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Experimental methods for determining the material properties of human cervical spine

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Abstract:

Objective: The purpose of this paper is to investigate the experimental methods for determining the material properties of human cervical spine.

Method: A computer-based online search was undertaken to identify English articles about the material properties of human cervical spine. The retrieved keywords were "material properties, cervical spine". Based on the principles of reliability, advancement and efficiency, the obtained experimental methods and data were primarily examined, and the original source was retrieved to read the full-texts.

Results: Specimen preparation technique, test classification strategy and experiment setup of human cervical tissues were summarized and analyzed in this study. Besides, elastic modulus of various cervical spine cords were obtained by using the above experimental methods.

Conclusions: Researchers should apply different experimental methods to determine the material properties of different tissue materials in cervical spine.

Keywords: Neck injury, Material properties, Experiment setups, Neck modeling

1 Introduction

Neck injuries are among the most common injuries reported for automotive rear end impacts or trauma. Although these injuries are typically considered minor, their high incidence rate and often long-term consequences lead to significant societal costs. To better understand neck injury mechanisms, there is a need to develop a physical and mathematical model of the human neck. An integral step in the development of these models is the accurate description of the material properties of the human cervical spinal tissues.

The material properties of the biological tissue/structure such as spine are determined from various forms of experiments conducted on specimens. The reliability and usability of those experimental data rely on the accuracy of those experiments. The aim of this paper is to investigate experimental methods of mechanical properties of the cervical spine tissue including the specimen preparation, measuring methods, and test apparatus design.

2 Methods

2.1 Literature data analysis

A computer-based online search was undertaken to identify English articles about material properties of cervical spine published from January 1950 to 2011 in PubMed database. The retrieved keywords were "material properties, cervical spine". Meanwhile, a manual search of relevant journals and monographs was performed for the articles and data published in Chinese. Based on the principles of reliability, advancement and efficiency, the data were primarily examined, and the full-texts of the data source were read. The repetitive studies and reviews were excluded.

2.2 Characteristic constants of material property

For the solid material, the relationships between induced stresses (force per unit area) and the resulting strains (change in length or angle) for a particular material are expressed as proportionality constants which are termed elastic constants. The elastic properties of any given material may differ according to the direction in which testing is performed. If the properties are different in every direction the material is said to be anisotropic and has thirty-six elastic constants. If, however, there is one plane in which the elastic properties are the same in every direction on that plane, the material is said to be transversely isotropic and has only five elastic constants. Finally, if there is no directional dependence of the elastic properties (complete symmetry) the material is called isotropic and has only two elastic constants, which are referred to in engineering terminology as Young's modulus and Poisson's ratio. Young's modulus (E) or stiffness is the slope of a stress-strain curve obtained for uniaxial stress, or in other words, the ratio between stress and strain. Poisson's ratio (ν), which is defined as the negative of the ratio of transverse strain to longitudinal strain in the direction of uniaxial loading, is a measure of the material's ability to conserve volume when loaded in one direction. For example, in the usual response of an object its sides expand under a compressive load and contract under a tensile load. This response is Poisson's effect. Another elastic constant is the shear modulus (G), defined as the ratio of induced shear to the resulting shear strain. In the isotropic case this constant is dependent on Young's modulus and Poisson's ratio and is quite often determined from a torsion test. The shear modulus relates the angular distortion (shear strain) to the shear stress in the material. For further discussion of these material constants and their mathematical manipulation, the reader is referred to the works of Lekhnitskii[1] and Love[2].

If the characteristic constants of a material are affected by the rate of deformation, then the material exhibits viscoelastic behavior. All biological materials display at least some degree of viscoelasticity.

There are some other constants to characterize material properties of solid matter, such as strength, stiffness, hardness, and elastic energy. In materials science, the strength of a material is its ability to withstand an applied stress without failure. Yield strength refers to the point on the engineering stress-strain curve (as opposed to true stress-strain curve) beyond which the material begins deformation that cannot be reversed upon removal of the loading. It is the lowest stress that gives permanent deformation in a material. Ultimate strength refers to the point on the engineering stress-strain curve corresponding to the maximum stress. It is a limit state of stress that leads to failure. The applied stress may be tensile, compressive, or shear. Hardness is the measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied. Stiffness is the resistance of an elastic body to deformation by an applied force along a given degree of freedom (DOF) when a set of loading points and boundary conditions are prescribed on the elastic body. Elastic energy is the potential mechanical energy stored in the configuration of a material as work is performed to distort its volume or shape. Forces applied to elastic material transfer energy into the material which, upon yielding that energy to its surroundings, can recover its original shape.

