Journal of Biomechanics 47 (2014) 1876–1884

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Mechanical characterisation of porcine rectus sheath under uniaxial and biaxial tension

Mathew Lyons [a,*], Des C. Winter [b,c], Ciaran K. Simms [a]

[a] Trinity Centre for Bioengineering, Department of Mechanical and Manufacturing Engineering, Parsons Building, Trinity College, Dublin 2, Ireland
[b] Department of Surgery, St. Vincent's University Hospital, Elm Park, Dublin 4, Ireland
[c] School of Medicine and Medical Science, University College Dublin, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Accepted 1 March 2014

Keywords:
Rectus sheath
Intra-abdominal pressure
Uniaxial tension
Biaxial tension
FeBio model

ABSTRACT

Incisional hernia development is a significant complication after laparoscopic abdominal surgery. Intra-abdominal pressure (IAP) is known to initiate the extrusion of intestines through the abdominal wall, but there is limited data on the mechanics of IAP generation and the structural properties of rectus sheath. This paper presents an explanation of the mechanics of IAP development, a study of the uniaxial and biaxial tensile properties of porcine rectus sheath, and a simple computational investigation of the tissue. Analysis using Laplace's law showed a circumferential stress in the abdominal wall of approx. 1.1 MPa due to an IAP of 11 kPa, commonly seen during coughing. Uniaxial and biaxial tensile tests were conducted on samples of porcine rectus sheath to characterise the stress–stretch responses of the tissue. Under uniaxial tension, fibre direction samples failed on average at a stress of 4.5 MPa at a stretch of 1.07 while cross-fibre samples failed at a stress of 1.6 MPa under a stretch of 1.29. Under equi-biaxial tension, failure occurred at 1.6 MPa with the fibre direction stretching to only 1.02 while the cross-fibre direction stretched to 1.13. Uniaxial and biaxial stress–stretch plots are presented allowing detailed modelling of the tissue either in silico or in a surrogate material. An FeBio computational model of the tissue is presented using a combination of an Ogden and an exponential power law model to represent the matrix and fibres respectively. The structural properties of porcine rectus sheath have been characterised and add to the small set of human data in the literature with which it may be possible to develop methods to reduce the incidence of incisional hernia development.

1. Introduction

Hernia development at wound sites after laparoscopic surgery has a prevalence rate of 1–3% (Boldo et al., 2006; Bowrey et al., 2001; Comajuncosas et al., 2011; Kadar et al., 1993; Tonouchi et al., 2004). The biomechanical driver behind hernia formation is evidently elevated intra-abdominal pressure (IAP), though this has not been proven. The rectus sheath, a fibrous layer encompassing the aponeurosis of the lateral abdominal muscles and enveloping the rectus abdominis muscle, is often implicated in hernia formation. However, there is surprisingly no literature on the mechanical environment that generates IAP and thus no fundamental understanding of the stress states during hernia formation in the rectus sheath. There is also limited data on the structural properties of rectus sheath, with varying protocols and conflicting results (Ben Abdelounis et al., 2013; Martins et al., 2012; Rath et al., 1997). Rath et al. studied human rectus sheath in uniaxial tension but only reported failure stress and elongation. Martins et al. measured uniaxial stress–strain behaviour in human tissue in both fibre and cross-fibre directions, but reported large scatter with stresses between 2.5 and 20 MPa and failure stretches up to 2.6 which seem doubtful. Statistical tests compared fibre and cross-fibre orientations, effects of BMI, and gender, but the sample sizes were small. Ben Abdelounis et al. recently examined the effect of loading rate on the cross-fibre direction response of human tissue in uniaxial tension. These authors also used an image based strain measure to address slippage at the tissue grip interface which may account for some of the findings of Martins et al. However, their sample size was also small. The aims of this paper are therefore to analyse the loading environment in the abdominal wall, to characterise the tensile structural properties of the porcine rectus sheath using appropriate mechanical tests and to evaluate whether a fibre reinforced computational material model can adequately replicate the observed experimental behaviour.

