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# The dynamic flexion/extension properties of the lumbar spine *in vitro* using a novel pendulum system

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**Abstract**

The biomechanical properties of the ligamentous cadaver spine have been previously examined using a variety of experimental testing protocols. Ongoing technical challenges in the biomechanical testing of the spine include the application of physiologic compressive loads and the application of dynamic bending moments while allowing unconstrained three-dimensional motion. The purpose of this study was to report the development of a novel pendulum apparatus that addressed these challenges and to determine the effects of various axial compressive loads on the dynamic biomechanical properties of the lumbar functional spinal unit (FSU). Lumbar FSUs were tested in flexion and extension under five axial compressive loads chosen to represent physiologic loading conditions. After an initial rotation, the FSUs behaved as a dynamic, underdamped vibrating elastic system. Bending stiffness and coefficient of damping increased significantly as the compressive pendulum load increased. The apparatus described herein is a relatively simple approach to determining the dynamic bending properties of the FSU, and potentially disc arthroplasty devices. It is capable of applying physiologic compressive loads at dynamic rates without constraining the kinematics of the joints, crucial requirements for testing FSUs *in vitro*.


*Keywords:* Pendulum; Dynamic; Unconstrained; Biomechanics; Lumbar functional spinal unit

## 1. Introduction

During daily activities, the human spine functions dynamically under complex loading, including large compressive loads (Nachemson et al., 1986). Understanding how the spine responds to these loads is crucial to advances in the understanding of spinal mechanics, clinical care and surgical treatment. The majority of studies on spinal mechanics have focused on the *in vitro* biomechanical properties, either of spinal segments, functional spinal units (FSUs), or individual vertebrae, since studying the biomechanical properties of the spine *in vivo* is extremely difficult.

A variety of apparatuses and protocols have been employed to study the *in vitro* biomechanical properties of the spine (Edwards et al., 1987; Goel et al., 1988, 1995; Hirsch and Nachemson, 1954; Izambert et al., 2003; Janevic et al., 1991; Markolf and Steidel, 1970; Miller et al., 1986; Panjabi et al., 2000; Patwardhan et al., 1999; Schultz, 1979; Spenciner et al., 2003). Conventional protocols include displacement-controlled testing (Edwards et al., 1987; Goel et al., 1995), constrained, load-controlled testing (Goel et al., 1985, 1995), and unconstrained, load-controlled testing (Goel et al., 1988; Panjabi, 1977, 1988; Wilke et al., 1994, 2001). However, experimental design constraints in these protocols have limitations in determining the mechanical properties of the spine. Displacement-controlled testing can lead to unwanted specimen damage since failure loads are easily reached in certain directions, even with minimal displacement. More importantly, the motion of the spine is constrained to the degree of freedom of the displacing actuator. Load-controlled testing has the advantage of readily applying compressive loads. However, if the spine specimen undergoes large deformations, such as those associated with multiple-level testing, bending moments applied to the spine become a function of the ensuing

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motion and the spine level. Several studies, therefore, have focused on the application of pure moments in an attempt to improve load-controlled testing. For the moment to remain pure, the apparatus must be designed such that the point of application does not restrict or constrain motion. Several systems have been developed to apply moments in an unconstrained fashion, however, these systems perform only quasi-static loading (Grassmann et al., 1998; Schultz, 1979; Wilke et al., 1994). A method for applying physiologic compressive preloads under dynamic loading conditions has been described, but is limited to extension and flexion motions (Patwardhan et al., 1999). Given the complex kinematics and the dynamic nature of the spine, an apparatus that is cost effective and capable of applying both physiologic compressive loads and a variety of dynamic bending moments without constraining the motion of the FSU would be a significant advance. A pendulum system has the potential to meet these goals.

A pendulum system with the interphalangeal joint as a fulcrum was first used to study synovial joint lubrication (Jones, 1936). Charnley (1959) used a pendulum to assist him in the design of his artificial hip joints, while Unsworth et al. (1975) used a pendulum with the ability to apply sudden loads to demonstrate the various modes of joint lubrication. Although the intervertebral joint is not a synovial joint, and though no work has recently been done with this methodology, the use of a pendulum system to examine the mechanical behavior of the spine is attractive. A pendulum allows for the application of physiologic compressive loads, the dynamic application of bending moments, and unconstrained motion thereby providing a realistic simulation of *in vivo* loading conditions. To our knowledge, no study has previously reported the dynamic *in vitro* biomechanical properties of FSUs utilizing various loads with unconstrained motion. The purpose of this study was to determine the dynamic, *in vitro* mechanical response of cadaver lumbar FSUs under various axial compressive loads, using a novel unconstrained three-dimensional pendulum system.

