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Basic Science

Evaluation of an injectable hydrogel and polymethyl methacrylate in restoring mechanics to compressively fractured spine motion segments

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Abstract

BACKGROUND CONTEXT: Compressive fracture can produce profound changes to the mechanical profile of a spine segment. Minimally invasive repair has the potential to restore both function and structural integrity to an injured spine. Use of both hydrogels to address changes to the disc, combined with polymethyl methacrylate (PMMA) to address changes to the vertebral body, has the potential to facilitate repair.

PURPOSE: The purpose of this investigation was to determine if the combined use of hydrogel injection and PMMA could restore the mechanical profile of an axially injured spinal motion segment.

STUDY DESIGN: This is a basic science study evaluating a combination of hydrogel injection and vertebroplasty on restoring mechanics to compressively injured porcine spine motion segments.

METHODS: Fourteen porcine spine motion segments were subject to axial compression until fracture using a dynamic servohydraulic testing apparatus. Rotational and compressive stiffness was measured for each specimen under the following conditions: initial undamaged, fractured, fatigue loading under compression, hydrogel injection, PMMA injection, and fatigue loading under compression. Group 1 received hydrogel injection followed by PMMA injection, whereas Group 2 received PMMA injection followed by hydrogel injection. This study was funded under a Natural Sciences and Engineering Research Council of Canada discovery grant.

RESULTS: PMMA injection was found to alter the compressive stiffness properties of axially injured spine motion segments, restoring values from Groups 1 and 2 to 89.3%±29.3% and 81%±27.9% of initial values respectively. Hydrogel injection was found to alter the rotational stiffness properties, restoring specimens in Groups 1 and 2 to 151.5%±81% and 177.2%±54.9% of initial values respectively. Prolonged restoration of function was not possible, however, after further fatigue loading.

CONCLUSIONS: Using this repair technique, replication of the mechanism of injury appears to cause a rapid deterioration in function of the motion segments. Containment of the hydrogel appears to be an issue with large breaches in the end plate, as it is posited to migrate into the cancellous bone of the vertebral body. Future work should attempt to evaluate methods in fully sealing the disc space.

Keywords: Intervertebral disc; Vertebroplasty; Hydrogel; PMMA; Disc mechanics; Minimally invasive repair

FDA device/drug status: Not applicable.

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Introduction

Compressive injury to the spine can initiate a series of degenerative changes. It has been shown to produce a variety of fracture patterns [1] with the potential to damage both the vertebral body and the intervertebral disc. Damage to the disc via fracturing of the underlying cartilaginous end plate could result in migration of nucleus into the vertebral body itself, causing depressurization of the disc space [2] and height loss. Mechanically, vertebral body fractures result in a loss of compressive stiffness, which could affect additional segments. Clinically, vertebral body fractures can result in a kyphotic deformity in the case of anterior wedge fractures [3,4]. Additionally, axial compression is shown to most commonly produce a fracture of the end plate [1]. The vertebral body's rich vascularity and nerve supply [5] could mean that damage results in sensitization and nociception [5,6].

From a mechanical perspective, any attempt to surgically repair a compressive fracture needs to address the loss in both disc height and nuclear material, as well as the damage to the underlying trabecular bone. Restoring the mechanical function of a spine segment injured via compressive fracture could help to mitigate any further degenerative changes. Two materials that could potentially restore the mechanical profile of a compressively damaged spine motion segment are hydrogel injection and vertebroplasty. Although both have been tested individually [7,8], they have never been combined. They provide a plausible solution to restoring both the compressive and the rotational mechanical properties of axial compressive injuries.

The use of injectable hydrogels is an emerging technique to restoring disc height and function to a disc exhibiting pathology. It is a minimally invasive procedure, able to restore disc height and replace the nucleus. In addition, vertebroplasty has been used to repair fractured vertebral bodies and restore stiffness characteristics to vertebrae. Vertebroplasty has been shown to restore stress distributions and stiffness to the vertebral body [8], and hydrogel implants have also been shown to do this for the disc [9]. The impact of these repair modalities combined has never been tested before but could offer a viable method of minimally invasive repair, maintaining function and restoring structural integrity.

The purpose of the following investigation was to determine if, in principle, the combined use of hydrogel injection and polymethyl methacrylate (PMMA) could restore the mechanical profile of an axially injured spinal motion segment. It was hypothesized that hydrogel injection would alter the rotational stiffness properties from the compressively fatigued state. It was also hypothesized that PMMA injection would alter the compressive stiffness properties from the compressively fatigued state.

Materials and methods

Specimens and preparation

Fourteen porcine cervical motion segments (age: 6 months, weight: 80 kg) were used for this investigation, as dictated by the quantity of vertebroplasty kits available. Each specimen consisted of two vertebral bodies and their intervening disc. Motion segments were randomly divided into two groups, which dictated the order in which they would receive the hydrogel and PMMA interventions.