For the hollow organ, fluid and loose tissues, the porosity, permeability, resistance, compliance and pressure are the measures to describe the properties of those tissues, such as the tissue encasing the CSF, blood vessel, and annulus of intervertebral disc. Porosity is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume. Tissue permeability characterizes the capacity of a tissue wall to allow the flow of small molecules. Resistance to flow must be overcome in order for fluid to circulate. Compliance is a measure of the tendency of a hollow organ to resist recoil toward its original dimensions upon removal of a distending or compressing force.

3 Results

3.1 Specimen preparation techniques

The specimens and preparation are the initial part of the experiment. Due to the shortage of human cadavers (ethical issues and sparsity of donor), animal is another source of the experimental specimens, the tissues of which are similar to the human's. Only a few investigators use the dry specimens for experiments while fresh specimens are used by the most of investigators, which are harvested from recently died cadavers and animals (normally restricted to less than 48 hours). The specimens harvested are wrapped in paper tissue and preserved in special liquid (saline solution, etc.) at a lower temperature to keep the tissues fresh, and this method of storage has been found to have no significant influence on the mechanical properties of the testing tissue[3]. Then it will be prepared by exciting the rest unrelated tissues when the test is beginning. The extraction and preparation of specimens should be very carefully, because the tissue is too small (millimetre-sized) and easily damaged. A precision diamond saw is used to ensure accuracy in the cutting of specimens. The diamond-edged circular saw is very thin and is set to rotate relatively slowly at speeds ranging from 150–250 rpm; this yields very flat cut surfaces and minimal damage to the tissue. During cutting, the blade and specimen are irrigated by saline water to minimise heat generation and its possible effects on the specimen. The specimens with different shapes (cylinder, rectangular, etc.) were produced using this procedure according to the need of experiments. Figure 1[4] and Figure 2[5] illustrate different shapes of specimens. The specimens were kept moist with saline solution throughout preparation and testing.

3.2 Test classification strategy

According to some previous published literatures, ultrasonic measurement and mechanical measurement are mostly used in the determination of material properties of tissues. Rho JY et al[6] determine the Young's modulus of individual trabeculae and micro-specimens of cortical bone cut to similar size as individual trabeculae with both method, ultrasonic technique and microtensile testing. However, it is much more popular to use the mechanical measurement to investigate the material properties of tissues. The mechanical measurement is always to take the changes on the index of tissues under out-side forces. According to previous literatures on determination of the material properties of human cervical spine, the test can be classified into three categories. 1) According to the forces applied on the specimens with different directions, the material properties of specimens are different between compression and tension. The forces applied on the specimens are always uniaxial. 2) The distinction between the destructive testing and non-destructive testing is the results of the tissue under the force. Destructive testing carried out to the specimens' failure, while the specimens are not damaged after the accomplishment of non-destructive testing. 3) Because of different strain rates the test fall into two classes (quasi static and dynamic). The strain rate of the quasi static test is approximately 0, thus in some literatures it is called static testing directly. The directions of the two class of tests on the specimens are different, such as circumferential and longitudinal. The material properties at circumferential direction are distinguished from that at longitudinal direction.

3.3 Experiment setups

In order to determine the material properties of spinal tissues, many different testing machines were used. Iatridis J C et al[4] obtained shear material properties of the annulus fibrous by using the shear testing apparatus illustrated in Figure 1. Cylindrical specimens were tested in torsional shear in a mechanical spectrometer (RM9-800, Rheometrics Scientific Piscataway, NJ, U S A). A parallel plate configuration was used with sintered stee1 porous platens (Figure 1). Static and dynamic shear tests were performed.

Drost M R et al[7] carried out uniaxial confined compression and swelling experiments on cylindrical specimens taken either in an axial or in a radial direction from a canine lumbar annulus fibrosis are presented. Figure 3 is the schematic view of the testing chamber. The mechanical load was applied to the tissue by the means of a conic impervious stainless steel piston (a), diameter 3.98 mm. The piston was greased with Vaseline to prevent leakage between the piston and the wall. The cylindrically shaped specimen (c), (diameter of the chamber 4.00 mm) rested on a sintered glass filter (d). The pore size of the glass filter was between 16 and 40 μm; its permeability, measured in a classic Darcy set-up was 10-12m4/(Ns). The loading arm was connected to a DC operated linear variable displacement transducer (LVDT, Schaevitz) interfaced by a Labmaster AD converter on an IBM-AT.

