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Research Paper

Biomechanical characteristics of the porcine denticulate ligament in different vertebral levels of the cervical spine—Preliminary results of an experimental study

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ABSTRACT

Background: Few studies exist on the mechanical properties of denticulate ligaments and none report the variation in these properties at different levels of the spine. The aim of this study was to perform an experimental determination of load–extension and stress–strain characteristics of the denticulate ligament and to establish if their properties change at different vertebral levels of the cervical spine.

Method: The study was carried out on a total of 98 porcine denticulate ligament samples dissected from seven fresh porcine cervical spinal cord specimens. All of the samples were subjected to an uniaxial tensile test at a speed of 2 mm/min, during which the load–extension characteristics were registered.

Results: The analysis revealed a decrease of the failure force in the caudal orientation indicated by significant differences between the C1 (1.04 ± 0.41 N) and C7 (0.55 ± 0.12 N) vertebral levels ($P = 0.037$). The average ultimate force that broke the denticulate ligaments was 0.88 N. The mean value of Young's modulus was 2.06 MPa with a minimum of 1.31 MPa for C7 and maximum of 2.46 MPa for C5.

Conclusions: The values of the denticulate ligament failure force in samples from different cervical vertebrae levels differ significantly. The presented data should be taken into consideration during numerical modelling of the human cervical spinal cord.

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1. Introduction

The denticulate ligament is an important anatomical structure, which stabilizes the spinal cord within the vertebral canal (Bilston and Thibault, 1996; Brieg, 1960; Panjabi and White, 1988; Parkinson, 1991; Tubbs et al., 2001). It is due to the connection between the side surface of the spinal cord and the spinal canal wall that the position of the central spinal cord can be maintained in the canal. In addition, the denticulate ligament prevents overloading of spinal nerve roots, which could occur during their excessive overstretching (Ceylan et al., 2012; Tubbs et al., 2001).

Each denticulate ligament is one of 18–20 triangular extensions of a narrow fibrous strip that extends from the craniovertebral junction to T12 and attaches to the dura at their apices. The apices of the extensions attach to the dura via fibrous bands at the cervical levels. Histological analysis revealed that the narrow fibrous strip of the ligaments features longitudinally oriented collagen fibres, whereas the triangular extensions are composed of transverse and obliquely oriented ones (Brieg, 1960; Ceylan et al., 2012; Tunturi, 1978).

The fundamental functions of the denticulate ligaments are recognised in the literature, where they are considered to take part in the spine's movements and belong to structures stabilizing the spinal cord. However, very few studies concerning mechanical properties of the denticulate ligaments are available and an extensive literature research revealed that a precise and detailed analysis of their biomechanical characteristics, such as load–extension and stress–strain characteristics, has not been conducted. In 2001, Tubbs et al. (2001) presented the results of an analysis of the influence the denticulate ligaments had on the movements of the spinal cord in the spinal canal subjected to an external force acting in the cranio-caudal direction. The authors showed that the ligaments had an effect on the stabilisation of the spinal cord in the three-dimensional space of the vertebral canal, particularly in the cephalo-caudal axis.

Furthermore, the motion capacity of the vertebral column varies along its length; the mobility of the cervical vertebrae is much higher than that of the thoracic or lumbar ones. Thus, the denticulate ligaments significantly differ in size and strength between particular cervical and thoracic levels of the human spinal cord (Ceylan et al., 2012). It may not be baseless to assume that some evident differences in their properties may be present even within one vertebral segment.

Establishing a reliable prognosis of the neurological outcome after spinal cord injury (SCI) and, subsequently, determining the therapeutic approach are difficult during the first hours following the trauma event. There are, however, studies suggesting the usefulness of the Finite Element Analysis (FEA) in the prediction of the neurological recovery after SCI (Czyż et al., 2012; Greaves et al., 2008; Maikos et al., 2008). The value of the distribution of mechanical loads after spinal cord injury was accepted by Panjabi and White (1988) as one of the main reasons for the severity of the neurological state. While examining mechanical properties of the spinal cord, Bilston and Thibault (1996) assumed the possibility of applying data obtained by them for research based on the FEA. Even though the spine and spinal cord have been subjects of interest for researchers engaged in numerical modelling, the role of the denticulate ligaments in spinal cord stabilisation has been omitted in existing models (Greaves et al., 2008; Hall et al., 2006; Ichihara et al., 2003; Li and Dai, 2009; Wilcox et al., 2004). Also, the assumptions that the denticulate ligament is an isotropic structure and that its properties are homogenous along the spinal cord are in contradiction with recent findings (Ceylan et al., 2012; Tubbs et al., 2001). The development of detailed and accurate spinal cord numerical models requires taking into account the mechanical properties of all the component structures in order to obtain reliable and appropriate results. Therefore, conducting a detailed analysis of the properties and biomechanical characteristics of the denticulate ligaments, which would provide vital data for further applications, is necessary.

The aim of this paper is the experimental determination of the load–extension and stress–strain characteristics of the denticulate ligaments through a tensile test, and evaluating the differences in their mechanical properties at different levels of the porcine cervical spinal cord.

2. Material and methods

2.1. Specimens

Due to the documented structural and functional similarity of the properties of human and porcine spinal cords (Sheng et al., 2010; Sparrey and Keaveny, 2009, 2011), porcine test material was used. Seven spines from 6-month old domestic swine were utilised with the consent of the local ethics committee. The animals were unified in respect of breed, weight, and age. The cervical region of the spinal cord together with the cervical dura mater was carefully dissected from the obtained material with the use of microsurgical tools. The samples were placed in 10 °C 0.9% NaCl solution for less than 24 h. A total of 14 samples of the denticulate ligament were obtained from each specimen of the cervical spinal cord by cutting the external attachments, along with a fragment of the dural sac and by cutting the meninges around the internal attachments (Fig. 1)—two from each segment, left and right. In total, 98 denticulate ligament samples were obtained.

2.2. Testing procedure

Uniaxial tensile testing was carried out on the Material Testing System Synergie 100 (MTS Systems, Inc., USA). In order to fix the specimens in the testing machine, the meninges, whose tensile strength is known to be 10–20 times greater than that of the ligaments (Mazgajczyk et al., 2012), were placed in jaws (Fig. 1) equipped with rubber rugged surfaces preventing slipping of the samples. Stretching at a test speed of 2 mm/min was performed until the sample's failure according to methodology applied previously by Mattucci et al. (2012). During each testing, the values of the tensile force, the displacement of upper jaw and the time