Specimens were dissected by removing as much muscular tissue as possible while leaving ligamentous structures intact. Following dissection, specimens were mounted in customized stainless steel cups and secured using screws drilled through the superior and inferior end plates and wire looped bilaterally through the lamina and anterior processes. Nonexothermic dental stone (Denstone, Miles, South Bend, IN, USA) further secured the specimens in their mounting cups.

Omnipaque (GE Healthcare, Little Chalfont, UK) was injected into the disc space using a 21-gauge needle; this facilitated monitoring of the location of the nucleus under x-ray and assist in determining whether the administered end plate fracture was created in the superior or inferior end plate.

Equipment

All specimens were tested in a servohydraulic dynamic testing machine (Instron, model: 8511, Instron Canada, Burlington, Ontario, Canada). Free translation of the bottom cup was facilitated by a platform of ball bearings while flexion-extension motions were applied by an electric brushless servomotor (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 hydrogel had reversible properties where it flowed as a free liquid at room temperature but formed an elastic gel at body temperature; it was therefore critical that specimens were heated to body temperature for testing. This was performed using a customized temperature chamber built around the servohydraulic testing apparatus (Fig. 1). The chamber allowed for steam to be delivered from a heated water bath through a polyvinyl chloride pipe and injected into the chamber, directed upward away from the specimen, preventing overheating. The chamber temperature was adjustable and monitored using a digital thermistor that provided instantaneous feedback to any changes.

Hydrogel

The hydrogel used has been described previously [7]; briefly, it was a composition of thermally responsive branched copolymer of poly(N-isopropylacrylamide) and polyethylene glycol [10]. This copolymer has a reversible phase transition from liquid to solid around 33°C. For this reason, it forms a space-filling elastic gel within disc defects. The copolymer was prepared by free radical polymerization of poly(N-isopropylacrylamide) monomer in the presence of polyethylene glycol (4600 g/mol) dimethylacrylate in a molar ratio of 700 to 1.

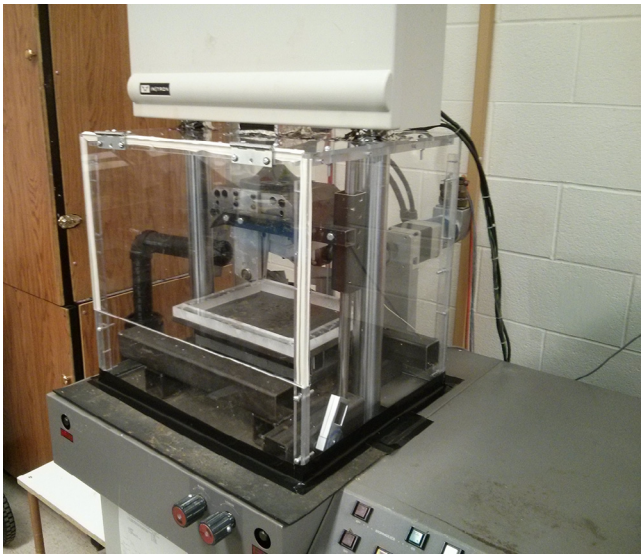

Fig. 1. Temperature chamber used to bring specimens to body temperature. A polyvinyl chloride (PVC) pipe (back left) brought steam into the chamber, which heated up the enclosed space. Temperature was monitored with a digital thermistor inside the chamber, and the temperature could be controlled via a vent at the back. An access door at the front facilitated access to the specimen.

Aqueous solutions containing 15 wt % copolymer were prepared and injected into the discs of the specimens using an 18-gauge needle and syringe. Injection was performed until the unloaded disc could not passively contain any more hydrogel; this varied between 1 and 1.2 mL. Following injection, specimens were left unloaded for 15 minutes at 37°C to ensure that it had fully changed to its gel state.

Vertebroplasty

The technique used to inject the PMMA cement was similar to that used by Landham and colleagues [11]. PMMA cement (Spineplex, Stryker Instruments, Howmedica International, Limerick, Ireland) was prepared by mixing 20 g of powder with the provided ampoule of liquid. Two 10-gauge needles were inserted through the pedicles of the fractured vertebra. Sagittal and frontal plane x-rays were used to ensure that the needles were placed near the fracture site. Two cubic centimeters of cement was injected through each needle, and the stylet of each cannula was reinserted to prevent backflow of cement. After 10 minutes, the needles were removed, and the cement was allowed to set over a 1-hour period. X-rays were taken to confirm that the cement had been placed properly. After this, specimens were loaded under 300N of axial compression for 30 minutes to allow the cement to consolidate.

