JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 61 (2016) 444–454

Available online at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/jmbbm

Research Paper

# Active behavior of abdominal wall muscles: Experimental results and numerical model formulation

J. Grasa[a,c,*], M. Sierra[a], N. Lauzeral[a], M.J. Muñoz[b], F.J. Miana-Mena[a], B. Calvo[a,c]

[a]Aragón Institute of Engineering Research, University of Zaragoza, Zaragoza, Spain
[b]Lagenbio, Aragón Institute of Engineering Research, University of Zaragoza, Zaragoza, Spain
[c]CIBER-BBN. Centro de Investigación en Red en Bioingeniería, Biomateriales y Nanomedicina, Spain

ARTICLE INFO

*Article history:*
Received 7 January 2016
Received in revised form
29 March 2016
Accepted 6 April 2016
Available online 14 April 2016

*Keywords:*
Abdominal muscle
*in vitro* active behavior
Finite element method

ABSTRACT

In the present study a computational finite element technique is proposed to simulate the mechanical response of muscles in the abdominal wall. This technique considers the active behavior of the tissue taking into account both collagen and muscle fiber directions. In an attempt to obtain the computational response as close as possible to real muscles, the parameters needed to adjust the mathematical formulation were determined from *in vitro* experimental tests. Experiments were conducted on male New Zealand White rabbits (2047±34 g) and the active properties of three different muscles: *Rectus Abdominis*, *External Oblique* and multi-layered samples formed by three muscles (*External Oblique*, *Internal Oblique*, and *Transversus Abdominis*) were characterized. The parameters obtained for each muscle were incorporated into a finite strain formulation to simulate active behavior of muscles incorporating the anisotropy of the tissue. The results show the potential of the model to predict the anisotropic behavior of the tissue associated to fibers and how this influences on the strain, stress and generated force during an isometric contraction.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

In mammals, the abdominal wall is composed of four muscle groups: *Internal Oblique* (IO), *External Oblique* (EO), *Rectus Abdominis* (RA) and *Transversus Abdominis* (TA). Unlike the thorax, internal organs are not protected by a bony structure and these muscles, together with fascial tissues, develop a protective function when acting passively. During active contractions, muscles in the abdominal wall participate in breathing, emesis, sneezing, coughing, defecation, micturition, phonation and postural control (Iizuka, 2011). Anatomically, the IO lies internal to the EO muscle in the lateral abdominal wall, whereas the TA, the most internal abdominal muscle, lies in the lateral and ventral abdominal wall

*Corresponding author at: Aragón Institute of Engineering Research, University of Zaragoza, Zaragoza, Spain.
E-mail address: jgrasa@unizar.es (J. Grasa).

http://dx.doi.org/10.1016/j.jmbbm.2016.04.013
1751-6161/© 2016 Elsevier Ltd. All rights reserved.

between the internal surface of the IO and the costal cartilage (Hwang et al., 2005; Hernández and Pe, 2011). Each one of the previously quoted muscles has a specific muscle fiber orientation. The EO muscle fibers radiate caudally to the iliac crest and inguinal ligament and medially to the linea alba while the IO muscle fibers arise from the inguinal ligament and iliac crest and insert into the anterolateral surface of the cartilages of the last three ribs and into the linea alba, perpendicularly to the EO fibers. The TA muscle fibers run circumferentially around the abdominal visceral mass from the inner surface of the lower six ribs, lumbar fascia, iliac crest and the inguinal ligament to the rectus sheath are directed downward (Ratnovsky et al., 2008). Finally, the RA muscle fibers are parallel to the linea alba.

The active force developed by single muscle fibers is transmitted through a hierarchical structure of connective tissues to the muscle insertions or aponeuroses. The three anatomical parts of these connective tissues (from most external to most internal: *epimysioum*, *perimysium* and *endomysium*) are mostly woven collagen fibers embedded in an amorphous ground substance. In some long strap-like muscles a two parallel sets of wavy collagen fibers in a crossed-ply arrangement have been observed in the *epimysium* (Purslow, 2010). The collagen fibers are arranged at angles of approximately 55° to the long axis of the muscle fibers. In other muscles, this arrangement is parallel to the muscle axis (Purslow, 2010). For the *perimysium* and *endomysium*, a distribution of collagen fibers running in all directions has been reported (Purslow, 2002, 2010; MacIntosh et al., 2006) covering bundles of muscle fibers. The three mentioned layers are connected together to transmit efficiently the muscle force. But focusing on the abdominal wall structure, another connective tissue plays an important role in the transmission of force and passive protection of internal organs that has become an object of increasing interest. This tissue, still without little consistent international terminology (Stecco et al., 2013) is known as fascia and in the abdominal wall is located covering the muscles and between them (Hernández and Pe, 2011).

