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Human cervical spine ligaments exhibit fully nonlinear viscoelastic behavior

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ABSTRACT

Spinal ligaments provide stability and contribute to spinal motion patterns. These hydrated tissues exhibit time-dependent behavior during both static and dynamic loading regimes. Therefore, accurate viscoelastic characterization of these ligaments is requisite for development of computational analogues that model and predict time-dependent spine behavior. The development of accurate viscoelastic models must be preceded by rigorous, empirical evidence of linear viscoelastic, quasi-linear viscoelastic (QLV) or fully nonlinear viscoelastic behavior. This study utilized multiple physiological loading rates (frequencies) and strain amplitudes via cyclic loading and stress relaxation experiments in order to determine the viscoelastic behavior of the human lower cervical spine anterior longitudinal ligament, the posterior longitudinal ligament and the ligamentum flavum. The results indicated that the cyclic material properties of these ligaments were dependent on both strain amplitude and frequency. This strain amplitude-dependent behavior cannot be described using a linear viscoelastic formulation. Stress relaxation experiments at multiple strain magnitudes indicated that the shape of the relaxation curve was strongly dependent on strain magnitude, suggesting that a QLV formulation cannot adequately describe the comprehensive viscoelastic response of these ligaments. Therefore, a fully nonlinear viscoelastic formulation is requisite to model these lower cervical spine ligaments during activities of daily living.

1. Introduction

Human spinal ligaments are viscoelastic, exhibiting time- and history-dependent mechanical behavior [1–8]. These ligaments stabilize the spine, prevent excessive (harmful) movements and contribute to the three-dimensional spinal motion patterns [9]. The ligamentous spine is known to exhibit viscoelastic behavior when subjected to dynamic and static loading regimes [10]. Therefore, accurate viscoelastic characterization of spinal ligaments is requisite in order to investigate the time-dependent behavior of the spine via development of computational analogues, such as high fidelity finite element models [11].

In the lower cervical spine (C3–C7), the anterior longitudinal ligament (ALL) and the posterior longitudinal ligament (PLL) stabilize the spinal column, while the ligamentum flavum (LF) prevents potentially damaging hyperflexion motion. The ALL and PLL connect adjacent anterior and posterior aspects of the vertebral bodies, respectively, and the LF connects adjacent lamina. These ligaments are interesting to study due to their known contributions to cervical spine motion patterns and because they possess significantly different microstructures that produce unique mechanical responses. The longitudinal ligaments (ALL and PLL) have similar morphologies that consist of a large amount of highly oriented collagen fibers [1], with the cervical PLL dry weight consisting of 67.1% collagen and 5.9% elastin fibers [12]. Conversely, the LF has a 2:1 elastin-to-collagen ratio, with the collagen fibers demonstrating a very weak preferred orientation within the elastic ground substance [4].

Throughout the activities of daily living, cervical spine ligaments are subjected to multiple strain magnitudes and loading rates. Therefore, in order to develop computational models that accurately simulate in vivo time-dependent motions, a thorough empirical understanding of the ligament viscoelastic behavior at multiple magnitudes of physiological strain and loading rates is required. Additionally, empirical evidence must be used to justify the use of linear viscoelastic, quasi-linear viscoelastic (QLV) or fully nonlinear viscoelastic formulations within these physiological loading regimes. While previous work has characterized the viscoelastic behavior of ALL, PLL and LF by fitting experimental data to the QLV formulation [3], there has been no rigorous experimental investigation that has explicitly shown which viscoelastic theory is most appropriate for modeling the time-dependent behavior of these ligaments. In fact, there is growing evidence to support that both ligament [2,13–16] and tendon [17] tissues exhibit fully nonlinear viscoelastic behavior within their physiological loading regimes, which cannot be comprehensively described by linear or QLV formulations. Therefore, the aim of this study was to characterize the viscoelastic response of human lower cervical ALL, PLL

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and LF by performing stress relaxation and cyclic loading experiments at multiple amplitudes of physiological strain and loading rates (frequencies). These data will provide empirical evidence of the necessary viscoelastic formulation requisite to comprehensively model these ligaments.

2. Materials and methods

2.1. Specimen preparation

Eight C5–C6 vertebra–disc–vertebra functional spinal units (FSUs) were isolated from human cadaveric cervical spines (mean age 59 ± 9.2 years; 2 females/6 males) with no pre-existing bone or ligament pathology. After carefully removing all nonosteoligamentous tissue, each FSU was transected at the pedicles to separate the anterior and posterior elements (Fig. 1a). On the separated posterior elements, the LF was isolated into bone–ligament–bone (BLB) preparations by carefully transecting the interspinous and supraspinous ligaments, and by disarticulating the facet joints with a scalpel. The LF was easily distinguished from the surrounding tissue by its relatively large size and yellow color [18]. The ALL and PLL were separated by sawing through the mid-coronal plane of the separated anterior elements (Fig. 1a). The intervertebral disc and endplates were carefully removed from the superior and inferior vertebral body surfaces and from the longitudinal ligaments using a bone curette and a scalpel. This resulted in BLB preparations for the ALL ($n = 8$), PLL ($n = 8$) and LF ($n = 6$) (Fig. 1b). Two LFs were damaged during dissection and were excluded from this study. Tissue hydration was maintained during dissection via periodic saline spray.