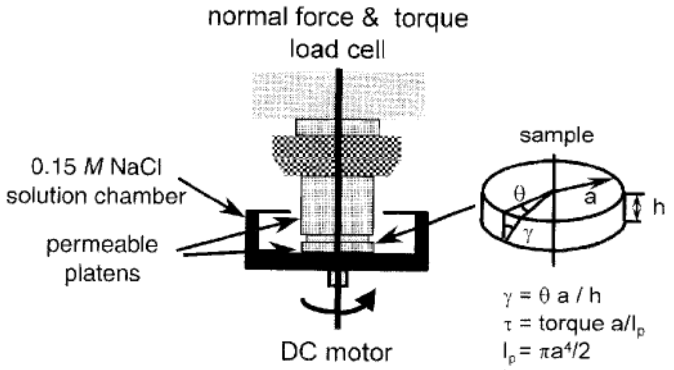

Figure 1. Shear testing apparatus and cylindrical specimens for shear strain and stress[4]

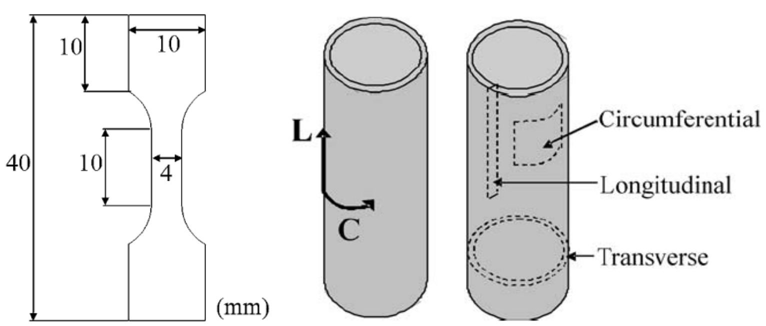

Figure 2. Left: specimen dimensions for uniaxial tensile testing; middle: longitudinal and circumferential specimen directions for mechanical testing; Right: where the histology sections were taken and how they were defined[5]

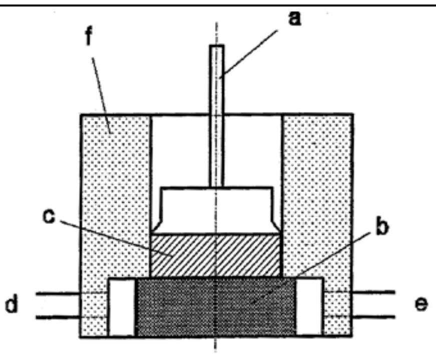

Figure 3. Schematic view of the testing chamber: (a) loading piston, (b) porous filter, (c) specimen, (d) fluid inlet, (e) fluid outlet, and (d) wall[7]

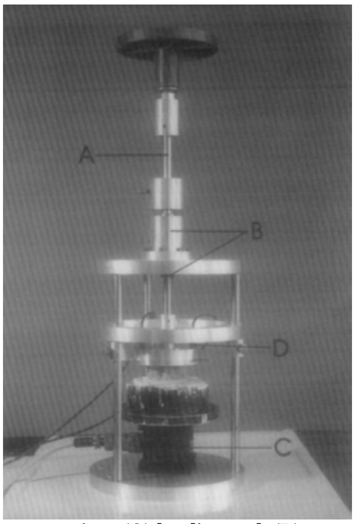

Figure 4. Apparatus for creep test in uniaxial compression: (A) loading rod, (B) ceramic linear bearings, (C) load cell, and (D) eddy current transducers[8]

Li S et al[8] accomplished creep test in uniaxial compression by utilizing the apparatus illustrated in Figure 4. An axial compressive load was applied by weights placed on the platform attached to a loading rod (A). The loading rod was inserted through ceramic linear bearings (B) in the center of the top plate to allow only axial deformation of the specimen. The specimen was placed on an AMTI multicomponent load cell (C) to monitor the reaction forces and moments acting on the specimen. Resultant axial displacement of the superior vertebral body was measured using two Kaman eddy current transducers (D) with resolutions of 1 pm. The cup holding the superior vertebral body served as the target for the transducers.

