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Research Paper

Thoracolumbar spinal ligaments exhibit negative and transverse pre-strain

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ABSTRACT

The present work represents the first reported bi-axial spinal ligament pre-strain data for the thoracic and lumbar spine. Ligament pre-strain (in-situ strain) is known to significantly alter joint biomechanics. However, there is currently a lack of comprehensive data with regards to spinal ligament pre-strain. The current work determined the pre-strain of 71 spinal ligaments (30 anterior longitudinal ligaments, 27 supraspinous ligaments and 14 interspinous ligaments). The interspinous ligament and the anterior longitudinal ligament exhibited bi-axial pre-strain distributions, demonstrating they are not uniaxial structures. The supraspinous ligament frequently exhibited large amounts of negative pre-strain or laxity suggesting it makes no mechanical contribution to spinal stability near the neutral posture. Upon implementing multi-axial pre-strain results into a finite element model of the lumbar spine, large differences in spinal biomechanics were observed. These results demonstrate the necessity of accounting for ligament pre-strain in biomechanical models. In addition, the authors present a unique experimental method for obtaining ligament pre-strain that presents a number of advantages when compared to standard techniques.

1. Background

When the spine is in the neutral position, the spinal ligaments are not in a strain free state. However, virtually all experimental measurements of ligament material properties are referenced from an ex vivo, strain free, condition. To resolve this disparity and correctly interpret ligament material constitutive properties, knowledge of the in situ strain state (i.e. pre-strain) of the spinal ligaments is required. However, experimental measurement of pre-strain poses a number of challenges (Fleming and Beynnon, 2004) and a very limited amount of data is available describing the normal pre-strain state of the spinal ligaments. Consequently, spinal ligament constitutive properties derived in previous studies (Chazal et al., 1985; Dumas et al., 1987; Hindle et al., 1990; Hukins et al., 1990; Myklebust et al., 1988b; Panjabi et al., 1982; Pintar et al., 1992; Robertson et al., 2012) have yet to be fully exploited and finite element (FE) models used to investigate back pain and spinal stability suffer intrinsic inaccuracies (Weiss and Gardiner, 2001).

Ligament pre-strain affects both joint kinematics and load sharing within the intricate ligament networks that surround our joints (Mesfar and Shirazi-Adl, 2006; Shirazi-Adl and Moglo, 2005). Furthermore ligament pre-strain is thought to be responsible for spinal stability in the absence of active muscle contraction and tendon forces and it has been hypothesized that abnormal amounts of pre-strain may lead to spinal instability, back pain, and idiopathic spine diseases, such as scoliosis (Jiang et al., 1997). As such, characterizing the pre-strain distribution in spinal ligaments represents not only a crucial stepping stone to

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furthering our understanding of ligament mechanics, but a necessary element to improving the clinical treatment of back pain.

As previously stated the body of literature with regards to spinal ligament pre-strain is relatively small and there is much work left to be done. Previous researchers have shown that the anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL) and ligament flavum (LF) are pre-strained in the parallel fiber direction and that pre-stress in the spinal ligaments not only affects their own stress and strain state but overall spine biomechanics (Hagelstam and Aminoff, 1949; Hukins et al., 1990; Meyer, 1873; Nachemson and Evans, 1968; Petter, 1933; Tkaczuk, 1968). Additionally, differences in disc pressure have been measured when resecting the interspinous ligament (ISL) and supraspinous ligament (SSL), suggesting they are pre-strained (Hagelstam and Aminoff, 1949; Petter, 1933). However, quantitative studies describing the amount of pre-strain in the SSL and ISL have not yet been reported.

The methods employed by virtually all previous spinal ligament studies have limited them to strictly reporting uniaxial pre-strain. In addition, the majority of these studies were focused on deriving constitutive relationships; therefore the methods employed to measure pre-strain were not carefully described. In particular, the position of the spinal posture before removal of the ligaments was often undefined. Yet, ligaments are not uniaxial structures (Fleming and Beynnon, 2004; Robertson et al., 2012) and spinal posture influences the strain state of the spinal ligaments. While many ligaments such as the SSL may have only two distinct attachment points and thus predominately be loaded in a uniaxial fashion, both the ALL and ISL have multiple attachment points (Fig. 1). As such it is logical to assume they could exist in a state of bi-axial pre-strain, which would substantially alter their in situ stress state. Furthermore, one could expect to find nonhomogeous pre-strain in the ALL, where the pre-strain in the regions covering the bony vertebral bodies may be significantly different from the pre-strain in the regions where it integrates with the external fibers of the intervertebral disc (Bogduk, 2005).