The unique anatomical arrangement of muscles and connective tissues in the abdominal wall has inspired descriptions and related hypotheses regarding its function as a composite-laminate structure (Brown et al., 2012; Brown, 2012; Hwang et al., 2005). Therefore, the material properties of this composite structure have been studied to better understand the abdominal wall mechanical behavior. The passive mechanical properties of the abdominal muscles have been investigated by several authors in different species: rat (Hwang et al., 2005; Brown et al., 2012; Brown, 2012), rabbit (Calvo et al., 2014; Simón-Allué et al., 2015), pig (Van Loocke et al., 2008; Lyons et al., 2014) and human (Förstemann et al., 2011). Moreover, the whole abdominal wall response to an increase of the intra-abdominal pressure has also been studied (Kotidis et al., 2011; Park et al., 2012; Rohlmann et al., 2006). Regarding the anisotropy of the tissue, this effect has been considered by Hwang et al. (2005) in a work where samples of tissue were loaded passively in two directions. Although these studies assist to understand how abdominal muscles behave, they focused only in the passive component meanwhile their active behavior remains unclear. Further research involving active behavior of this tissue would increase the knowledge to develop more and more efficient prosthesis in case of hernias meshes (Hernández and Pe, 2011) or to understand the different contributions of muscles to the trunk stability (Olson, 2014; Arokoski et al., 2001).

From a biomechanical point of view, muscle tissue presents some special characteristics as large deformations, anisotropic relationship between stress and applied strain and above all, a complex geometry. Consequently, closed-form solutions of the mathematical equations cannot be found for non-trivial problems. The Finite Element Method (FEM) is a powerful tool to find good numerical solutions for these equations (Oomens et al., 2003). FEM has been successfully implemented for studying skeletal muscles with complex shapes for both active and passive behaviour (Böl and Reese, 2008; Tang et al., 2009; Grasa et al., 2011, 2014; Webb et al., 2014). The abdominal wall biomechanics has been studied by means of this technique assuming the presence of hernia defects (Hernández-Gascón et al., 2011) and the influence of different prostheses (Hernández-Gascón et al., 2013). In these studies, only the passive behavior of the tissues was considered.

In the present study, the authors investigate the biomechanical characteristics of the abdominal wall contractions on New Zealand White rabbits. This animal model is commonly used for the study of hernia repair meshes (Aramayo et al., 2013; Pascual et al., 2013; Peeters et al., 2013) and authors characterized previously its passive response (Hernández and Pe, 2011; Calvo et al., 2014). *In vitro* experimental active tests are presented here for the RA, the EO and samples formed by three muscles (EO, IO and TA). Different parameters related to the active behavior were adjusted by means of a 3D electro-mechanical continuum model. This model, initially proposed by Hernández-Gascón et al. (2013), has been modified here to take into account the influence of the fiber contraction velocity in the force development.

## 2. Material and methods

The experimental study was conducted on 10 male New Zealand White rabbits aged two months with a body mass of $2047 \pm 34$ g. All experiments were approved by the University of Zaragoza Ethics Committee for the use of animals in experimentation in accordance with the provisions of the European Council (ETS 123) and the European Union (Council Directive 86/609/EEC) regarding the protection of the animals used for experimental purposes. The animals were kept in a temperature controlled room ($22 \pm 1$° C) with 12 h light–dark cycles and free access to water and food.

### 2.1. *In situ muscle preparation*

All animals were anesthetized by intramuscular injection of a mixture of Medetomidine (0.14 mg/kg), Buprenorfine (0.02 mg/kg) and Ketamine (20 mg/kg) and euthanized by intravenous overdose of sodium pentobarbital. Immediately afterwards, animals were placed on their back and the abdominal skin was removed to define three different regions

Download English Version:

https://daneshyari.com/en/article/7207919

Download Persian Version:

https://daneshyari.com/article/7207919

Daneshyari.com