Maikos J T et al[9] tested spinal and cranial dura samples in uniaxial tension using a Bose/Enduratec ELF 3200 (Bose Corporation, Eden Prairie, MN) with a 1-N cantilever load cell (Measurement Specialties, Hampton, VA). A schematic of the setup and an image of a loaded sample are provided in Figure 5(C, D). Separate, thin plastic plates were secured to the actuator (via compression grips) and to the load cell (via a rigid bolt), which was calibrated with the plate in place. The two plastic plates were then positioned to be 10 mm apart. The ends of the dura sample were placed on the plastic plate and covered with a cyanoacrylate adhesive (Krazy Glue, Columbus, OH), and two additional, separate plastic plates were placed on top of the dura on each grip, sandwiching each end of the dura between the plastic plates and creating plastic-plastic as well as dura-plastic adhesion to prevent any slipping of the dura relative to the plastic plate. Small pieces of reflective plastic (glitter) were placed on each dura sample to measure strain uniformity.

Mazuchowski E L et al[10] obtained the tensile strength of the spinal cord and pia mater using a new method to peg the specimen absence of contact with gripper (Figure 6). Specimens were attached at each end to a stiff, wire mesh screen with 4.0 silk sutures. The mesh screens were attached via custom designed grips to a MTS 858 MiniBionix machine fitted with a 25-lb. load cell.

Bilston L et al[11] tested cervical spinal cord samples in uniaxial tension at moderate strain rate. Figure 7 is the schematic view of mounting of sample and testing apparatus. The sample was mounted at each end between two rigid plastic plates, with the use of fast curing cyanoacrylate adhesive. The plates were then gripped at the ends by pneumatic grips in the testing device to avoid the exertion of direct force on the specimen. The gauge length was measured between the plastic plates where the sample was glued. The upper grip was attached to a load cellular on the moving crosshead, which allowed measurement of force data during the test.

Ng H W et al[12] determined the material properties of human cervical spine ligaments using the experimental apparatus illustrated in Figure 8. To ensure rigid anchoring of bone within quick setting bondo mounts (Evercoat Z-Grip, Fibre Glass-Evercoat, Cincinnati, OH), two perpendicular thru-holes were drilled into each bone in which 19-gauge needles were inserted. Each mount contained an anchoring screw for subsequent attachment to the experimental apparatus. To increase the fixation of ALLs and PLLs to the bone, plastic plates were glued atop the ligament attachments and rigidly secured with machine screws. A custom apparatus was constructed to generate highspeed elongation of the bone-ligament-bone preparations. The apparatus consisted of a pneumatic cylinder (model 1.5 x 5 Allenair, Mineola, NY) supplied with compressed air via an air tank. Air flow from the tank to the pneumatic cylinder was controlled by a solenoid valve. A controlled gap in the system permitted the pneumatic piston to achieve sufficiently high speed before the onset of ligament elongation. Air flow caused movement of the piston rod, and therefore ligament elongation. Force was measured with a uni-axial load cell (667 N capacity, model LCCA-150, Omega, Stamford, CT). Elongation was measured using a Hall effect sensor (A3506LU, Allegro Microsystems, Worcester, MA) positioned between two magnets (13 x 13 x 5 mm, part no. PR28ES4187B, Dexter Magnetic, Billerica MA).

Bass C R et al[13] investigate the material properties of cervical spinal ligaments under fast strain rate deformations with the apparatus illustrated in Figure 9. The bone-ligament-bone complexes were potted in aluminum cups. Small wood screws were inserted into the bone on either side of the ligament and were used as an adherent to a 2-part urethane casting resin (Fast Cast; Goldenwest, Cedar Ridge, CA). The potted bone-ligament-bone complexes were mounted in a universal test machine (No. 8874; Instron, Inc., Canton, MA) for uniaxial tensile tests and were aligned with an X-Y positioning table in a superior-inferior orientation that represented physiologic conditions. The fixture was enclosed in an environmental chamber to maintain physiologic temperature (37.2C0±0.6C0) and humidity (>90%). The reaction force was measured at the fixed load cell inferior to the specimen.

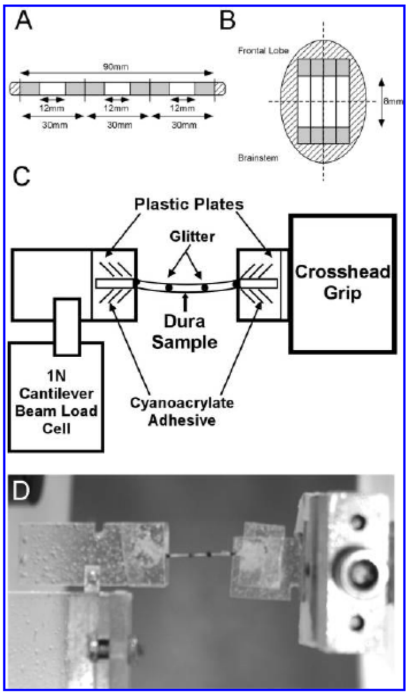

Figure 5. Description of samples and testing setup: (A) spinal sample, (B) cranial sample, (C) The dura samples were secured,and (D) A sample in the setup[9]