Each BLB perpetration was potted in polymethylmethacrylate (PMMA) bone cement for attachment to the mechanical testing apparatus. To anchor the bony segments in the PMMA, wood screws were affixed to the superior and inferior surfaces of the cranial and caudal vertebral bodies, respectively, of the ALL and PLL BLB preparations, and to the superior and inferior surfaces of the articulating processes of the LF BLB preparations. During potting, consistent ligament alignment was ensured by affixing a wooden tongue depressor across the coronal cut surface of the longitudinal ligament BLB preparations (Fig. 1c) and across the transected pedicle surface of the LF preparations. Two additional tongue depressors were attached perpendicular to the previously affixed tongue depressor to longitudinally align the BLB preparation with the axis of loading (Fig. 1c). A custom apparatus was used to ensure alignment of the potting fixtures (Fig. 1d). During potting, the exposed portion of each BLB preparation was wrapped in saline-soaked gauze in order to maintain ligament hydration and to prevent thermal damage which could have resulted from the exothermic reaction of the PMMA hardening process. After the PMMA was fully cured, the wooden tongue depressors were removed and the potted BLB preparations were wrapped in fresh saline-soaked gauze, placed in a sealed bag, and stored at −20 °C until the day of testing. Similar storage methods have been shown to have a minimal effect on ligament cross-sectional area and viscoelastic properties [19], and have been recently used to characterize the viscoelastic properties of tendon [17].

All experiments were performed in an environmental chamber filled with physiological saline warmed to 37 °C to control for the effects of temperature [20] and hydration [21]. Temperature was monitored in real-time using the digital readout of a thermocouple placed near the specimen (Fig. 2). The environmental chamber was attached to a translation ($x - y$) table rigidly fixed to the base of a servo-hydraulic materials testing machine (Bionix 858, MTS, Eden Prairie, MN). A uniaxial load cell (500 N capacity, ±1.0% tolerance, model 661.11B-02, MTS, Eden Prairie, MN) was placed in the

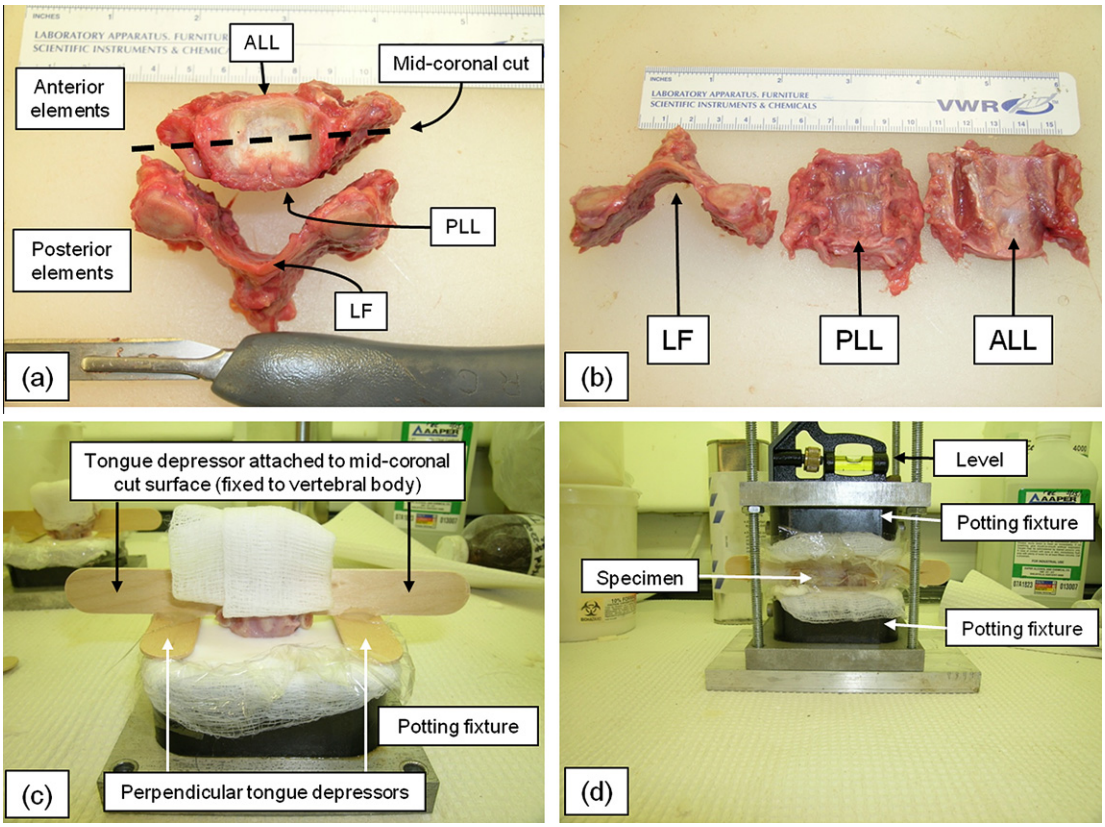

Fig. 1. Sequence of dissection and potting procedures. (a) To isolate the ALL, PLL and LF, each FSU was cut at the mid-coronal plane (dotted line) of the vertebral body and at the pedicles. (b) The resulting BLB preparations for the LF, PLL and ALL. (c) Wooden tongue depressors were attached to the BLB preparations to maintain alignment during the potting procedure. (d) Custom apparatus used to ensure fixture alignment during potting of adjacent bone.

ID	Title	Pages
978	Human cervical spine ligaments exhibit fully nonlinear viscoelastic behavior	10