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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

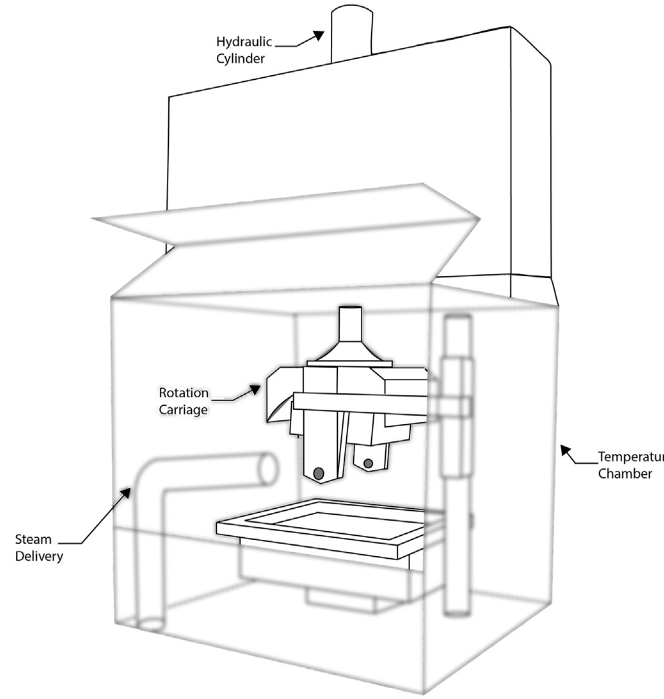
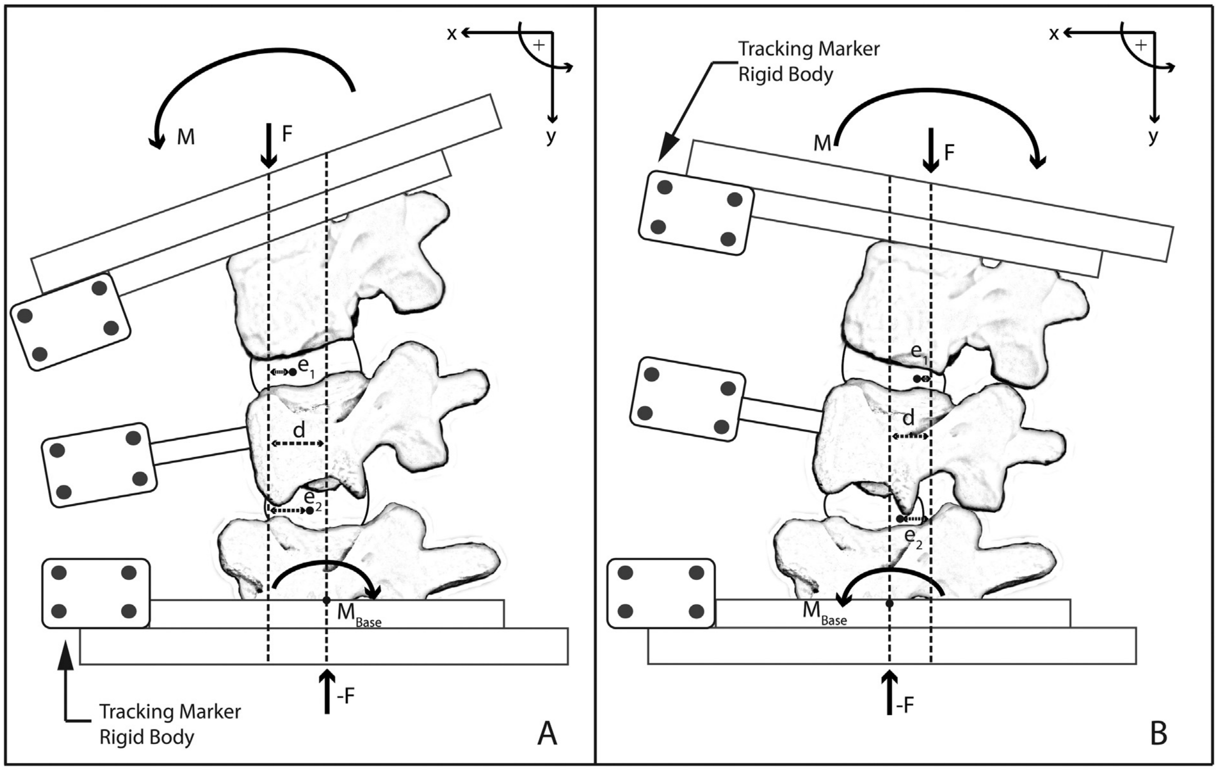


