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Short communication

Sagittal rotational stiffness and damping increase in a porcine lumbar spine with increased or prolonged loading

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ABSTRACT

While the impact of load magnitude on spine dynamic parameters (stiffness and damping) has been reported, it is unclear how load history (exposure to prolonged loading) affects spine dynamic parameters in sagittal rotation. Furthermore, it is unknown if both spine stiffness and damping are equally affected to prolonged loading. Using a pendulum testing apparatus, the effect of load magnitude and load history on spine sagittal rotational stiffness and damping was assessed. Nine porcine lumbar functional spine units (FSUs) were tested in an increasing compressive load phase (ICP: 44.85, 68.55, 91.75, 114.6 kg) and then a decreasing compressive load phase (DCP: 91.75, 68.55, and 44.85 kg). Each trial consisted of flexing the FSU 5° and allowing it to oscillate unconstrained. During the ICP, both stiffness and damping linearly increased with load. However, in the DCP, stiffness and damping values were significantly higher than the identical load collected during the ICP, suggesting load history affects sagittal rotational dynamic parameters. In addition, spine damping was more affected by load history than spine stiffness. These results highlight the importance of controlling load magnitude and history when assessing spine dynamic parameters.

1. Introduction

Several research groups have developed dynamic models of the spine to better understand the role of intrinsic properties (i.e., spine stiffness and damping) and/or motor control (i.e., reflexive contributions) in spine function (Franklin et al., 2008; Goodworth and Peterka, 2009; Lee et al., 2008; Moorhouse and Granata, 2007; Reeves et al., 2009; van Drunen et al., 2013). As these models become more comprehensive, there is a need to better define the intrinsic properties within the models, such as the rotational stiffness and damping coefficients of the osteoligamentous spine. The intrinsic properties of the osteoligamentous spine can be quantified through *in vitro* testing of a functional spine unit (FSU). Earlier experimental and modeling work has shown that an FSU can be described by a second order system, represented by rotational inertia, stiffness, and damping components (Crisco et al., 2007). However, this same work has also demonstrated rotational stiffness and damping are affected by changes in axial compressive loading (Crisco et al., 2007). Therefore, when developing models of the spine it is important to account for the effects of load magnitude on osteoligamentous stiffness and damping coefficients.

Furthermore, in addition to load magnitude, prolonged loading also appears to change spine biomechanical properties. With prolonged axial loading, disc height and hydration decrease over time (McMillan et al., 1996; O'Connell et al., 2011; Race et al., 2000) and are correlated with an increase in stiffness (Costi et al., 2002; Koeller et al., 1984; McMillan et al., 1996). Therefore, rotational stiffness and most likely damping coefficients will vary depending on previous load exposure (Keller et al., 1990).

The long-term goal of this line of research is to develop *in vitro* testing protocols to reliably assess osteoligamentous stiffness and damping in various planes of motion. Specific to this study, we will assess not only the effect of load magnitude on osteoligamentous rotational stiffness and damping in the sagittal plane, but also the effect of load history. Based on the work of Keller et al. (1990) who studied creep behavior in a porcine spine in the axial direction, we hypothesize that exposure to prolong loading will significantly increase both rotational stiffness and damping coefficients. A secondary objective of the study is to determine if changes in rotational stiffness and damping in the sagittal plane are equally effected by load history.

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2. Methods

2.1. Specimen preparation

Nine fresh-frozen porcine lumbar functional spinal units (three FSUs of each: L1-2, L3-4, L5-6) were used for this study. It has been shown that the porcine lumbar spine has similar anatomic and biomechanical properties to that of a human lumbar spine (Busscher et al., 2010; Dath et al., 2007; McLain et al., 2002; Wilke et al., 2011). Preliminary work by our group confirmed, as with human lumbar spines, porcine spines also increase stiffness and damping under compressive loading, suggesting that the porcine spine can be used as a surrogate. The FSUs were dissected of all musculature, leaving the osteoligamentous structures intact. After dissection, the superior and inferior portions of the FSU were potted in a polyurethane resin (BJB Enterprises Inc., Tustin, CA), such that the mid-transverse plane of the disc was parallel with ground and allowed for full range of motion of the FSU. The specimens were then wrapped in fresh saline soaked gauze, vacuum-sealed and stored at −20 °C. Ten hours before testing, the FSU was placed in a room temperature bath to thaw while still in a vacuum-sealed package. Once thawed, the FSU was removed from its package and rewrapped with fresh saline soaked gauze.