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* Corresponding author. Tel.: +353 1 896 2978.
E-mail address: lyonsm2@tcd.ie (M. Lyons).

http://dx.doi.org/10.1016/j.jbiomech.2014.03.009
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2. Methods

2.1. The loading environment in the abdominal wall under IAP

IAP is generated through the action of the diaphragm and the abdominal muscles. During quiet breathing, the abdominal muscles are inactive (Campbell and Green, 1953) and contraction of the diaphragm reduces the craniocaudal diameter of the abdominal cavity and the IAP causes the dorsoventral diameter to increase passively (Fig. 1(a)). This results in a minimal variation of IAP during normal breathing of ca. 1 kPa (Malbrain et al., 2004; Sanchez et al., 2001; Sugerman et al., 1997). From Eq. (1), modelling the abdomen as a cylinder and assuming a radius of 200 mm and an abdominal wall thickness of 2 cm (Sandler et al., 2010) (Fig. 1(a)) the circumferential stress in the abdominal wall during breathing would be around 10 kPa.

$$\sigma = \frac{Pr}{t}. \qquad (1)$$

In contrast, in an abdominal straining manoeuver the muscles of the abdominal wall contract and the diaphragm is then lowered, significantly reducing the volume of the abdominal cavity. Approximating the cavity as an elliptical hemi-cylinder, the volume is

$$\tfrac{1}{2}L\pi r_1 r_2. \qquad (2)$$

Using CT scanning, Duez et al. (2009) found the dimensions of the abdomen as length: 341 mm, $R1$: 141 mm and $R2$: 104 mm which equates to a volume of 7.9 L using Eq. (2). Talasz et al. (2011) used MRI to evaluate the change in these dimensions during coughing and found the length decreased to 304 mm, $R1$ remained the same and $R2$ reduced to 94.5 mm giving a new, reduced volume of 6.4 L.

Applying Boyle's law ($PV = k$), assuming the abdomen was sealed and gas filled, a reduction in volume of 1.5 L (19%) would create a 19% increase in pressure. Given a resting IAP of 1 kPa this would generate an IAP of only 1.19 kPa during coughing, much less than the average of 11 kPa reported (Cobb et al., 2005). However, with only 115 ml of gas in the abdomen at rest (Bedell et al., 1956), blood must be expelled from the abdomen via the venous and arterial networks to permit this volume reduction. Central venous pressure is approximately 2 kPa (Egan et al., 2009) but blood can only flow proximally through the venous network due to valves. Diastolic arterial blood pressure is approximately 10.5 kPa (Kshirsagar et al., 2006), and thus to expel arterial blood via the arterial network, the IAP must exceed this.

Since contracting the abdominal muscles reduces the abdominal circumference, the transversalis fascia and peritoneum should not be under tension as they do not act in series with the muscles (Fig. 1(b)). However, contraction of the internal and external oblique muscles and the transverse abdominis would load the anterior and posterior rectus sheath and the linea alba (Fig. 1(b)). Application of Eq. (1) shows that an IAP of 11 kPa in an abdominal cavity of radius 200 mm and thickness 2 mm (Martins et al., 2012; Song et al., 2006) would yield an average circumferential stress in the abdominal wall of 1.1 MPa. Defects, caused by abdominal surgery, would be particularly stressed in this configuration.

This preliminary analysis has shown that the biomechanics of abdominal wall loading during high IAP is complex. For future physical and computational modelling of the abdominal wall for wound closure analysis, it is of interest to establish the stress–strain relationship of the rectus sheath for stresses of the order of megaPascals. Furthermore, during periods of increased IAP the stress in the cross-fibre direction is likely to be non-negligible, and the biaxial tensile behaviour of the rectus sheath is therefore also of interest. Accordingly, mechanical testing in these modes was performed and is reported next.