Fig. 1. Customized temperature chamber surrounding the servohydraulic testing apparatus. A PVC pipe (back left) delivered steam into the chamber, while the internal temperature was continuously monitored using a digital thermistor. Temperature was controlled and maintained at approximately 37 °C. An 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.

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.

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



$$M_{e1} = -Fe_1 - M \qquad M_{e1} = Fe_1 + M$$

$$M_{e2} = -Fe_2 - M \qquad M_{e2} = Fe_2 + M$$

$$M_{Base} = -Fd - M \qquad M_{Base} = Fd + M$$

Fig. 2. Schematic of forces and moments applied to each level of the specimen during testing. Where: M is the moment applied by the motor arm, F is the vertical compressive force, d is the total horizontal translation of the specimen, e_1 is the perpendicular distance from the vertically applied force and the center of rotation of the superior disc (assumed to be the fulcrum), e_2 is the perpendicular distance from the vertically applied force and the center of rotation of the inferior disc (assumed to be the fulcrum), and M_{Base} is the moment at the base of the inferior mounting cup. A. The moment at the base of the inferior mounting cup was the result of the pure moment applied to the top of the superior mounting cup combined with the bending moment that was dependent on the quantity of relative specimen translation and the applied vertical compressive force. The cumulative moment at each segment therefore was a value between the pure moment applied to the superior mounting cup and the moment at the base of the inferior mounting cup. Four circular reflective tracking markers were attached to rectangular rigid bodies. Two bodies were fixed to the superior and inferior mounting cups (representing motion of the superior C3 and inferior C5 vertebrae), while another rigid body was fixed onto the anterior aspect of the C4 vertebra. Tracking the movement of these three vertebral bodies allowed for the calculation of relative angular displacement of the two functional joints. Translation of the specimen was calculated via the horizontal movement of the inferior rigid body. B. Specimen in the extended posture, the same cumulative moment relationship exists as in (A). Tracking marker rigid bodies are depicted in the same configuration as in (A).

each group). The needle used was the smallest gauge needle that would still allow for the flow of the nucleus from the disc, initiating immediate disc height loss in the punctured disc without any other damage occurring.

After puncture, each specimen underwent 50 cycles of repeated flexion to extension under 1000 N of compressive load to ensure that no more nucleus could be forcibly extruded from the disc. A second angular displacement trial was then performed, following the standard 10 cycle repetitive flexion to extension protocol (additional to the 50 cycles performed for nuclear extrusion). Disc height was restored using the thermally responsive hydrogel developed previously (Vernengo et al., 2008; Balkovec et al., 2013). The punctured disc was injected with hydrogel until it would not passively contain any more, and then left unloaded for 15 min in order to fully ensure it had changed state from liquid to gel form. The needle was left in the disc during this 15-minute period and acted as a stopper to prevent any outflow of fluid hydrogel. Once testing recommenced, the needle was removed. Following disc height restoration, a final angular displacement trial was taken, with specimens undergoing 10 cycles of repeated flexion to extension under 1000 N of compressive load.

