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Is intervertebral disc pressure linked to herniation?: An in-vitro study using a porcine model

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ABSTRACT

Approximately 40% of low back pain cases have been attributed to internal disc disruption. This disruption mechanism may be linked to intradiscal pressure changes, since mechanical loading directly affects the pressure and the stresses that the inner annulus fibrosus experiences. The objective of this study was to characterize cycle-varying changes in four dependent measures (intradiscal pressure, flexion–extension moments, specimen height loss, and specimen rotation angle) using a cyclic flexion–extension (CFE) loading protocol known to induce internal disc disruption. A novel bore-screw pressure sensor system was used to instrument 14 porcine functional spinal units. The CFE loading protocol consisted of 3600 cycles of flexion–extension range of motion (average 18.30 (SD 3.76) degrees) at 1 Hz with 1500 N of compressive load. On average, intradiscal pressure and specimen height decreased by 47% and 62%, respectively, and peak moments increased by 102%. From 900 to 2100 cycles, all variables exhibited significant changes between successive time points, except for the specimen posture at maximum pressure, which demonstrated a significant shift towards flexion limit after 2700 cycles. There were no further changes in pressure range after 2100 cycles, whereas peak moments and height loss were significantly different from prior time points throughout the CFE protocol. Twelve of the 14 specimens showed partial herniation; however, injury type was not significantly correlated to any of the dependent measures. Although change in pressure was not predictive of damage type, the increase in pressure range seen during this protocol supports the premise that repetitive combined loading (i.e., radial compression, tension and shear) imposes damage to the inner annulus fibrosus, and its failure mechanism may be linked to fatigue.

1. Introduction

Approximately 40% of low back pain (LBP) cases are attributed to internal disc disruption (Dammers and Koehler, 2002; DePalma et al., 2011; Schwarzer et al., 1995), which is characterized by damage to the internal structure of the intervertebral disc (IVD) and is a precursor to herniation and other degenerative disc diseases (Adams et al., 2003; Bogduk and Twomey, 1991). LBP due to internal disc disruption is significantly more prevalent in middle-aged adults, which is representative of North America's workforce population (DePalma et al., 2011; Statistics Canada, 2014). Therefore, understanding the mechanism that initiates internal disc disruption may be the key to minimizing the risk of chronic LBP through early detection and intervention.

Patients with LBP have demonstrated higher levels of stress in annulus tissue and lower nucleus pulposus pressure profiles on discography, indicating that the initial changes may be linked to intradiscal pressure (McNally et al., 1996). This high stress profile has been suggested to occur due to a decrease in intradiscal pressure, which subsequently leads to inward collapse or buckling of the inner annulus, causing increased radial strain on the outer annulus (Adams et al., 2003, 2000; McNally et al., 1996; Tanaka et al., 1993). A decrease in pressure may occur as a result of disc degeneration (Adams et al., 1996; Nachemson, 1981) or pre-existing endplate damage (Adams et al., 2000, 1996; Holm et al., 2004). A study comparing human discs at different stages of degeneration found that Grade III and IV discs had a 30% reduction in hydrostatic pressure and higher stress peaks in the posterior annulus (Adams et al., 1996). Several studies where endplate

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damage was induced have also exhibited 25–30% reduction in intradiscal pressure (Adams et al., 2000; Holm et al., 2004), and the cyclic loading after fracture caused further intradiscal pressure reduction and peak stress increases in the annulus (Adams et al., 2000). The results from finite element models also support this cascade of events where a decrease in pressure increases compressive loads carried by lamella, leading to inner annulus fibrosus instability (Argoubi and Shirazi-Adl, 1996; Schmidt et al., 2013; Shirazi-Adl, 1992). As evidenced by this body of literature, there is a link between intradiscal pressure and internal disc disruption; however, it remains unknown how mechanical loading directly influences intradiscal pressure and subsequently initiates inner annulus fibrosus disruption.

The purpose of this study was to characterize intradiscal pressure, flexion–extension moments, specimen height, and specimen rotation angle during a cyclic flexion–extension (CFE) loading protocol known to induce internal disc disruption (Callaghan and McGill, 2001; Drake et al., 2005; Tampier et al., 2007; Yates et al., 2010). An alternative method of measuring intradiscal pressure that does not induce annular damage during instrumentation – a bore-screw pressure sensor system based on prior IVD work (Schechtman et al., 2006; Schollum et al., 2008; Simunic et al., 2004; Veres et al., 2009, 2008) – was adapted, fabricated, and used in this study. Following the CFE loading protocol, the functional spinal unit (FSU) was dissected and morphology of the discs was examined.

2. Methods

2.1. Bore-screw pressure sensor system preparation

A custom fabricated bore-screw pressure sensor system was used to monitor intradiscal pressure throughout mechanical testing. Details of the bore-screw pressure sensor validation process can be found in the Supplementary Material. The system consisted of a hydraulic pump filled with hydrated silica gel (Veres et al., 2009), a high-pressure valve, a steel bore-screw, and a pressure sensor (Fluke PV350, Fluke, Everett, WA) (Fig. 1). The steel bore-screw was filled with nucleus pulposus that was harvested from adjacent IVDs using a syringe. The remainder of the system was primed with the hydrated silica gel. The steel bore-screw was first inserted into the FSU (see Section 2.2), and the hydraulic pump was completely detached from the enclosed pressure system (see Section 2.3) prior to mounting the specimen in a modified materials testing system for mechanical loading.

