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Mechanical characterization of stomach tissue under uniaxial tensile action

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ABSTRACT

In this article, the tensile properties of gastric wall were investigated by using biomechanical test and theoretical analysis. The samples of porcine stomach strips from smaller and greater curvature of the stomach were cut in longitudinal and circumferential direction, respectively. The loading-unloading, stress relaxation, strain creep, tensile fracture tests were performed at mucosa-submucosa, serosa-muscle and intact layer, respectively. Results showed that the biomechanical properties of the porcine stomach depended on the layers, orientations and locations of the gastric wall and presented typical viscoelastic, nonlinear and anisotropic mechanical properties. During loading-unloading test, the stress of serosa-muscle layer in the longitudinal direction was 15–20% more than that in the circumferential direction at 12% stretch ratio, while it could reach about 40% for the intact layer and 50% for the mucosa-submucosa layer. The results of stress relaxation and strain creep showed that the variation degree was obviously faster in the circumferential direction than that in the longitudinal direction, and the ultimate residual values were also different for the different layers, orientations and locations. In the process of fracture test, the serosa-muscle layer fractured firstly followed by the mucosa-submucosa layer when the intact layer was tested, the longitudinal strips firstly began to fracture and the required stress value was about twice as much as that in the circumferential strips. The anisotropy and heterogeneity of mechanical characterization of the porcine stomach were related to its complicated geometry, structure and functions. The results would help us to understand the biomechanics of soft organ tissue.

1. Introduction

Minimally invasive surgery (MIS) is a focus and development trend of the surgery, due to these merits such as micro-traumatic, less bleeding, short wound healing time, rapid recovery after operation, and short hospitalization et al. (Bos et al., 2013; De et al., 2007; Marucci et al., 2000). However, minimally invasive devices such as forceps could cause soft tissue injury when clamping force is excessive, while small clamping force easily cause grasper and tissue slipping as dragging tissue operation. Hence, the safety operation at the interface of minimally invasive devices and soft tissue is necessary in the MIS. From the perspective of biomechanics, the biomechanics characteristics of soft tissue have very important guiding significance to study the interaction mechanism of minimally invasive devices and soft tissue. However, due to the complex geometry and structure of soft tissue, especially viscera organs, it is difficult to study their biomechanical properties.

The stomach is a multifunctional organ that controls nutrient and drug delivery to the intestines. It grinds, mixes, stores liquid and semisolid chyme, and releases content into the duodenum at a rate controlled by nutrient-stimulated duodeno-gastric reflexes (Horowitz et al., 1994; Pal et al., 2004). Therefore, the mechanical characterization of the stomach is essential to understand physiological functions of gastric accommodation and mechanosensation, or to provide mechanical data for the MIS operation on the stomach. On the investigation of the mechanical behavior of the stomach, some studies in animal and human stomach measured pressure-volume relations for evaluation of tone, compliance and tension in the gastric fundus by using a barostat (Azpiroz and Malagelada, 1985; Whitehead et al., 1997). The main assumptions made in these studies were that the mechanical properties in all directions and different layers were the same and that the wall was infinitely thin. Other studies on the stomach of the pig, rat and rabbit have demonstrated that the mechanical properties of the stomach are location-dependent, direction-dependent and species-dependent due to its geometric and structural complexity (Liao et al., 2005; Zhao et al., 2005, 2008). Egorov et al. (2002) reported that the tensile properties of the human cadaver stomach were the following: the values of maximal stress and destructive strain for stomach axial specimens were 0.7 MPa and 190%, for stomach transversal specimens

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were 0.5 MPa and 190%. In addition, some studies revealed the mechanical properties of the digestive organs. Lyons et al. reported that the porcine intestines showed a peak extrusion force ranging from 9 N to 14.8 N when pushed through a 13 mm hole in extrusion test, and similar extrusion properties between cleaned and uncleaned fresh porcine intestines were observed. Furthermore, viscoelastic testing (7.5 mm/min, 15 mm/min and 30 mm/min) showed little rate dependency in the extrusion properties for the porcine intestines (Lyons et al., 2013). Although the mechanical properties of the stomach have conducted in some researches, little current data is available about the influence of its anisotropy and heterogeneity on the biomechanical properties.

Therefore, in the present work, the uniaxial tensile properties of gastric wall at the different layers, orientations, and locations were investigated by using biomechanical test and theoretical analysis to study the mechanical anisotropy and heterogeneity of the stomach. The results would help us understand the biomechanics of soft organ tissue and provide experimental data to investigate the interaction mechanism of minimally invasive devices and soft tissue.