2.3. Data analysis

Specimen height was measured using the relative position of the hydraulic ram on the servohydraulic testing apparatus. Total torque applied by the motor arm during motion trials was recorded and normalized to the first repetitive trial to facilitate comparison between specimens. Reflective markers were digitized semi-automatically using commercially available software (Maxtraq: Innovision Systems, Columbiaville, MI, USA). Following digitization, the relative angular displacements of each vertebral joint in the sagittal plane were computed using customized Matlab software (Mathworks, Natick, MA, USA) following the least-squares method outlined by Veldhuis et al. (2005). Magnitudes of angular displacement for each joint (C3/C4 and C5/C6) were taken from the 10th repetition of flexion/extension in each of the data trials (Bisschop et al., 2013). The sum of both joint angular displacements from the 10th repetition was then used for normalizing both joint angular displacements. Joint angular displacement magnitudes were normalized to the total magnitudes (sum of both joints) for each trial to facilitate comparisons across specimens and trials. Specimen translation was calculated by the horizontal movement of the bottom mounting cup and facilitated analysis for determining the upper and lower bounds of the cumulative moment across the specimen.

2.4. Statistical analysis

A two-factor (group, trial) mixed ANOVA was used to test for differences within specimens in normalized segmental angular displacement data across the three trials for relative angular displacement of the affected segment (initial, disc height loss, disc height restored), and across the two groups (superior segments with height loss vs. inferior segments with height loss). Pairwise comparisons were made between the initial, disc height loss, and disc height restoration trial. A Bonferroni post-hoc was used to correct for multiple comparisons. All statistical tests were performed using SPSS software (IBM, Somers, NY, USA).

3. Results

A systematic effect was seen across specimens for the relative angular displacement at each level for the three movement trials. When disc height loss was induced, less motion occurred about the segment with disc height loss (Fig. 3A, B) compared to the segment without height loss (Fig. 4B). A significant interaction was also identified between the group and trial variables ($p = 0.00015$), this is not surprising, as the magnitude of relative angular displacement change between superior and inferior disc height loss groups was visibly different (Figs. 3A, B, 5). Due to this, the interaction pairwise comparisons were tested to identify significant differences between the relative magnitude of angular displacement for the segment with height loss within each group. Pairwise comparisons revealed whether the disc height loss trial or disc height restoration trial was significantly different from the initial trial. Average relative angular displacement decreased 13.8% (SD = 5.3%) at the affected segment for the group with height loss in the superior disc and was identified to be statistically significant compared to the angular displacement of the initial trial ($p = 9.4 \times 10^{-9}$). Angular displacement decreased 4.5% (SD = 2.1%) at the affected segment for the group with height loss in the inferior disc, and was also found to be statistically significant compared to the angular displacement of the initial trial ($p = 0.008$). Following disc height restoration, relative

