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Characterization and prediction of rate-dependent flexibility in lumbar spine biomechanics at room and body temperature

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Abstract

BACKGROUND CONTEXT: The soft tissues of the spine exhibit sensitivity to strain-rate and temperature, yet current knowledge of spine biomechanics is derived from cadaveric testing conducted at room temperature at very slow, quasi-static rates.

PURPOSE: The primary objective of this study was to characterize the change in segmental flexibility of cadaveric lumbar spine segments with respect to multiple loading rates within the range of physiologic motion by using specimens at body or room temperature. The secondary objective was to develop a predictive model of spine flexibility across the voluntary range of loading rates.

STUDY DESIGN: This in vitro study examines rate- and temperature-dependent viscoelasticity of the human lumbar cadaveric spine.

METHODS: Repeated flexibility tests were performed on 21 lumbar function spinal units (FSUs) in flexion-extension with the use of 11 distinct voluntary loading rates at body or room temperature. Furthermore, six lumbar FSUs were loaded in axial rotation, flexion-extension, and lateral bending at both body and room temperature via a stepwise, quasi-static loading protocol. All FSUs were also loaded using a control loading test with a continuous-speed loading-rate of 1-deg/sec. The viscoelastic torque-rotation response for each spinal segment was recorded. A predictive model was developed to accurately estimate spine segment flexibility at any voluntary loading rate based on measured flexibility at a single loading rate.

RESULTS: Stepwise loading exhibited the greatest segmental range of motion (ROM) in all loading directions. As loading rate increased, segmental ROM decreased, whereas segmental stiffness and hysteresis both increased; however, the neutral zone remained constant. Continuous-speed tests showed that segmental stiffness and hysteresis are dependent variables to ROM at voluntary loading rates in flexion-extension. To predict the torque-rotation response at different loading rates, the model requires knowledge of the segmental flexibility at a single rate and specified temperature, and a scaling parameter. A Bland-Altman analysis showed high coefficients of determination for the predictive model.

CONCLUSIONS: The present work demonstrates significant changes in spine segment flexibility as a result of loading rate and testing temperature. Loading rate effects can be accounted for using

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IRB approval: All human cadaveric specimens were obtained and tested following an institutional research board–approved acquisition and testing protocol.

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the predictive model, which accurately estimated ROM, neutral zone, stiffness, and hysteresis within the range of voluntary motion.

Keywords: Spine; Loading Rate; Flexibility; Biomechanics; Viscoelasticity; Temperature

Introduction

Spinal biomechanical studies enhance our understanding of the healthy, injured, and aging spine [1,2]. These studies also provide target behavior for medical devices and validation criteria for analytical spine studies [2–10]. The flexibility method [11,12] has become a standard for testing spine biomechanics and involves applying a pure moment as the resulting motion is measured. Common flexibility parameters used to evaluate and compare biomechanical flexibility data from spinal studies include the segmental range of motion (ROM), neutral-zone stiffness (K), hysteresis (H), and various metrics for defining the ‘‘neutral zone’’ (NZ), where small changes in loading result in large changes in segmental motion [2–4,8,13–19].

Traditionally, researchers tested spinal flexibility by using a quasi-static, stepwise loading protocol, which involves applying the load in select increments of torque for a specified time period and measuring the position at the end of the time-step, therefore obtaining the static response of the segment at the respective positions. Researchers recently have adopted a dynamic spinal flexibility testing protocol that uses ‘‘very slow’’ continuous-speed loading rates [20–22], which provides a pseudo-static response of the spinal segment. Dynamic testing requires increasing complex testing equipment (eg, motors, load cells, data acquisition, and control systems); however, it also provides increased congruity with the in vivo kinesiology of the spine.

Temperature, compressive preload, and loading rate are known to affect the biomechanics of the functional spinal unit (FSU); however, the magnitude of these effects has not been comprehensively reported. The majority of reported spine biomechanics tests were performed at room temperature, without a compressive pre-load, and at different loading rates [1,8,11,15,16,21,23–28]. Past studies in which authors addressed either the temperature or rate dependence were conducted before the adoption of the compressive follower-load as a standard during testing [27,29–34]. Also, various types and rates of loading have been used in biomechanics studies [3–5,8,10,21,35]. Although these different factors are known to affect biomechanics, an objective comparison of the results is not possible while accounting for the different test methodology, which may significantly alter the observed mechanical response [1–7]. This paper presents a simple method to objectively compare the results for the different rates of continuous-speed dynamic loading.

Materials and methods

We have no study-specific conflicts of interest associated with the present work. In this study, we build on past work by characterizing the effects of spine segment loading rate while testing at body and room temperature with a compressive follower load. All three primary modes of loading are investigated by using both stepwise and dynamic flexibility testing. Flexion-extension flexibility is examined in substantially more detail by our investigation of 11 distinct loading rates with a redundant testing protocol to ensure repeatability. On the basis of these data, we have developed a stochastic model that uses a single flexibility test and accurately predicts the segmental flexibility of a lumbar spine segment at any rate within the range of voluntary motion rates.

A custom spine simulator capable of applying pure moment loads in each primary mode of spinal flexibility was used to perform all flexibility tests. It was based on designs published by Goertzen et al. [36] and is similar to previously reported simulators that provide ‘‘pure moment loading’’ [20,22,37,38]. The tester was substantially modified by the inclusion of a guided follower load, a multicamera three-dimensional motion tracking system, and an environmental chamber that is capable of maintaining the environment at desired settings of temperature at near 100% humidity. A LabVIEW (National Instruments Corporation, Austin, TX, USA) program was used with a torque sensor (TRT-200; Transducer Techniques, Temecula, CA, USA) to control a stepper motor (STP-MTRH-34127; Automation Direct, Atlanta, GA, USA) with a microstepping drive (STP-DRV-80100; Automation Direct). Post-hoc analysis of charged coupled device (ie, CCD) video (Basler Vision Technologies, Exton, PA, USA) provided three-dimensional position data, which was synchronized with the corresponding torque for describing the torque-rotation response.

Specimen preparation

Specimen preparation and testing followed published protocols [3,11,17,19–23,26,27,30,35,38–45]. Twelve human lumbosacral spines (T12-S5) with no known spinal disorders were obtained from an accredited tissue bank and cleaned of all extraneous soft tissue, leaving the intervertebral disc, spinal ligaments, and facet capsules intact. The lumbosacral spines were further segmented into 27 single-level FSU specimens. During dissection, each