2.2. Specimen preparation and instrumentation

Fourteen porcine cervical FSUs (5 C3-C4 and 9 C5-C6), each consisting of two adjacent vertebrae and the intervening IVD, were used in this study. The porcine cervical spine has similar anatomical and functional structures to human lumbar spines while providing better control over age, gender, and activity level (Yingling et al., 1999). In terms of IVD structure, porcine cervical discs have similar collagen composition, number of lamellae, and fiber orientation to human discs (Tampier, 2006). The specimens were obtained immediately following death and stored at -20 °C. Prior to testing, frozen specimens were thawed at room temperature for approximately 12 h. Excess muscle was removed from each specimen, leaving only the osteoligamentous structure for testing. The longitudinal ligament and facet joints remained intact. The specimens were misted with a 0.9% saline solution to avoid dehydration during the experiment.

Prior to potting the specimen in the aluminum cups, a pilot hole was drilled longitudinally from the approximate center of the exposed inferior cartilaginous endplate of the caudal vertebra. The specimen was drilled using a 3.2 mm drill bit, followed by a 4.8 mm drill bit, using a hand drill. Drilling was stopped immediately once resistance from the endplate was perceived. The steel bore-screw filled with nucleus pulposus was then threaded through one of the aluminum cups and was inserted along the same path as the pilot hole until its distal end reached the surface of the superior cartilaginous endplate of the caudal vertebra. To ensure proper placement of the bore-screw within the cavity of the nucleus (located at the approximate center and through the surface of the superior endplate of the caudal vertebra), an x-ray was taken (Mercury Modulator X-Ray) and viewed digitally using a Kodak Direct View CR 500 prior to the CFE protocol (Fig. 2) and visually examined following the CFE protocol during dissection. The cranial vertebra was then fixed in another aluminum cup using the wood screw. Non-exothermic dental stone (Denstone®, Miles, South Bend, IN) was used to ensure fixation of the cranial and caudal vertebrae in their respective aluminum cups. Once the dental stone set, the specimen in the aluminum cup was properly secured to the rest of bore-screw pressure sensor using a T-joint (Fig. 2).

2.3. Baseline pressure setting

Prior to mounting each FSU into the modified material testing system, the baseline (unloaded) pressure within the IVD was set at approximately 0.15 MPa, which was measured with the Gaeltec needle pressure sensor during the pilot stage, to replicate the existing pressure present before the nucleus was breached by the bore-screw system. A hydraulic pump was used to increase pressure, and once the desired pressure was obtained, a high-pressure valve was locked and the pump was detached from the closed system.

2.4. Specimen conditioning procedures

The testing apparatus used for specimen conditioning and the CFE protocol was designed to allow the center of rotation of FSU to be aligned with the geometric center of IVD (Fig. 3). The compressive force was applied in load control using a servo-hydraulic materials testing system (8872, Instron, Canton, MA), and pure-moment was applied simultaneously in the sagittal plane in position control using an independent brushless servomotor (AKM23D, Danaher Motion, Radford, VA) connected in series with a torque cell (T120-106-1K, SensorData Technologies, Sterling Heights, MI). The caudal vertebra (fixed in a bottom aluminum cup) was secured to a rigid platform, which provided space for the pressure system to fit in. The caudal vertebra was free to translate via a bearing surface in the anterior–posterior and medial–lateral directions, which enabled the center of rotation to translate within the joint.

Specimen conditioning procedures consisted of applying a preload, performing a passive flexion–extension (PFE) test, and determining maximum flexion and extension angles to define the test range of motion. A 300 N static compressive load was applied for 15 min to reduce any post-mortem swelling. The average (SD) intradiscal pressure at the beginning of this load application was 0.53 (0.09) MPa. During this preload phase, the angular position with minimal resistive moment was established as the FSU's neutral position.

A PFE test was performed through a sagittal range of motion, and the passive flexion–extension/moment relationship was determined. In each test, a 300 N compressive load was applied and three cycles of PFE were completed at a rate of 0.5 degrees per second. The applied moment and angular displacement were sampled at 15 Hz using custom software. The direction of loading was reversed when the peak flexion–extension moment reached ± 6 Nm from the baseline value. From the data obtained during the PFE test, flexion and extension limits were defined (Thompson et al., 2003) using a 400% of neutral zone boundary criterion (average (SD) range of motion of 18.30 (3.76) degrees). Given that the failure occurs with a flexion angle of 39 degrees and the bending moment of 61 Nm in porcine

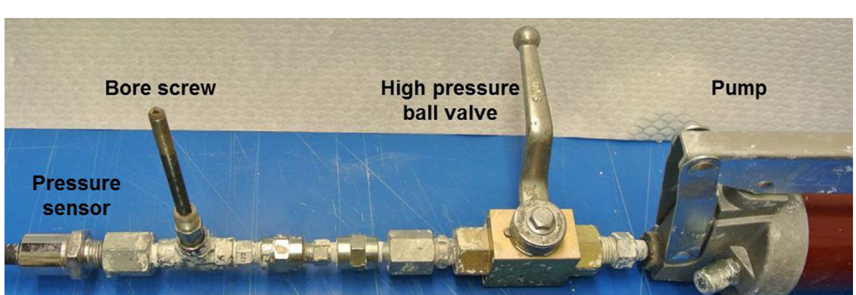

Fig. 1. Bore-screw pressure measurement sensor system design.