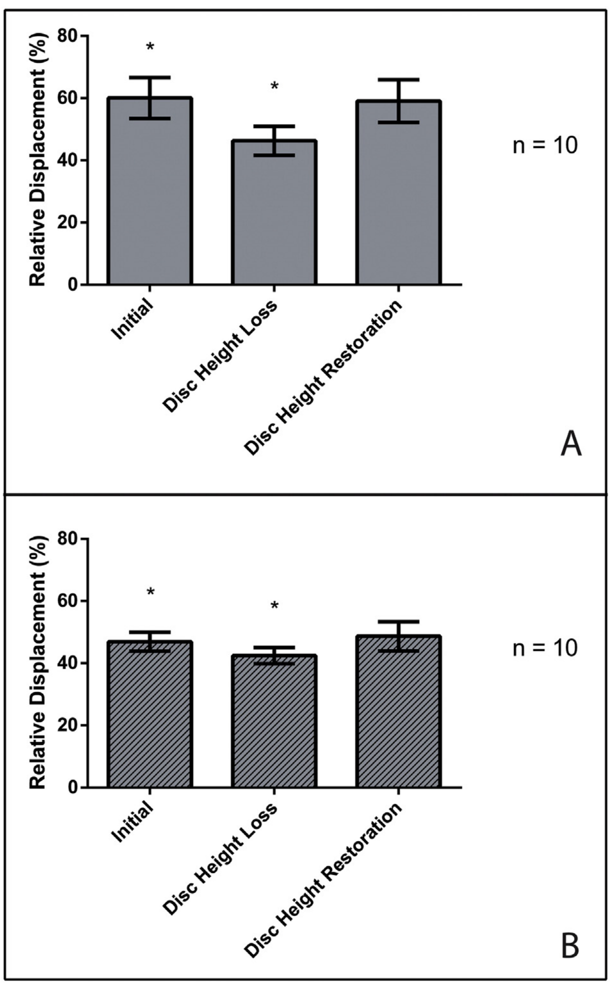


Fig. 3. Summary of angular displacement data reveals the kinematic influence of disc height loss. A. Summary of relative angular displacement data for the superior disc height loss group. Disc height loss in the superior disc resulted in less angular displacement about the superior segment, with greater displacement occurring about the inferior segment. After disc height restoration via hydrogel injection, the relative angular displacement for both segments returned to initial values. Asterisks denote statistical significance compared to the initial condition. B. Summary of relative angular displacement data for the inferior disc height loss group. A similar trend is seen as in (A) where less displacement occurs about the segment with disc height loss, and more displacement occurs about the adjacent segment. Hydrogel injection restores the relative angular displacement for both segments back to initial values. Asterisks denote statistical significance compared to the initial condition.

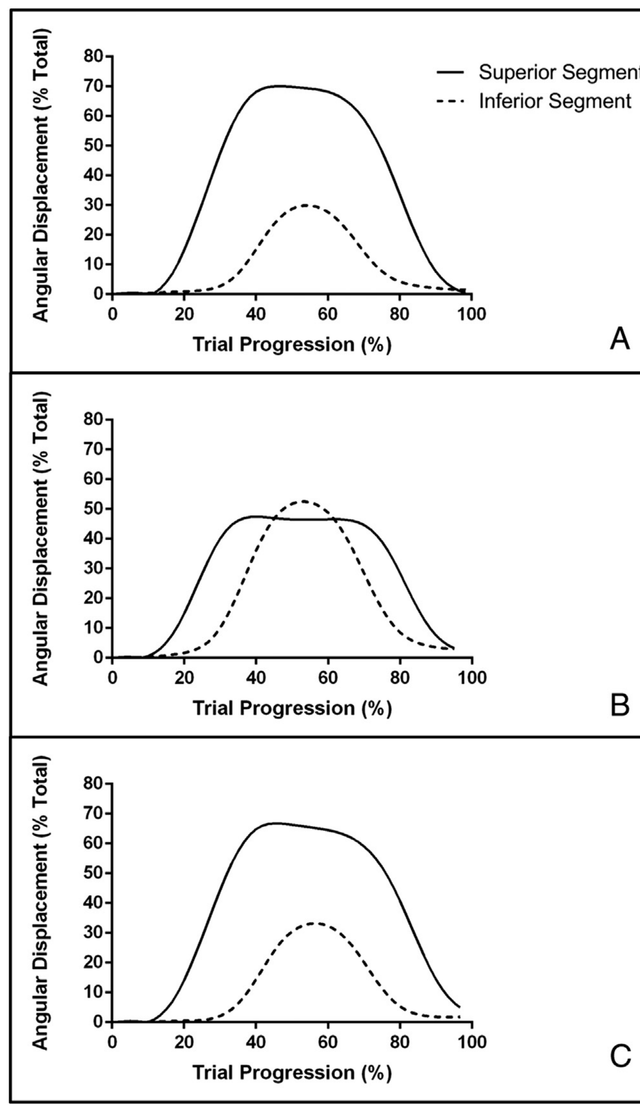


Fig. 4. Time-history graphs depict the influence of disc height loss on the affected and adjacent segment. A. There is an initial relationship between the superior and inferior segments with respect to the angular displacement occurring at each while a specimen is brought to a given target angle. B. Following height loss in the superior disc, less motion occurs about this segment while more motion (compared to A) occurs about the inferior segment. C. Hydrogel injection restores height to the superior disc and restores the motion characteristics of both segments to initial conditions.