2.2. Physical tests

Twenty porcine abdominal walls were sourced from a local abattoir. All pigs were aged 26–28 weeks and all females were nulligravida. Animals were slaughtered and dissected in the abattoir as per their procedures where the abdominal walls were harvested. They were subsequently kept frozen at −20 °C. Prior to testing, abdominal walls were defrosted at 5 ± 1 °C for 40 h and dissected to isolate

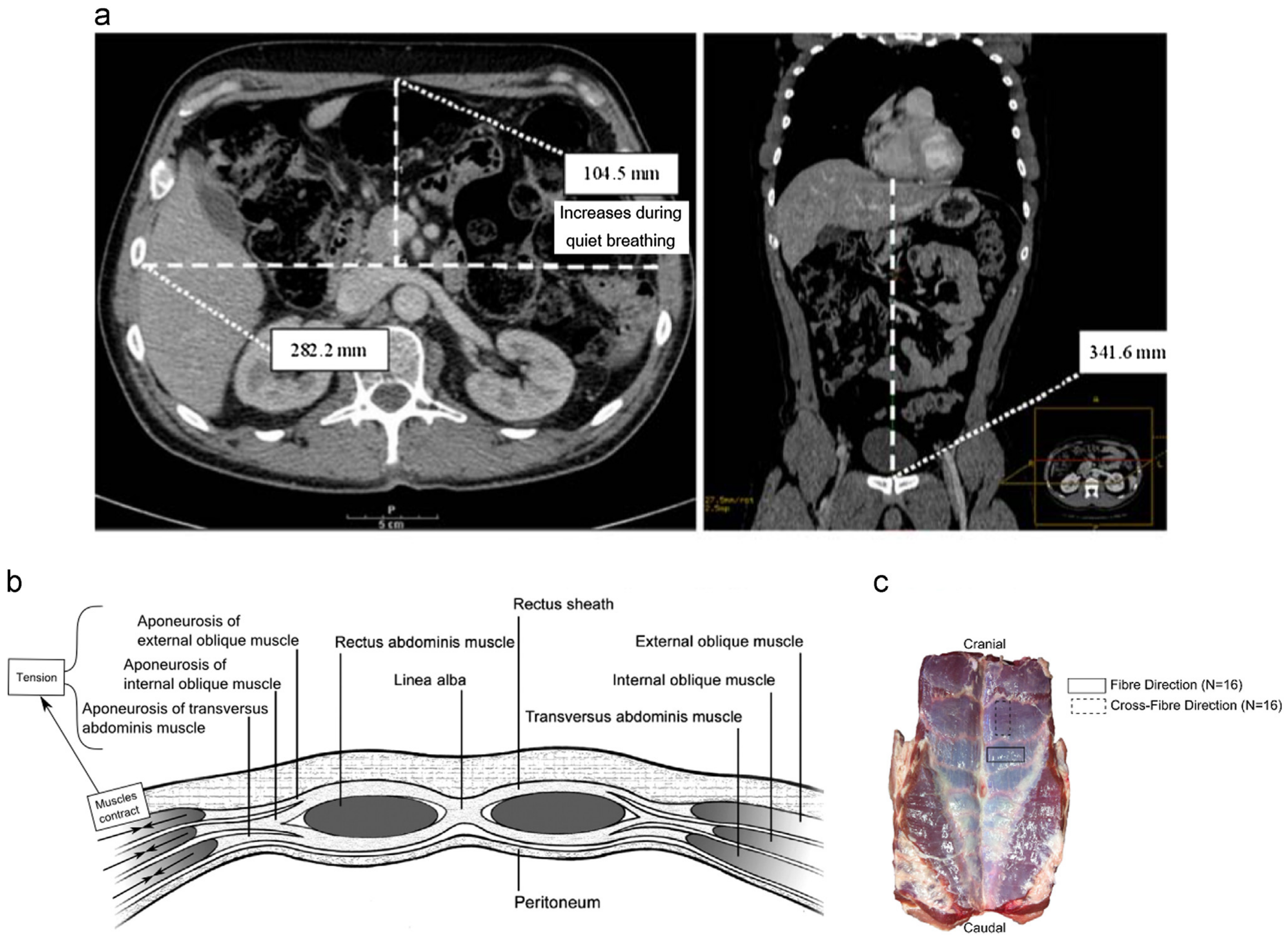

Fig. 1. Dimensions of the abdominal cavity, from Duez et al. (2009), (b) layers of the abdominal wall from Yarwood and Berrill (2010) and (c) posterior view of a porcine belly showing fibre and cross-fibre directions.