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Disc height loss and restoration via injectable hydrogel influences adjacent segment mechanics in-vitro

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ABSTRACT

Background: Height loss can have a profound influence on the local mechanical environment of the disc. While disc height loss is incorporated into scales of degeneration, its direct influence on spine kinematics is unclear. Further, there is a need for minimally invasive techniques to restore disc height; injectable hydrogels are a potential solution. Tandem investigation of disc height loss and subsequent restoration will enhance understanding of spine dysfunction and aberrant movement.

Methods: Twenty porcine spine specimens with two functional segments were tested in repeated flexion and extension. Relative angular displacement of each segment was measured with full specimen disc height, disc height loss in one of the segments (superior or inferior), and disc height restoration via hydrogel injection.

Findings: Disc height loss decreased the range of motion at the affected segment and increased the range of motion at the adjacent segment. Relative angular displacement decreased at the affected segment by 13.8% (SD = 5.3%) and 4.5% (SD = 2.1%) for specimens with height loss in the superior and inferior discs respectively. Hydrogel injection was able to restore segmental kinematics to the pre-injury state, with 12.7% (SD = 5.5%) and 6.4% (SD = 4.2%) of motion regained at the affected segment for superior and inferior disc height loss specimens respectively.

Interpretation: Acute disc height loss reduces motion at an affected segment, while increasing motion at an adjacent segment in-vitro; relative motion appears to be governed by local stiffness. Injectable hydrogels show promise in their ability to restore kinematics to segments with disc height loss.

1. Introduction

There are few degenerative changes in the spine that create such a radical shift to the local mechanical environment as disc height loss. Disc height loss has the potential to involve the facet joints, nerve roots, and cause the annulus to bulge (Arbit and Pannullo, 2001); it has been characterized as an important biomarker in degenerative changes (Jarman et al., 2015). Current measures of disc degeneration use height loss as part of their grading criteria, but also include additional features such as hydration, distinction between nucleus and annulus, appearance of annulus, nucleus, endplate, and vertebral body, and presence of annular fissures/defects (Adams et al., 1986; Pfirrmann et al., 2001; Thompson et al., 1990). Determining the effect that disc height loss has on both affected and adjacent segments in sagittal plane movements will enhance understanding of the functional limitations of an easily identifiable feature.

Injectable hydrogels are a unique method to restore disc height and the injection procedure is minimally invasive. There has been little assessment of these materials under flexion/extension motions, a critical daily movement for the spine. An injectable hydrogel has been developed that is composed of poly(N-isopropylacrylamide) grafted with poly(ethylene glycol) (PNIPAAm-PEG) (Vernengo et al., 2008). Aqueous solutions of PNIPAAm-PEG undergo a phase transformation at a lower critical solution temperature (LCST) around 33 °C. Below the LCST, the polymer is hydrophilic, while above the LCST, the polymer becomes hydrophobic, so the polymer and water separate, forming a compact gel. This phase transition offers a significant advantage for using the copolymer for disc augmentation, since the hydrogel can be injected through a small needle puncture at room temperature and create a customized nucleus implant in situ at physiological temperature. Furthermore, the hydrogel has been shown previously to restore the rotational stiffness profile to a cyclically fatigued spine specimen (Balkovec et al., 2013). Evaluating the efficacy of an injectable hydrogel to restore both disc height and sagittal plane kinematics to an injured, multi-articulated spine specimen will help advance the development of disc repair techniques.

Previous work has evaluated the effects of degenerative grade on spine mechanics. This has been performed in-vitro (Tanaka et al., 2001), in-vivo (Lee et al., 2015), and in-silica (Kim et al., 1991; Ruberte et al., 2009). In the in-vitro work, higher degenerative grades

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were associated with increased stiffness and loss of motion (Tanaka et al., 2001). Interestingly, higher degenerative grade includes loss of disc height, but it is unclear whether disc height loss is the cause of the reduced motion and increased stiffness seen or whether it is due to other factors such damaged annular tissue (Adams et al., 1986), presence of osteophytes (Al-Rawahi et al., 2011), or even ligamentous damage producing segmental instability (Oxland et al., 1991). Investigating disc height loss in an in-vitro environment with a homogeneous animal model removes confounding factors such as pain (de Vries et al., 2015; Mehta et al., 2015), muscle guarding (Fryer et al., 2004), movement variability (Frost et al., 2015), and additional anatomic anomalies such as osteophytes (Al-Rawahi et al., 2011; Videman et al., 1995) or facet tropism (Chadha et al., 2013).

The purpose of this investigation was to determine the influence of disc height loss on the sagittal plane kinematics of a multi-segmented spine specimen. We also sought to evaluate the ability of an injectable hydrogel to restore disc height and kinematics to the affected segment. It was hypothesized that the relative angular displacement about the affected segment with disc height loss would decrease. With restoration of disc height via hydrogel injection, it was hypothesized that the affected segments would return to their initial levels of relative angular displacement.

2. Materials and methods

2.1. Specimens and preparation

Twenty porcine cervical spines (age: 6 months, weight: 80 kg) were used for this study. Two groups of 10 specimens were created and differentiated based on whether disc height loss was induced in the superior or inferior segment. Specimens were dissected into a multi-segmented unit consisting of levels C3/C4 and C4/C5. Specimens were mounted in stainless steel cups using wood screws, non-exothermic dental stone (Denstone®, Miles, South Bend, IN, USA), and wire looped bilaterally around the lamina and anterior processes. This model has been shown to represent human spinal joint behavior for the purposes of investigating kinematics, kinetics, and injury mechanisms (Yingling et al., 1999).

