Available online at www.sciencedirect.com

ScienceDirect

Biosurface and Biotribology 3 (2017) 56–65

www.elsevier.com/locate/bsbt

Experimental creep behavior of porcine liver under indentation with laparoscopic grasper for MIS applications

Cheng-mo Cai, Qing-yuan Yu, Wei Li*, Jing Zheng, Zhong-rong Zhou

Tribology Research Institute, Key Laboratory for Advanced Technology of Materials of Ministry of Education, Southwest Jiaotong University, Chengdu 610031, China

Received 26 April 2017; accepted 28 June 2017

Abstract

Mechanical response of soft tissues behaved disparate due to fast and large deformation during surgical grasping, so there is a need for experimental databases of biomechanical characteristics of soft tissue under the contact of MIS tool, which are more useful for designing new surgical instruments, training inexperienced surgeons, improving surgical simulations and developing surgical robotics system. A novel indentation test to simulate the real-time surgical operation condition was present in this paper. The creep behavior of porcine liver in vitro was studied under uniaxial indentation by using MIS grasper. The nominal stress between the grasper and the liver was 0.02 to 0.1 MPa, the loading velocity was 1 to 3 mm/s, and the holding time was 300 s to simulate clamping tissue operation. Results showed that the creep process of the liver during 300 s of duration can be divided into three stages: loading stage I, transition creep stage II and steady creep stage III. The creep characteristic of liver behaves time-dependent, load-dependent and strongly loading velocity-dependent due to its nonlinear viscoelastic characteristics and hysteresis characteristics. These creep behavior might also be associated with the deformation, migration and biochemical reaction of the liver cells. The phenomenological model derived in this paper may describe the creep behavior of the liver. The results would provide experimental databases and phenomenological models for investigating biomechanical characteristics of soft tissue under the contact of MIS tool.

Keywords: Porcine liver; Creep behavior; Laparoscopic grasper; Compression test; Phenomenological model

1. Introduction

Minimally Invasive Surgery (MIS) is a widespread new technique with various advantages than traditional open surgical operation during the past few decades, which assembles new instruments, microelectronics, new materials and automation. A surgeon operates with specially designed surgical tools through access ports requiring incisions of about 1 cm in size, which can decrease the pain of patients, reduce the recovery time and limit the surgical trauma to tissues. Computer science will be large-scale used in minimally invasive medicine in the future, and virtual reality technology will take MIS to a new level [1]. However, there are two hindrances in the progress of the more advanced, intelligent and widespread MIS: one is lack of tissue response database of tissue-tool for surgical simulations and training surgeons, the other is lack of biomechanical model for researching intelligent surgical robotics system.

A number of studies have investigated the biomechanical characteristics of liver by performing compression and tensile tests on a whole block of liver or partial liver [2–6]. Nevertheless, Ahn and Kim investigated the characterization of porcine livers by using various shapes of indenter. The results showed that the mechanical response behaved disparate based on the shapes of indenter even under the same indentation depth [7]. These potential differences indicate the limitation of past studies on biomechanical characteristics of liver and the need to perform biomechanical test of intra-abdominal tissues

---

*Corresponding author. Fax: +86 28 87603142.

E-mail address: liweijiani@home.swjtu.edu.cn (W. Li).

Peer review under responsibility of Southwest Jiaotong University.

http://dx.doi.org/10.1016/j.bsbt.2017.06.002

2405-4518/

Nomenclature

F	Compression force
A	Contact area of the jaw
H_0	Initial thickness of the liver
H_S	Compressed instantaneous thickness of the liver
σ	Nominal stress
λ	Compression ratio
λ_S	Characteristic compression ratio
D	Creep speed of the liver
Δ_L	The increment of the average compression ratio λ between the loading velocities of 1 mm/s and 2 mm/s
Δ_H	The increment of the average compression ratio λ between the loading velocities of 2 mm/s and 3mm/s
$\lambda_{T_i}^{\nu}$	The compression ratio λ with specified loading velocity and time point
T_i	Time point of every 25 seconds within 100–300 s
Δ	The differential value between the fitted line and the test curve
α	Coefficients determined by fitting the experimental data
β	Coefficients determined by fitting the experimental data
τ	Time constant