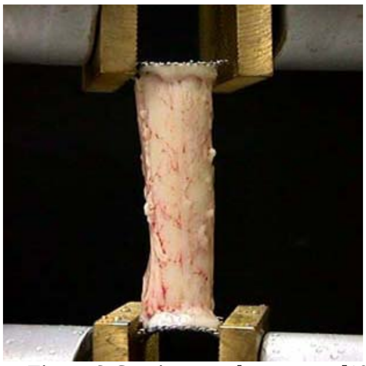

Figure 6. Specimen and apparatus[10]

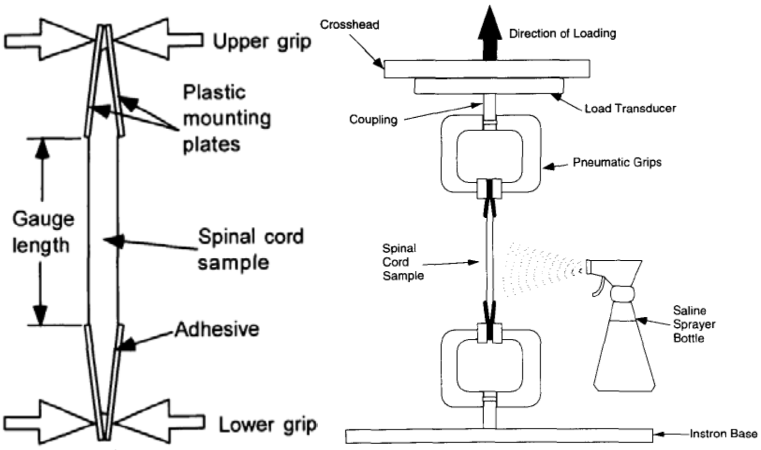

Figure 7. Left: specimen mounting procedure; Right: apparatus and specimen setup[11]

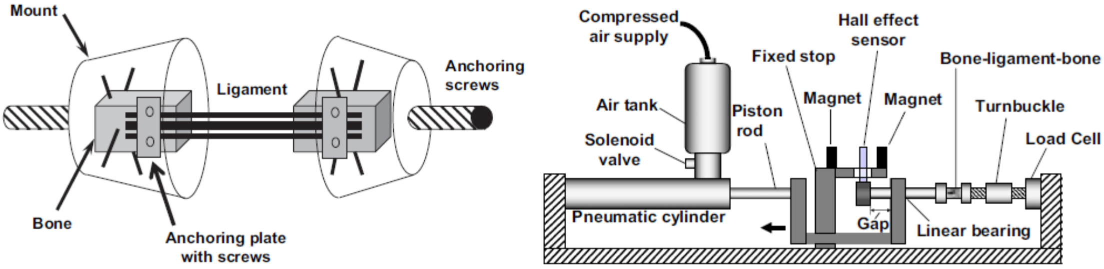

Figure 8. Left: schematic of bone-ligament-bone-preparation; Right: schematic of the experimental apparatus[12]

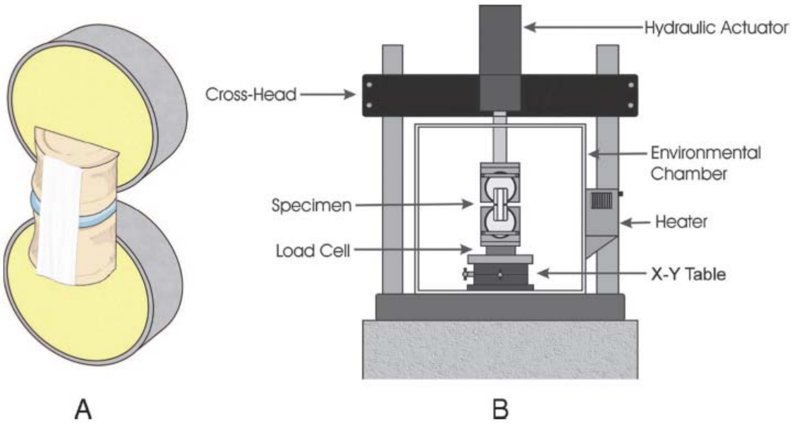

Figure 9. (A) Schematic illustration of an anterior longitudinal ligament prepared for mechanical testing by "potting" the bones in resin; (B) Schematic illustration of experimental apparatus[13]