## 2. Methods

### 2.1. Specimen preparation

A total of five thoracolumbar FSUs (three from level T12/L1, one from level L2/L3, and one from level L4/L5) were obtained from four unembalmed human spines (average age $57.3 \pm 9.9$ years). FSUs were prepared by removing all residual musculature but leaving the ligamentous structures intact. Both the superior and inferior vertebrae were cast in a urethane-molding compound within 89 mm diameter cylindrical aluminum potting cups. To provide secure fixation while maintaining full range of motion of the facets, the vertebral bodies were potted to the pars interarticularus. Specimens were kept frozen until the day of testing, at which point they were completely thawed. During testing, the FSUs were kept moist with saline-soaked gauze. For this study, the coordinate system comprised three orthogonal anatomic axes with the origin at the intersection of the mid-sagittal plane of the disc, the mid-transverse plane of the disc, and a frontal plane posterior to the anterior wall of the disc by $\frac{2}{3}$ of the disc depth. The axes were considered positive with respect to the specimens' left ($+X$), superior ($+Y$), and anterior ($+Z$) directions.

### 2.2. Pendulum apparatus

A novel pendulum apparatus was built with the intervertebral disc of the FSU serving as an unconstrained fulcrum (Fig. 1). The lower vertebral body was mounted via its potting cup to a rigid platform. The pendulum (steel square tubing, 3.81 cm × 3.81 cm) was mounted to the upper vertebral body via its potting cup. The pendulum was an open rectangular shape (66 cm long × 23 cm wide) oriented in the frontal plane. This open shape permitted the pendulum to be mounted to the FSU with its weights directly below the FSU.

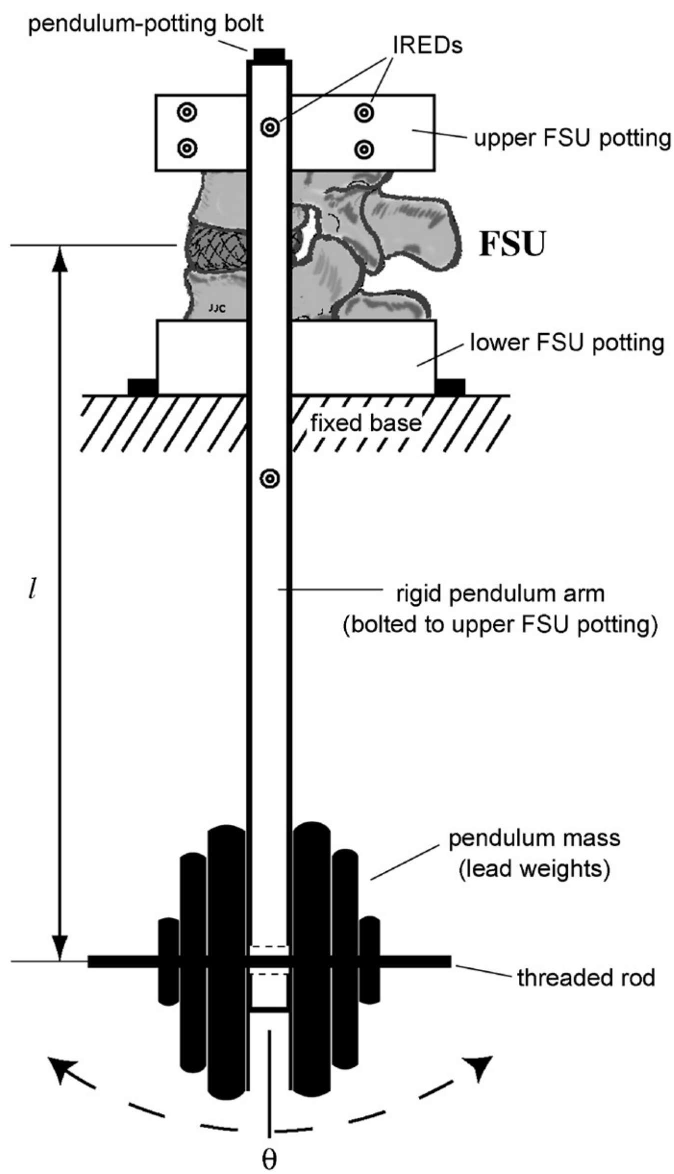


Fig. 1. Schematic of the pendulum apparatus showing the lower potted vertebra rigidly fixed and a pendulum arm fixed to the upper potted vertebra so that the intervertebral joint served as the fulcrum. The length of the pendulum ($l$) was fixed and the compressive load applied to the FSU was varied by changing the weight of the pendulum mass. The pendulum was set in motion by manually rotating it to 5° in extension and then releasing it. The three-dimensional motion of the pendulum ($\theta$) was tracked using the infrared-emitting diode (ired) markers and the relative motion of the upper FSU with respect to the lower FSU calculated.