2. Materials and methods

2.1. Experimental materials

Excised fresh porcine stomach was chosen as an experimental model for this study due to its structural and functional similarity to the human stomach. The test stomach models were taken from three pigs of a local pig slaughterhouse. The weight of the pigs was about 140 kg and the age was18–20 weeks. The three stomach models were preserved in an icebox and transported to the laboratory within 1 h postmortem, and tested within 4 h after extraction to avoid dehydration. The stomach models were dissected along the middle of the smaller curvature and gently washed by using saline (Fig. 1). The stomach wall test samples were taken from the gastric smaller curvature and greater curvature. Then the stomach wall samples were cut into strips in the longitudinal direction (parallel to the direction of gastric mucosal fold of the greater curvature or the smaller curvature) and the circumferential direction (perpendicular to the direction of gastric mucosal fold of the greater curvature or the smaller curvature), respectively, as shown in Fig. 1. The strips were divided to two groups in the same sampling position of greater or smaller curvature. In order to study the mechanical properties of different layers of gastric wall, one group was separated into mucosa-submucosa layer and serosa-muscle layer, and another group was non-separated (Intact layer). Each group had three strip samples, and each strip was about 120 mm long and 10 mm wide. All samples were prepared and tested at a nominal room temperature of 20 ± 3 °C and relative humidity of 60 ± 5%. During the tests, the stomach strip samples were sprayed with physiological saline every half an hour to simulate their surface moisture in the body.

2.2. Experimental equipment

The biomechanical tests were carried out using a microcomputer control electronic universal material testing machine (HY0580, Shanghai Hengyi Testing Machine Co., Ltd., China), which was usually used to conduct the mechanical tests of soft tissues such as tensile, compression, laceration, peeling trial et al., as shown in Fig. 2. The HY0580 is composed of a force transducer (Transcell Technology Inc., America), a full digital AC servo motor (Panasonic MINAS A4 SERIES Corp., Japan), a high precision synchronous speed reducer and four differently shaped clamps. The force transducer's resolution is 0.01% and its measurement range is from 1 mN to 100 N. The displacement accuracy is ≤ 0.2% and the displacement range is up to 800 mm. The test speed range is 0.001 to 500 mm/min. It is fully computer-controlled and a sampling rate is at 50 samples per seconds to data files. The testing repeatable accuracy is ≤ 0.5%.

2.3. Experimental method

While testing, the stripe sample was fixed on the fixtures of the HY0580 (Fig. 2). Both ends of the stripe sample were wrapped

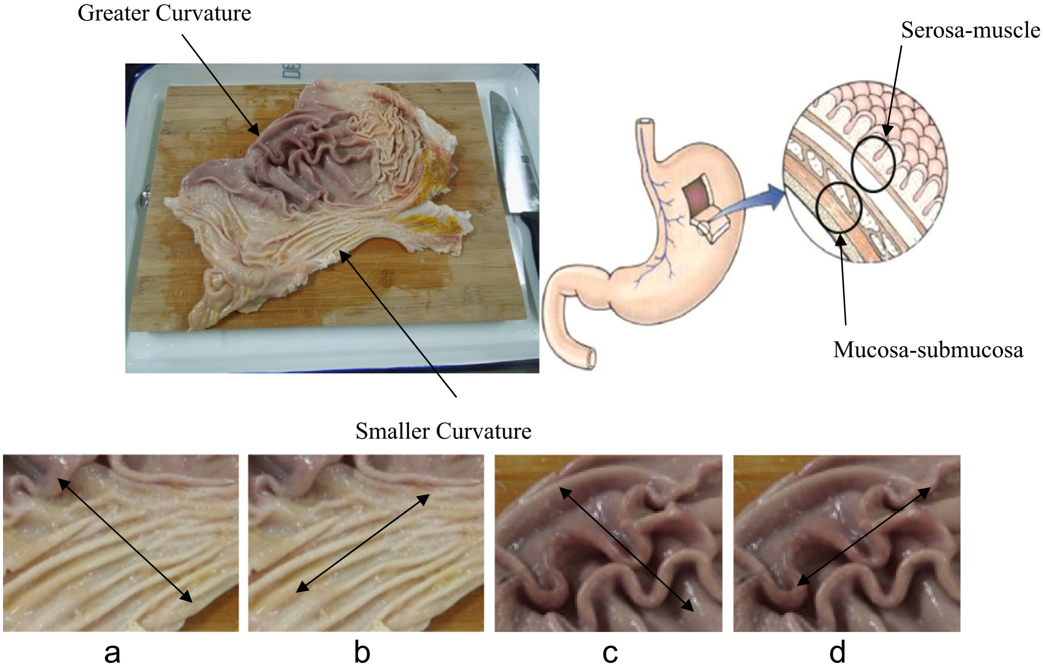

Fig. 1. Porcine stomach and gastric wall structure and the definition of circumferential and longitudinal direction, (a) Circumferential direction of smaller curvature, (b) Longitudinal direction of smaller curvature, (c) Circumferential direction of greater curvature, (d) Longitudinal direction of greater curvature.