2.2. Testing apparatus

The pendulum design was based on Crisco et al. (2007), which has been shown to accurately predict sagittal rotational stiffness and damping for a known entity. The testing apparatus consisted of two main components: a pendulum arm and a support frame (Fig. 1). The inferior portion of the porcine FSU was mounted to the support frame and the superior portion of the FSU affixed to the pendulum arm. The pendulum arm's center of mass was aligned over the FSU center of rotation. At the bottom of the pendulum arm was a bar to mount weights. During *in vitro* testing, four sets of weights were used to apply axial compressive loads to the spine specimens, corresponding to load magnitudes of 44.85, 68.55, 91.75, and 114.6 kg. The corresponding rotational inertias about the center of mass of the pendulum arm with these weights were 3.07, 3.70, 4.17, 4.64 kg m^2, respectively.

2.3. Specimen testing procedure

FSUs underwent 1–2 preliminary trials to assess proper mounting and alignment. A trial consisted of rotating the pendulum arm about the FSU center of rotation in the sagittal plane, causing the FSU to flex to approximately 0.087 rad (5°). The FSU was then released, allowing the FSU to oscillate unconstrained. Each FSU was tested under a progressively increasing compressive load phase (ICP: 44.85, 68.55, 91.75, and 114.6 kg) followed by a decreasing compressive load phase (DCP: 91.75, 68.55, and 44.85 kg). At each load, 3 trials were performed with 1 min between each trial and 3 min between each load change. Specimens were sprayed with saline solution between each trial to prevent tissue dehydration.

A Visualeyez motion capture system (VZ3000, Phoenix Technologies Inc., Burnaby, BC, Canada) was used to track the 3-dimensional motion of the pendulum arm relative to the support frame. LEDs were placed on the pendulum arm (contiguous with the superior vertebra) and on the support frame (contiguous with the inferior vertebra). These markers were used to assess the relative position of the superior and inferior vertebrae. For all trials, LED positions were recorded at a rate of 100 samples per second. A custom-written program using MATLAB 7.12 (MathWorks, Natick, MA, USA) was used to calculate angular displacement of the FSU in the sagittal plane.

2.4. Data analysis

The rotation of the pendulum apparatus with the FSU was modeled in the sagittal plane (flexion/extension) to produce the fundamental dynamic equation of motion of the system, described by the homogeneous nonlinear differential equation

$$\left[J_{cm}+ml^2\right]\ddot{\theta}(t)+b\dot{\theta}(t)+k\theta(t)+mgl\sin\theta(t)=0 \qquad (1)$$

where J_{cm} (kg m^2) is the rotational inertia of the pendulum arm with weights about its Center of Mass (*CM*), m is the mass (kg) of the pendulum arm with weights, l is the radial distance from the *CM* to the FSU center of rotation, b is the coefficient of damping (N m s/rad) of the FSU, k is the stiffness (N m/rad) of the FSU, and g is gravity. The angular position, velocity, and acceleration of the pendulum are represented by θ (rad), $\dot{\theta}$ (rad/s), and $\ddot{\theta}$ (rad/s^2), respectively.

The damping ratio ζ and undamped natural frequency ω_n (rad/s) of the oscillating pendulum system were found using the general solution (Thomson, 1988) for a viscously damped freely vibrating system linearized for small angles

$$\theta(t)=e^{-\zeta\omega_n t}\left(C_1\sin\sqrt{1-\zeta^2}\,\omega_n t+C_2\cos\sqrt{1-\zeta^2}\,\omega_n t\right) \qquad (2)$$

The arbitrary constants, C_1 and C_2, are determined from the initial conditions of velocity (0 rad/s) and angular displacement (0.087 rad), respectively.