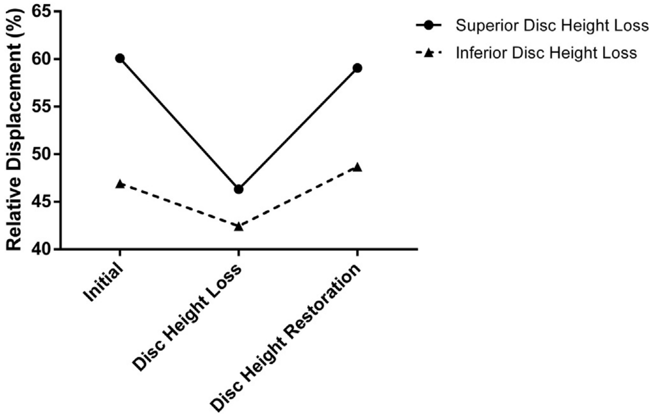


Fig. 5. Interaction plot reveals differences between groups. There was an interaction between group and trial. Here, the differences in relative angular displacement change across the three trials are shown for the group with disc height loss at the superior level (solid line) and at the inferior level (dashed line). While the relative magnitude of change differs between groups, the overall trend seen across trials is the same.

motion between superior and inferior segments returned to pre-disc height loss magnitudes (Figs. 3A, B, 4C). On average, the superior disc height loss group regained 12.7% (SD = 5.5%) of relative motion while the inferior disc height loss group regained 6.4% (SD = 4.2%), this was a greater range of motion regained than initially lost. Both of these values were found to be non-significant compared to the angular displacement of the initial trial for the group with height loss in the upper segment ($p = 1.00$) and for the group with height loss in the lower segment ($p = 0.49$). This indicated that the hydrogel was able to restore the relative angular displacement of segments with height loss back to initial magnitudes.

Average specimen height lost after disc puncture and nucleus extrusion was 0.97 mm (SD = 0.41 mm), while after hydrogel injection, specimen height was within 0.09 mm (SD = 0.44 mm) of pre-disc height loss values. Normalized torque values resisted by specimens after disc height loss increased by 20.9% (SD = 14.6%) relative to pre-disc height loss trials. After hydrogel injection, normalized torque values decreased by 7.8% (SD = 9.5%) relative to pre-disc height loss trials. Translations of the bottom cup were 7.3 mm (SD = 1.2 mm), 7.6 mm (SD = 1.7 mm), and 7.6 mm (SD = 1.4 mm) for the initial (pre-disc height loss) trials, disc height loss trials, and disc height restoration trials respectively.

From the compressive load used and the maximum specimen translations, the maximum upper and lower bounds of the cumulative moment were 15 Nm and 22.6 Nm, with actual moments at each disc corresponding to a value within that range (Fig. 2). The cumulative moment at a given point on the specimen during flexion could be represented by the following equation:

$$M_{point} = -Fd_{point} - M \quad (1)$$

where: M_{point} is the moment at an arbitrary point on the specimen, F is the vertically applied compressive load, d_{point} is the perpendicular distance from the vertical compressive load to the arbitrary point, and M is the moment applied by the motor arm. As a conservative estimate, the maximum difference in cumulative moment at the superior and inferior discs was 3 Nm during full flexion, based on a pure applied moment of 15 Nm, and estimated moment arms of 1 mm and 4 mm at the superior and inferior discs respectively.

