JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 41 (2015) 68–82

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

Uniaxial and biaxial mechanical properties of porcine linea alba

Gerard M. Cooney[a,*], Kevin M. Moerman[b], Michael Takaza[a], Des C. Winter[c,d], Ciaran K. Simms[a]

[a]Trinity Centre for Bioengineering, Department of Mechanical and Manufacturing Engineering, Parsons Building, Trinity College, College Green, Dublin 2, Ireland
[b]Academic Medical Centre, Department of Radiology, Meibergdreef 9, 1100 DD Amsterdam, The Netherlands
[c]School of Medicine and Medical Science, University College Dublin, Belfield, Dublin 4, Ireland
[d]Department of Surgery, St. Vincent's University Hospital, Elm Park, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 24 June 2014
Received in revised form
23 September 2014
Accepted 26 September 2014
Available online 7 October 2014

Keywords:
Linea alba
Uniaxial tension
Biaxial tension
FEBio model
Physical sample size effect

ABSTRACT

Incisional hernia is a severe complication post-laparoscopic/laparotomy surgery that is commonly associated with the linea alba. However, the few studies on the mechanical properties of the linea alba in the literature appear contradictory, possible due to challenges with the physical dimensions of samples and variations in protocol. This study focuses on the tensile mechanical characterisation of the porcine linea alba, as determined by uniaxial and equi-load biaxial testing using image-based strain measurement methods. Results show that the linea alba demonstrated a non-linear elastic, anisotropic behaviour which is often observed in biological soft tissues. The transverse direction (parallel to fibres) was found to be approximately eight times stiffer than the longitudinal (cross-fibre) direction under both uniaxial and equi-load biaxial loading. The equi-load biaxial tensile tests revealed that contraction could occur in the transverse direction despite increasing load, probably due to the anisotropy of the tissue. Optical surface marker tracking and digital image correlation methods were found to greatly improve the accuracy of stretch measurement, resulting in a 75% change in the apparent stiffness compared to using strain derived from machine cross-head displacement. Additionally, a finite element model of the experiments using a combination of an Ogden and fibre exponential power law model for the linea alba was implemented to quantify the effect of clamping and tissue dimensions (which are suboptimal for tensile testing) on the results. The preliminary model results were used to apply a correction factor to the uniaxial experimental data prior to inverse optimisation to derive best fit material parameters for the fibre reinforced Ogden model. Application of the model to the equi-load biaxial case showed some differences

*Corresponding author. Tel.: 00353 83 3060295.
E-mail addresses: cooneyg@tcd.ie (G.M. Cooney), k.m.moerman@amc.uva.nl (K.M. Moerman), takazam@tcd.ie (M. Takaza), des.winter@gmail.com (D.C. Winter), csimms@tcd.ie (C.K. Simms).

http://dx.doi.org/10.1016/j.jmbbm.2014.09.026

compared to the experimental data, suggesting a more complex anisotropic model may be necessary to capture biaxial behaviour. These results provide an improved assessment of the mechanical properties of the porcine linea alba for wound closure and other studies.

1. Introduction

Laparoscopic surgery is a surgical procedure performed through small incisions in the abdomen that has significantly changed the way abdominal surgery has been performed since the late 1980s (Wexner and Cohen, 1995). Considerably reducing trauma, lowering the risk of infection, shortening hospital stays and improving cosmetic results, it has rapidly increased in popularity with over two million patients undergoing laparoscopic procedures in the USA each year (Laparoscopic trocar injuries: a report from a U.S. Food, 2005). However, incisional hernia can form post-operatively, a situation whereby contents of the abdominal cavity protrude through a weakness in the abdominal wall as a result of improper trocar site wound closure (commonly at the linea alba near the umbilicus (Hegarty, 2007; Katkhouda, 2010; Moran and Farquharson, 2005)). Such cases have a prevalence of approximately 1–5% (Boldo et al., 2007; Bowrey et al., 2001; Helgstrand et al., 2011; Heniford et al., 2000; Kadar et al., 1993; PLAUS, 1993), meaning that, in the U.S alone, up to 100,000 cases of port site incisional hernia occur each year. This outlines a clear need for a more robust solution to the current methodology of wound closure in laparoscopic surgery.