2.2. Equipment and testing

Specimens were placed in a servohydraulic testing apparatus (Instron, model: 8511, Instron Canada, Burlington, Ontario, Canada) and heated to body temperature prior to any testing taking place using a custom temperature chamber surrounding the machine (Fig. 1). Free translation of the bottom cup was facilitated by a platform of ball bearings while flexion–extension motions were applied by an electric brushless servo-motor (motor arm) (model BNR3018D, Cleveland Machine Controls, Billerica, MA, USA) and planetary gear head (model 34PL040, Applied Motion Products, Watsonville, CA, USA) controlled using a customized software interface.

The apparatus applied both a bending moment and a vertical compressive force to each specimen. Thus, the cumulative moment was the result of the moment applied to the superior vertebra via the motor arm, and the bending moment applied as a result of the compressive force (Fig. 2). This application of moments was unique, in that it mimicked an individual flexing their torso forward. The applied compressive force was representative of the gravitational loading that would occur from the mass of the torso above a segment, together with muscle and passive-tissue tensions required to hold the quasi-static posture. The force vector in this posture follows the principle of transmissibility, it moves anterior relative to lower segments when the torso is flexed, creating a larger bending moment.

Pilot testing revealed that the temperature at the disc periphery, taken with a digital probe thermometer, was a suitable surrogate for the temperature inside of the disc. After heating, specimens were preloaded under 300 N of compressive load for 15 min in order to reduce any post-mortem swelling (Adams et al., 1996; Callaghan and McGill, 2001). Following this, a passive flexion/extension test was performed under 1000 N of compressive load. Due to the specimens having multiple segments, there were two distinct linear regions of torque vs. angular displacement. The flexion/extension angular displacement limits were based on where the beginning and end of both linear regions were.

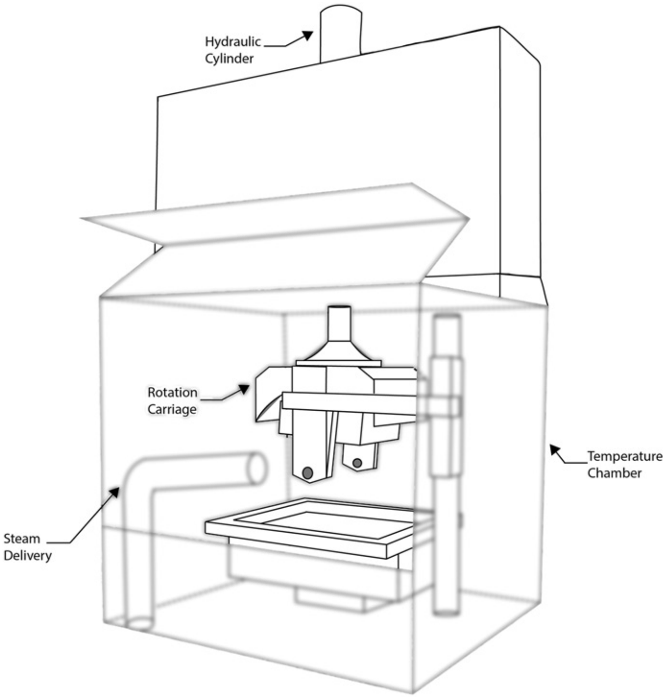

Fig. 1. Customized temperature chamber surrounding the servohydraulic testing apparatus. A PVC pipe (back left) delivered steam into the chamber, while the internal temperature was continuously monitored using a digital thermistor. Temperature was controlled and maintained at approximately 37 °C. An access door facilitated placement and removal of the specimen and allowed sagittal plane movement trials to be recorded with an orthogonally placed video camera. Specimens were mounted to the rotation carriage, where an electric brushless servo-motor (not depicted) applied pure moments in the sagittal plane. A hydraulic cylinder was used to apply vertical compression to specimens during testing.

Sagittal movement of each vertebral joint was recorded using a digital video camera (GoPro, model: Hero3, GoPro, San Mateo, CA, USA) placed orthogonally to the specimen. Video was captured using the narrow field of view, at 60 frames per second, and a resolution of 1920 × 1080 pixels. Three small rigid bodies with four circular reflective markers on each were placed on the specimens: two were placed on the superior and inferior mounting cups and one was rigidly fixed using screws onto the C4 vertebra (Fig. 2). Relative orientation of the vertebral bodies could then be used to calculate relative vertebral joint angles.

Prior to any angular displacement trials, a video calibration trial was taken with the specimen in a neutral starting position. This was the point where there was zero torque applied to the specimen by the motor arm. Calculated vertebral joint motion was based off of this position. Specimens were first tested under 1000 N of compression and angular displacement range determined from the passive test. Each specimen underwent 10 cycles of repeated full flexion to extension while the positions of the rigid bodies were recorded. Following this initial angular displacement trial, the superior or inferior disc (randomly selected) was punctured anteriorly using a 12-gauge needle. Specimens were divided into groups based on whether the superior or inferior disc was punctured (n = 10 in