Following disc height restoration and injection of the hydrogel into the disc space, partial ejection of hydrogel material was seen in some cases once the specimen was put under 1000 N of load. This was observed to occur within the first or second cycle of flexion to extension. This was due to the relatively large diameter needle used to initiate the extrusion of the nucleus from the disc, creating a large cavity that material could flow out of with ease. Previous work found no issues with hydrogel containment when a smaller gauge needle was used (Balkovec et al., 2013).

4. Discussion

This is the first study to examine the effects of disc height loss on an affected and adjacent segment. The influence of disc height loss on the kinematics of a spine segment and its adjacent counterparts was revealed; the hypothesis that disc height loss would result in a decreased relative angular displacement about the affected segment with disc height loss was supported. Promising data for disc height and restoring kinematics was also shown, through evidence supporting the hypothesis that disc height restoration via hydrogel injection would return segments with disc height loss to their initial levels of relative angular displacement.

The use of the hydrogel in this study provides mechanical evidence that disc height restoration can bring relative angular displacement magnitudes back to pre-height loss conditions. It is important to note that the discs tested in this investigation were acutely injured and then repaired, it is unclear how kinematics would be restored in a spine that is further degenerated. Regardless, it provides a viable alternative to more invasive surgical procedures when warranted; future work should further investigate its viability in live-animal models as well as in degenerate tissue models. Degenerative features such as endplate fractures (Dolan et al., 2013), osteophytes (Al-Rawahi et al., 2011), annular fissures, and a weakened annulus (Stefanakis et al., 2014) all present a challenge with respect to hydrogel containment and the degree of repair that is achieved. It is likely that weakened structures such as the annulus will also require augmentation in order to sufficiently contain the hydrogel. In some cases, degenerated discs with higher stiffness (Tanaka et al., 2001) may also present a challenge with respect to fully restoring disc height; additional work will allow the feasibility of restoring kinematics to spine segments with various degenerative features to be assessed. Clinically, the use of this hydrogel could help to mitigate aberrant motions at adjacent segments that elevate risk for further degenerative change (Ruberte et al., 2009). This could potentially decrease risk for development of painful symptoms associated with some cases of degeneration (de Schepper et al., 2010).

When disc height is lost, the same level of angular displacement cannot occur about the affected disc, and thus, compensation, via increased angular displacement about the adjacent segment is seen. One explanation for why this occurs could be due to local rotational stiffness at each segment. Previous work has shown that when a segment undergoes cyclic flexion to extension motions, the stiffness increases (Balkovec et al., 2013; Callaghan and McGill, 2001). Disc height during this process has also been shown to decrease (Balkovec et al., 2013; Scannell and McGill, 2009). In the present study, the torque resisted by specimens was observed to increase by 20.9% when disc height loss was induced, indicating an increase in specimen stiffness, presumably at the affected level. When reaching a target angle, there are two possible segments in the current experimental setup that motion could be elicited from; motion occurred about the most compliant segment. This investigation used position control to bring specimens to the same target angle, as opposed to torque control which would have used the same applied moment across trials. Under torque control, less motion would have occurred given the increased overall stiffness of the specimens. Thus, the results from this investigation apply to scenarios where movement is position controlled.

Previous research on cadaveric specimens (Tanaka et al., 2001) and finite element models (Kim et al., 1991; Ruberte et al., 2009) has focused on grouping based on degenerative grade, which makes direct comparison with the present research difficult. Interestingly, higher grades of degeneration include disc height loss or disc thinning (among other visual features) in their criteria (Adams et al., 1986; Pfirrmann et al., 2001; Thompson et al., 1990). In work that examines cadaveric tissue at higher grades of degeneration, there is an associated decrease in range of motion, presumably due to the fibrotic nature of the tissue that leads to a higher stiffness (Lao et al., 2015; Tanaka et al., 2001). In vivo work has found similar results, with higher grades of degeneration (and thus disc height loss) being associated with less angular displacement at that particular level and a compensatory effect of other segments (Lee et al., 2015). Recent work has also examined the effects of Schmorl's nodes on spine kinematics in vivo, resulting in observations that movement is reduced at the level of damage (Hayashi et al., 2014; Yin et al., 2015). A Schmorl's node would result in disc height loss due to the migration of the nucleus into the vertebral body space. While there are certainly other factors that may have affected segmental mechanics in those studies, the results from this research outline that disc height loss is a potentially large contributing factor.