in-vivo or in-situ by using MIS device for surgical simulations, researching surgical robotics and training surgeons. At present, quite few studies referred to the mechanical proprieties of liver under compression by using MIS device have been reported [8–12]. These works have provided valuable data for later research on tissue finite element models (FEMs) and surgical devices development. However, these studies have mainly reported the stress-strain and stress relaxation of liver *in vivo, in situ and ex corpus*. Mechanical responses of the livers show the nonlinear viscoelastic characteristics and time-dependent. Insufficient data can support latter deeper and wider research. Besides, the grasper clamping tissue is a time continuation behavior. The grasping duration ranges from several seconds to several minutes with an almost constant grasping force [13,14]. So the study on creep behavior of porcine liver by using MIS grasper seems to be meaningful for further research on the interactions of tool-tissue.

The desire to develop more intelligent surgical instrument for improving healthcare has prompted research into the areas of micro and real-time feedback grasper and more accurate characterization of biological tissue models. Currently, the development of medical device rely on tissue finite element models (FEMs) to evaluate and reduce tissue damage during grasping [15–18]. Realistic surgical simulators also rely on computer- reconstructed 3D models to obtain both realistic graphics and haptic feedback throughout the surgical task. Liver is a solid-fluid interacted and mixed material. There is a layer of connective tissue composed of dense collagenous fiber on the surface of the liver to keep its integrity. A mass of complex vascular systems are distributed in the liver, in which 28% of blood is under circulation. Liver behaves as a non-homogeneous, anisotropic, nonlinear and viscoelastic material [19]. Owing to the highly complex nature of biological tissue, constitutive models must be developed to accurately reflect the biomechanical characteristics of the tool–tissue interaction. Recently, real-time finite element methods have been applied to the surgical simulation [17,20–23]. However, most studies modeled tissues as isotropic and homogeneous which simplify parameter identification and FEM. These models must be validated based on appropriate biomechanical test data which is obtained under the simulation of clamping tissue operation.

Consequently, in this paper, the creep behavior of liver *in vitro* was studied under various load conditions by using MIS grasper to simulate the real tissue-surgical operation condition. A large deformation (nominal strain: 20–50%) and non-quasi-static (loading rates: 1–3 mm/s) indentation test with specific indenter was shown in this paper. The purpose was to provide experimental databases and phenomenological models for investigating biomechanical characteristics of soft tissue with the contact of MIS tool. The results would be also useful for designing new surgical instruments, training inexperienced surgeons, improving surgical simulations and developing surgical robotics system.

2. Materials and methods

2.1. Sample preparation

Since liver is one of the solid organs with relatively more homogeneous structure than other tissues in abdominal cavity, it was chosen as an experimental sample for this study. Four excised fresh porcine livers were used for the experiments because of their structural and functional similarities to the human liver, which were taken from four pigs of a local pig abattoir. The weight of the pigs was about 60 kg and the age was18 to 20 weeks. The livers were kept in an icebox and transported to the laboratory within 2 h postmortem, and tested within 4 h after extraction to avoid dehydration and blood clotting. During the compression tests, all liver samples were kept in their natural shape, but were trimmed into the same thickness of 20 ± 2 mm in the thickness direction. All samples were prepared and tested at a nominal room temperature of 20 ± 2 °C and relative humidity of 50 ± 5% to simulate the operation room temperature and humidity. During all the tests, the physiological saline were sprayed on the surface of the liver samples every 20 min to simulate their surface moisture in the body.

In order to observe the microstructure of the liver tissue, the histological section was made according to the routine method of dermatopathology [24]. The liver sections were got through the processes of formaldehyde fixation, alcohol dehydration, paraffin embedding, serial sections and hematoxylin and eosin (H&E) staining. Subsequently, they were observed by a biological microscope (BX63, OLYMPUS, JAPAN).

2.2. Experimental setup

The creep tests were conducted by using a microcomputer control electronic universal material testing machine (HY0580, Shanghai Hengyi Testing Machine Co., Ltd., China), as shown in Fig. 1(a). The HY0580 is composed of a force sensor, a full digital AC servo motor, a high precision control