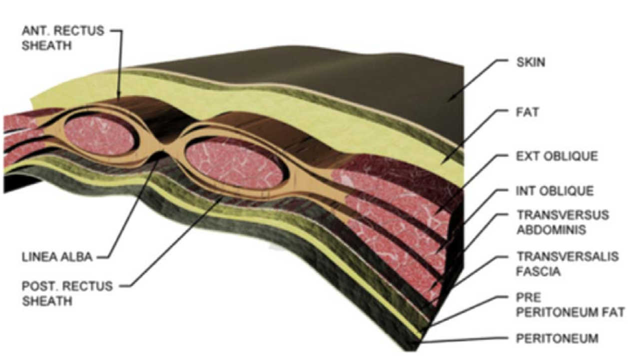

Fig. 1. Schematic showing the various layers of the human abdominal wall (reprinted with permission from Kalaba et al. (2016)).

Furthermore, specific layers often exhibit unique and complex compositional and structural properties, which further challenge efforts to characterize these tissues and fully describe their properties. For example, the linea alba, a midline band of connective tissue that separates the two parallel portions of the rectus abdominis muscle, has been described as a highly structured, three-dimensional meshwork composed predominantly of type I collagen. In addition to exhibiting location-specific width and thickness (increasing/decreasing in the cranio-caudal direction, respectively), the linea alba has several zones throughout its thickness that exhibit distinct structural properties (Axer et al., 2001). Specifically, from ventral to dorsal, the linea alba exhibits sequential layers of intermingling oblique fibers, predominantly transverse fibers, and variable small irregular fibers (Grabel et al., 2005). In addition to this intricate collagenous organization, elastic fibers have also been shown to form an interdigitating layer perpendicular to collagen bundles in human and porcine linea alba, and are hypothesized to contribute to the mechanical properties of this tissue (e.g., elastic recoil) (Levillain et al., 2016). Similar to the linea alba, other tissues of the abdominal wall also exhibit variable and unique structural organization profiles, which likely correlate directly with mechanical properties and function, but which complicate mechanical analysis of individual or composite abdominal tissues. The first sections of this paper will summarize experimental studies to date that have measured mechanical properties of specific tissue layers or whole abdominal walls, of humans and animals, and provide an overview of theoretical and computational models that have been developed to further represent and understand fundamental concepts relative to abdominal wall mechanics.

2.2. Mechanical properties of the human abdominal wall

2.2.1. Mechanical evaluation of individual components of the human abdomen

Several studies have investigated the mechanical properties of specific isolated layers of the abdominal wall structure (Table 1). We note that studies in the literature have used a wide range of different measures and parameters to report mechanical properties of abdominal tissues, which can make interpretation and direct comparison challenging. A few of the more common terms merit definition: stiffness is the slope of the force-elongation curve, modulus is the slope of the stress-strain curve, compliance is the inverse of modulus (or amount of strain per given stress), deformation is the change in length or shape, and strain is the deformation normalized by original geometry (i.e., length or area).

Uniaxial tensile tests of the linea alba in longitudinal (cranio-caudal) and transverse (medial-lateral) directions showed anisotropic properties; higher compliance in the longitudinal direction correlated well with reported descriptions of microstructural collagen fiber alignment (Grabel et al., 2005). Transverse stresses in the linea alba have been reported to be 2–3 times larger than longitudinal stresses (Levillain et al., 2016; Hollinsky and Sandberg, 2007; Forstemann et al., 2011), while a study using biaxial tensile testing reported a much larger anisotropy ratio of 8–9 (Cooney et al., 2016). One study found that mechanics of the linea alba were significantly stronger (~30%) than scar tissue (Hollinsky and Sandberg, 2007), which provides some insight into heightened susceptibility to incisional hernia development following surgical access through the linea alba (Muysoms et al., 2015). A recent study reported non-linear viscoelastic anisotropic properties of human linea alba and showed non-uniform realignment of collagen fibers in different layers under load, demonstrating the complex nature of this connective tissue (Levillain et al., 2016).