Disc height loss potentially limits motion due to the interaction between physical elements of neighboring vertebrae such as the facet joints (Dunlop et al., 1984). Increased proximity of the facet joints and spinous processes could physically limit motion in extension. Disc height loss also has the potential to alter the stress distribution within the disc (Adams et al., 1996; Brinckmann and Grootenboer, 1991), which has implications for transferring load to the neural arch and posterior elements in the spine (Adams and Hutton, 1980; Pollintine et al., 2004). This would undoubtedly alter how readily a segment rotates due to the increased passive stiffness. Apparent differences between the superior disc height loss group and inferior disc height loss group could be due to the different moments that were applied to each as a result of the test apparatus. The lower segment only began to move when there was an applied bending moment which occurred through translation of the specimen. Given that there was initially no specimen translation, the majority of the rotation occurred at the superior segment due to the pure moment applied by the motor arm.

Limitations of this study include its use of a juvenile porcine spine model. Nevertheless, the porcine cervical spine has been shown to be a suitable analog for the human lumbar spine with respect to anatomy, geometry (Oxland et al., 1991; Yingling et al., 1999), and function (Tampier et al., 2007) for the purpose of discerning injury mechanisms. In order for the cantilevered head to be supported in a quadruped, a large extensor moment must be applied, resulting in large compressive forces on the cervical vertebrae. Additionally, the rooting behavior exhibited by pigs results in further applied compression via an extensor moment, which creates a loading profile similar to a human lumbar spine. Further, Wilke and colleagues present data that shows while the porcine cervical spine is not a suitable analog for the human cervical spine, it has functional capabilities that closely match the range of data that exists on the movement properties of the human lumbar spine for sagittal plane movement (Wilke et al., 2011). A further limitation was the relatively short time period that changes were observed over, without any prolonged testing to evaluate the fatigue properties of the hydrogel. Previous work with this hydrogel in a porcine model has shown that the mechanical profile of specimens after injection will return back to injury conditions with repeated cyclic loading (Balkovec et al., 2013).

Further considerations for the testing apparatus and its influence on the observed kinematics need to be taken into account. A limitation of the apparatus used was that each segment was subject to different applied moments. This caused the observed effect of the superior segment rotating almost fully to its observed end-range before rotation was initiated about the inferior segment. As we have shown however, the estimated maximum difference in applied moment to each segment was 3 Nm. Further, rotation of each segment was limited by the resistance of its passive tissues and inherent stiffness. When disc height was lost, stiffness increased and motion occurred to a greater extent about the non-affected (and more compliant) segment. The local stiffness of each segment would be the same property driving motions in-vivo. Further, bending of the torso in-vivo results in variable bending moments being applied to each of the segments. This type of movement would also create translations at the pelvis similar to the translations seen in this study, as a person bends further forwards. Thus, the findings of this study are limited to activities involving torso flexion and do not necessarily reflect the influence of disc height loss under other loading paradigms. Future work will begin to identify the influence of disc height loss under additional motions, postures, and loads.

This study has shown that disc height loss through loss of the nucleus pulposus induces kinematic changes which have consequences at the adjacent segment, beyond the affected level. When disc height is lost, the sagittal plane range of motion of the affected segment is reduced, and the angular displacement at an adjacent segment is increased. This study is the first of its kind to identify how disc height loss produces changes to multiple segments along the spinal linkage. Further, it has tested and shown a viable method that restores kinematics via a minimally invasive hydrogel. Future work will further probe the mechanism of disc height loss across additional loading paradigms and identify viable methods of repair.

Acknowledgments

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