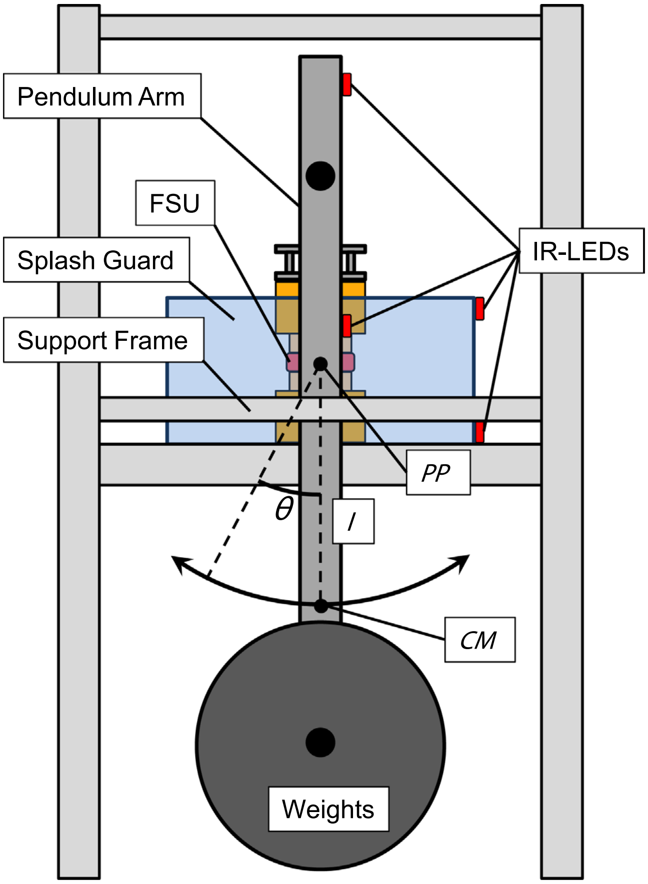

Fig. 1. Schematic drawing of a pendulum system for assessing stiffness and damping of a functional spinal unit (FSU). The length (l) from pendulum pivot (*PP*) to the center of mass of the pendulum arm with weights (*CM*) varied with amount of weight added and FSU anatomy.

The model kinematic response was produced using initial estimates for the four unknown parameters (see Fig. 2 for initial values: $\zeta, \omega_n, C_1, and C_2$). This model kinematic response was compared to the measured experimental kinematic response to produce an error term *e*. An iterative process ('fminsearch', MATLAB 7.12) was used to adjust the unknown parameters until *e* was minimized (see Fig. 2), thus representing the best fit between experimental and model kinematic responses.

Using the known system parameters (J_{cm}, m, and l) and fitted parameters (ζ and ω_n) from the general solution (Adams and Hutton, 1983), the sagittal rotational stiffness k and damping b of the FSU were calculated

$$k=\left(J_{cm}+ml^2\right)\omega_n^2-mgl \qquad (3)$$

$$b=2\left(J_{cm}+ml^2\right)\zeta\omega_n \qquad (4)$$

The known system parameters (J_{cm}, m, and l) were updated for each individual FSU and compressive load to obtain the unknown parameters (k and b).

2.5. Statistical analysis

Sagittal rotational stiffness k and damping b were estimated for each load magnitude in ICP and DCP and the mean value obtained from the 3 trials for each FSU. Using FSU mean stiffness and damping values, linear regression analysis was used to determine the linear relationship between stiffness and load as well as damping and load. Normality of data was tested using the Shapiro–Wilk test (Shapiro and Wilk, 1965) and equality of variance was tested using Tukey's test (Tukey, 1949). Level of significance was adjusted using the Bonferroni Correction to account for repeated testing effects (Dunn, 1961). The regression line was used to estimate two slopes: the change in stiffness with respect to load (S) and the change in damping with respect to load (D).

The effect of load history on the dynamic parameters of a FSU were assessed by comparing the ICP slopes of stiffness (S_{ICP}) and damping (D_{ICP}) with DCP slopes of stiffness (S_{DCP}) and damping (D_{DCP}). Paired *t*-tests (Student, 1908) were used to determine if the slopes of stiffness and damping were greater for ICP than DCP. In addition, for each load magnitude, rotational stiffness k and damping b were compared between