It is first important to understand the mechanical properties of the linea alba, which is the load-bearing tissue commonly involved in midline hernia formation. Unfortunately, there is limited data on the mechanical properties of the linea alba with current studies presenting conflicting results and varying experimental protocols (Förstemann et al., 2011; Gräßel et al., 2005; Campbell et al., 1989; Descoux et al., 1993; Hollinsky and Sandberg, 2007). A particular challenge is the aspect ratio of the linea alba (approximately 2:1), complicating tensile testing significantly. Förstemann et al. (2011) presented the uniaxial tensile response of cadaveric human tissue, yielding a stress variation of between 2–5 MPa at 10% strain in the transverse direction (parallel to fibres) and 0.2–0.85 MPa in the longitudinal direction (cross-fibre). Gräßel et al. (2005) also performed uniaxial mechanical tests on fresh human linea alba, reporting considerably less stiff mechanical profiles, but with greater scatter. Both studies use machine crosshead displacement to approximate the strain occurring in the material. However, this approach does not account for slippage of the tissue from the grips or transducer deformation. The use of image-based strain measurement methods (Ben Abdelounis et al., 2013; Lyons et al., 2014) may have a significant improvement on the accuracy of observed mechanical properties. Furthermore, uniaxial tensile tests may not adequately represent in-vivo deformations of the tissue. The tissue is most likely loaded biaxially in-vivo during increased intra-abdominal pressure (IAP).

The aims of this paper are therefore to characterise the uniaxial and biaxial tensile behaviour of porcine linea alba using image-based strain measurement. Given the sub-optimal shape of the linea alba specimens for tensile testing, a finite element model is used to assess the influence of sample dimensions and clamping on the experimental results presented and provide a correction factor for the uniaxial experimental data.

2. Materials and methods

2.1. Sample preparation

Fresh human tissue that has not been embalmed is difficult to obtain, and accordingly porcine tissue was used in this study. Pigs have a similarly sized heart and body length to humans but it is unknown if they share histological similarities. Nevertheless, pigs were chosen as a suitable substitute to humans. Twenty porcine abdominal walls were obtained from a swine abattoir (Rosderra Meats, Edenderry, Co.Offaly, Rep. of Ireland). Specimens were chosen at random from both male and female populations; all females being nulligravida. All were adults, approximately 26–28 weeks in age and were frozen within 24 hours of death.

Prior to sample extraction the porcine belly specimens were allowed to defrost for 36 hours at 4 °C. A rectangular section was then cut from the abdominal wall following the midline

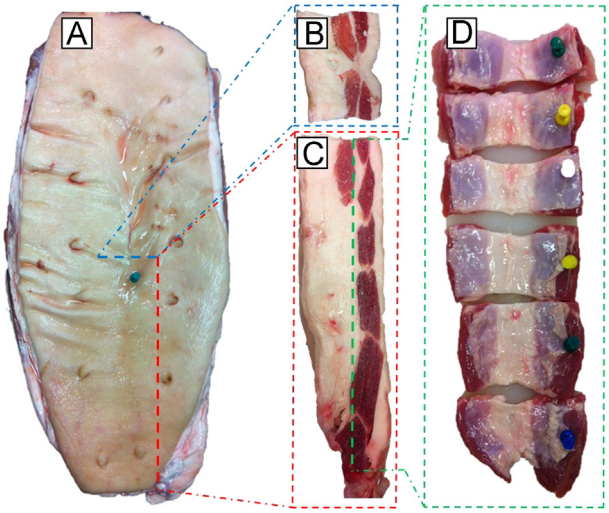

Fig. 1 – The porcine abdominal wall (A) with corresponding cross-sectional cuts of the approximate area of interest (B and C) and the tissues (posterior side) having been cut along the tendinous insertions of the rectus abdominis following anterior and posterior fat removal (D).