3.4 Application of experimental methods

Here the above experiment methods were applied to determine Elastic's modulus of spinal cord and pia mater. As shown in Table 1, E is elastic modulus, En is neo-Hooken elastic modulus, G is tangent modulus. As to many viscoelastic materials, the cervical spinal cord and pia mater also display some viscoelasticity. Bilston, L. et al[11] elongated the spinal cord with intact pia mater with three different strain rates. The results suggested that the modulus of tissue increased with the increasing of strain rate (Table 1). The quasilinear viscoelastic model was developed to describe the viscoelastic behavior of the spinal cord tissue by them. The gray mater and white mater of spinal cord also exhibit viscoelasticity which had been researched by Ichihara K. et al[14]. The modulus of gray mater and white mater increased with the increasing of strain rates (Table 1).

Table 1. Elastic modulus of cervical spinal cord

Specimens	Elastic modulus (kPa)	Author
Human spinal cord + pia mater	En= 1400 (SEM 88)	Mazuchowski, E.L. et al[10]

Human spinal cord		En= 89 (SEM 21)	
Human pia mater		G= 600, 1200, 1800, 2400, 3000	Carolyn J et al[15]
Human spinal cord	Gray matter	G= 65, 90, 115, 140, 165	
	White matter	G= 65, 90, 115, 140, 165	
Human spinal cord + pia mater		0.068s-1 strain rate: E= 1020±750	Bilston, L. et al[11]
		$0.14s^{-1}$ strain rate: E= 1170±510	
		$0.21s^{-1}$ strain rate: E= 1370±390	
Rabbit spinal cord + pia mater		E= 16±5	Ozawa H et al[16]
Rabbit spinal cord		E= 5±2	
Rabbit spinal cord	Gray matter	E= 3	
	White matter	E= 3.3	
Rabbit spinal pia mater		E= 2300	
Rabbit spinal pia mater	Elastic fiber	E= 600	
	Collagen fiber	E= 1000	
Canine spinal cord + pia mater		A lower load: E= 16.8	Tunturi AR[17]
		A higher load: E= 11.9	
		$0.21s^{-1}$ strain rate: E= 1370±390	
Bovine spinal cord	Gray matter	30%stain, 0.5 s^{-1} strain rate: G= 64.5±18.1	Ichihara, K. et al[14]
		30%stain, 0.05 s^{-1} strain rate: G= 43.3±4.0	
		30%stain, 0.005 s^{-1} strain rate: G= 30.5±5.5	
	White matter	30%stain, 0.5 s^{-1} strain rate: G= 112.3±10.2	
		30%stain, 0.05 s^{-1} strain rate: G= 95.6±5.0	
		30%stain, 0.005 s^{-1} strain rate: G= 63.9±7.9	
Canine spinal cord		E= 260	Chang, G. L. et al[18]
		E= 265 (215~295)	Hung, T. K. et al[19]
Feline and canine spinal cord		E= 213~613	Chang, G. L. et al[20]
Feline spinal cord		E= 260	Hung, T. K. et al[21]
Surrogate cord		Tension: G= 261±18	Shannon G et al[22]
		Compression 5%~15% strain: G= 250±13	
		Compression 15%~25% strain: G= 417±12	
		Compression 25%~35% strain: G= 566±17	
		Compression 35%~45% strain: G= 830±30	
		Compression 45%~55% strain: G= 1366±57	
		Compression 55%~65% strain: G= 2595±58	
Human spinal cord		E= 125, 62.5	C. D. Bertram et al[23]
Feline spinal cord		Incremental modulus: 0~56000	Hung et al[24]
		Longitudinal modulus: 0~45000	
		Pseudo Young's modulus: 2400~3000	

4 Discussions and Conclusion

The experimental methods such as specimen preparation technique, test classification strategy and experiment setups of cervical tissue materials, developed by various research groups, were summarized and analyzed in this paper. Elastic modulus, neo-Hooken elastic modulus and tangent modulus of various cervical spine cords were obtained by using such experimental methods. The results indicated that researchers should apply different experimental methods to determine the material properties of different tissue materials in cervical spine. Perhaps, the methods and data reported in this paper are helpful to the development of the neck modeling and the understanding of neck injury mechanisms.

Acknowledgement

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