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Research Paper

Transversely isotropic material characterization of the human anterior longitudinal ligament

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ABSTRACT

The present work represents the first study to report transversely isotropic material parameters for the human anterior longitudinal ligament (ALL) in the thoraco-lumbar spine. Force-deformation data from multi-axial testing was collected from 30 cadaveric spine test specimens using an anisotropic quarter punch test technique. The experimental data was fit to a commonly used anisotropic soft tissue material model using an FEA system identification technique. The material model correlated well with the experimental response ($R^2 \geq 0.98$). The constitutive parameter values, as well as the nonlinear anisotropic stress–strain response of the ALL specimens are reported to facilitate application to biomechanical models (including finite element models) of the spine.

1. Introduction

Finite element analysis has become an important tool in understanding the biomechanical consequences of spinal degeneration, disease and treatment (Bowden, 2006). The accuracy of a finite element analysis relies heavily on the material models and parameters used to represent the spinal components, such as ligaments and bones. Therefore, it is important to utilize accurate and comprehensive material parameters for spinal ligaments to ensure model accuracy and utility (Weiss et al., 2005). This study focuses on the anterior longitudinal ligament, which runs along the anterior side of the entire vertebral column (see Fig. 1). Transection of this ligament has been shown to cause an increased loading in the adjacent vertebral bodies (Von Forell and Bowden, 2013) which could lead to bone or disc degeneration (Seligman et al., 1984) if damaged or removed. All ligaments are known to exhibit non-linear, anisotropic properties (White and Panjabi, 1990) and while the response of other spinal ligaments has recently been reported (Robertson et al., 2013; Bradshaw, 2011), the nonlinear anisotropic constitutive response of the ALL has not yet been defined in a way that allows it to be easily implemented in an FEA setting.

Previous work on characterizing the ALL has relied on uniaxial testing (Neumann et al., 1992; Yoganandan et al., 2000) and has primarily reported data on the ligament tensile

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Abbreviations: ASPT, anisotropic small punch test; AQPT, anisotropic quarter punch test; ALL, anterior longitudinal ligament; SSL, supraspinous ligament; ISL, intraspinous ligament

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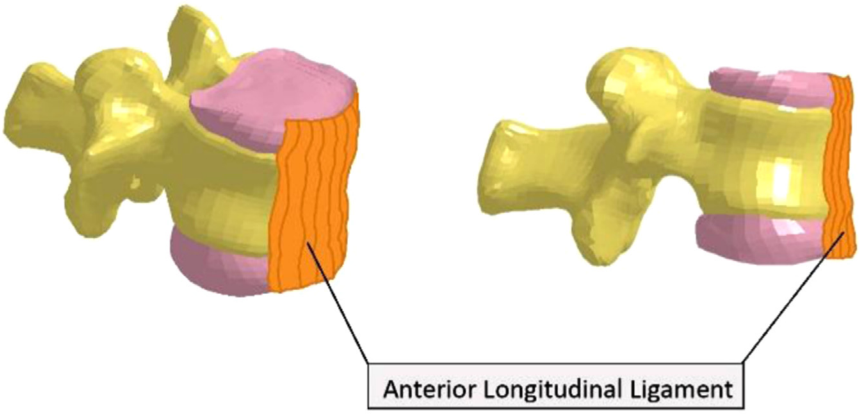

Fig. 1 – Location of the anterior longitudinal ligament on the vertebrae.

strength and Young's modulus (i.e., linear ligament stiffness) of the ligament. These quantities are useful when modeling the ligament as a linear elastic spring, which is common in many finite element models (Wu and Chen, 1996; Zhang and Bai, 2005; Panzer and Cronin, 2009). However, finite element modeling of other joints has demonstrated a significant increase in accuracy with more fidelic constitutive material models to represent the anisotropic, nonlinear properties of the ligament. This is particularly the case when the ligament is the main focus of the model and a three dimensional representation of ligaments is used (Robertson et al., 2013; Park et al., 2010). For these more fidelic models, additional constitutive parameters are necessary to completely define the material response of the ligament. Inclusion of nonlinear, anisotropic properties for spinal ligaments could similarly improve the fidelity of finite element models of the spine. However, to date, limited anisotropic material characterization data is available for spinal ligaments.

One of the impediments to acquiring anisotropic material constitutive parameters for spinal ligaments has been that traditional material testing techniques commonly require an entire functional spinal unit (ligament with 2 attached vertebrae) (Neumann et al., 1992; Myklebust et al., 1988). Additionally, independent samples are required in order to obtain off-axis properties of the ligament. Thus, priority is given to characterizing the dominant (fiber direction) properties. Recent work has been done in planar biaxial testing (Sacks, 2000; Nielsen et al., 1991), which represents a significant step forward in characterizing the anisotropy of soft tissues. Planar biaxial testing utilizes a square planar sample that is pulled along each edge of the sample, allowing collection of anisotropic data from a single sample. The boundary effects of this method limit the viable test region to a small central portion of the tissue (Cox et al., 2006) and thus require relatively large sample sizes (3–6 cm^2) (Sacks, 2000). Additionally, biaxial testing requires two inputs (longitudinal and transverse forces) and the results are dependent on the combination of these two inputs. In recent work, the anisotropic small punch test (ASPT) (Robertson et al., 2013) has been demonstrated to accurately characterize the nonlinear, anisotropic constitutive response based on a single multiaxial test of a single, very small testing specimen (e.g., 10 mm square samples with a 0.5 mm thickness). Additionally, a punch test captures an important mode of in vivo loading that is not obtained from uniaxial and biaxial planar testing techniques. In the present work, an alternative version of the ASPT known as the anisotropic quarter punch test (AQPT) is utilized to characterize the material constitutive behavior of the ALL. The AQPT eliminates the potential for the central punch of the ASPT to pierce the ligament, as well as a potentially higher discrimination between the deformation profiles of the orthogonal directions of the testing as compared to the ASPT.

2. Materials and methods

2.1. *Testing specimen preparation*

Two cadaveric spines (29 year old female, 80 lbs, 61 in. tall, 42 year old female, 145 lbs, 63 in. tall) were obtained from an accredited tissue bank following an IRB approved acquisition and testing protocol. Anterior longitudinal ligament segments were then individually excised from thoraco-lumbar spinal sections, flash frozen, and stored in a $-20\,^{\circ}$C freezer. Prior to testing, the ligaments were thawed and allowed to reach room temperature and sectioned approximately 2 mm thick using a microtome blade. Testing specimens with dimensions of 10×10 mm^2 were cut from the sectioned tissue. In total, 2 cadaveric spines yielded 30 viable testing specimens from 14 ALL ligament segments. Prior to testing, the exact thickness of each specimen was measured using calipers. During dissection, handling and testing, specimens were spritzed with an isotonic saline solution every 5–10 min to keep them hydrated. All testing was conducted at room temperature.

2.2. *Anisotropic quarter punch test*

The chosen test method is an advanced version of the anisotropic small punch test (ASPT) known as the anisotropic quarter punch test (AQPT). This method vertically displaces the inner portion of a quarter-circle shaped section of the testing sample using a motorized linear actuator while holding the outer portion fixed (see Fig. 2). Thus tension is produced in every direction of the 90° arc of the quarter circle