To address these important questions the present work measured the multi-axial pre-strain state of the ALL and ISL and the uniaxial pre-strain state of the SSL. We hypothesized that both the ALL and ISL would exhibit bi-axial pre-strain distributions and that the amount of pre-strain in the ALL would be greater where it attached to intervertebral disc as compared to where it attached to the vertebral bodies. The effects of upper body weight on spinal ligament pre-strain were also investigated using a compressive follower load (Patwardhan et al., 1999). Results were implemented into a highly validated, non-linear, FE model of the lumbar spine to determine the effect of spinal ligament pre-strain on overall spinal mechanics.

2. Methods

2.1. *Experimental pre-strain measurements*

Freshly frozen cadaveric thoracolumbar spines (T1-S1) were acquired following an Institutional Review Board approved protocol. All adipose tissue, muscle, and fascia were removed to reveal the superficial spinal ligaments (ALL, SSL, ISL). The spine was then placed in an upright posture (sacrum angle $=50^{\circ}$ (Campbell-Kyureghyan et al., 2005; Jackson and McManus, 1994)) and manually exercised in flexion-extension, lateral bending, and axial rotation to establish the neutral posture (neutral position). The neutral position can be defined as the spinal posture in which the overall internal stresses in the spinal column and muscular effort to hold the spine erect are minimal (Panjabi, 1992). Once in the neutral position the spine was fused posteriolaterally using steel plates and pedicle screws, immobilizing the spine in that position. Multiple optical markers were then attached to each of the superficial spinal ligaments by inserting a minute amount of pigment (Prizm ink, Superior tattoo, Phoenix, AZ) just beneath the ligament surface using a 32 gauge needle. Two markers were created for the SSL, four for the ISL (one near each of its insertions) and 12 for the ALL (four rows of three). Fig. 2 displays the location of the fusion hardware and the marker patterns employed.

After creating optical markers, a small calibration block was placed on the surface of each ligament and a digital photograph (1080 pixels $\times$ 1080 pixels) was captured using a portable digital

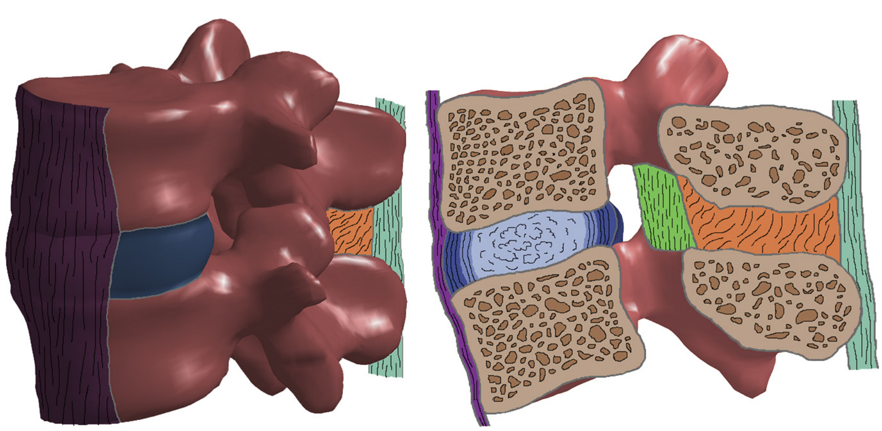

Fig. 1 – Attachment points of the interspinous ligament and anterior longitudinal ligament. It is hypothesized that the multiple attachment points of the ALL and ISL induce multi-axial pre-strain distributions. The ISL (orange) attaches to both the superior and inferior spinous processes (red) as well as to the SSL (blue) and LF (green). The ALL (purple) covers the anterior portion of the vertebral bodies and outermost fibers of the intervertebral disc.