Rotational and compressive stiffness

For measuring compressive stiffness, specimens were loaded in axial compression to 50% of their estimated compressive strength at a loading rate of 1,000N/s; this was performed twice to ensure that there was no aberrant stiffness value produced by unloading the specimen. Compressive stiffness was calculated by dividing the peak compressive load that specimens were exposed to by the relative vertical displacement of the hydraulic ram on the Instron to yield compressive stiffness expressed in units of kN/mm. The predictive equation for estimating compressive strength by Parkinson and colleagues [12] was used to determine compressive loading values. Dimensions of the intact disc were estimated by using the equation for the surface area of an ellipse ($\pi/4\times$anterioposterior length$\times$mediolateral width) in the same manner as Callaghan and McGill [13].

Rotational stiffness measurement was performed by bringing specimens through a trial of 10 cycles of flexion and extension. Rotational stiffness was calculated by taking the average value for each time point over the course of the trial; values were expressed in units of Nm/°. To facilitate comparison between specimens, compressive stiffness and rotational stiffness values were normalized as a percentage of the initial values.

Specimen testing protocol

The full testing protocol is outlined in Fig. 2. Specimens were preloaded for 15 minutes at 300N to counter any post-mortem swelling that may have occurred. Specimens were then loaded to 1,000N of axial compression and brought through a passive range of flexion and extension to establish the linear range of angular displacement and torque [14] and the angular targets that specimens would be taken to.

Following the passive test, specimens were brought to a reference load of 300N in the neutral position; this was used for the measurement of specimen height via the hydraulic ram position of the Instron. Specimens were then subjected to a compressive stiffness test and a rotational stiffness test in random order.

After the initial set of measurements was made, specimens were loaded in axial compression to failure (Table 1). Failure was defined as a deflection in the force-displacement curve of 3.125% over a period of 25 ms (Fig. 3). Specimens were then subjected to cyclic compressive loading to 30% of their estimated compressive strength for 1,000 cycles at a loading rate of 0.5 Hz [15–17].

Following failure and fatigue loading, the reference load, compressive stiffness, and rotational stiffness measurements were repeated, and then specimen Group 1 was injected with hydrogel, whereas Group 2 was treated using PMMA. After this first intervention, measurements were repeated followed by the second intervention, with Group 1 receiving PMMA injection and Group 2 receiving a hydrogel injection. The second intervention for each group was followed by another series of measurements.

After groups had received interventions of both hydrogel and PMMA injection, specimens were subjected to a final 1,000 cycles of repeated compressive loading at 30% of their estimated compressive strength and a final set of measurements.

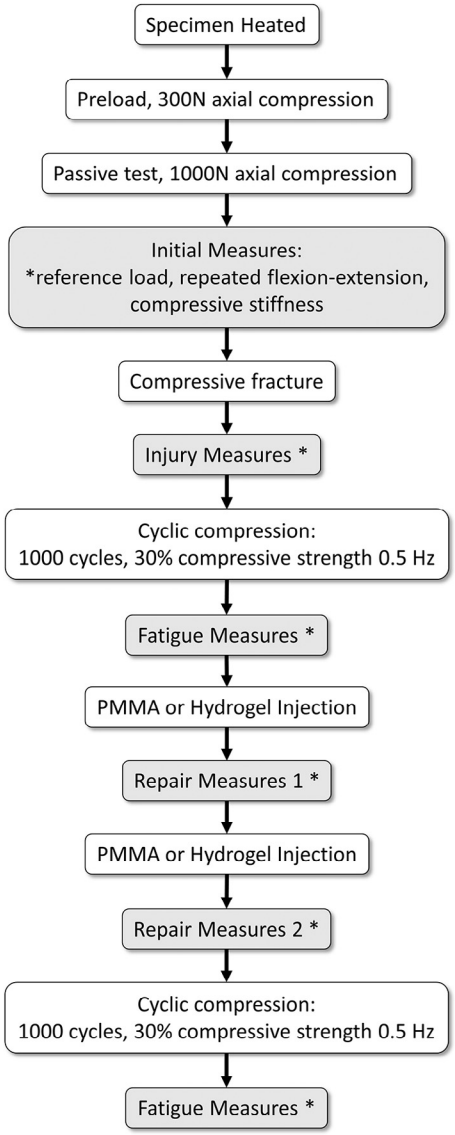

Fig. 2. Flow diagram of the experimental protocol. The order in which specimens received polymethyl methacrylate (PMMA) or hydrogel injection was randomly assigned. Measures of specimen height, rotational, and compressive stiffness were taken at six points during the protocol. All values were normalized to the initial measurement values and used for analysis.

Statistical analysis

At each point that measurements were made during the testing protocol, a single value for rotational stiffness and compressive stiffness was obtained. For analysis, all measurement time points combined yielded six values each of rotational stiffness and compressive stiffness (Fig. 2). Because all values were normalized to the initial set of measurements, five values each for rotational and compressive stiffness (all values except initial values) were used for analysis. A 2×5 repeated measures analysis of variance was performed for both rotational stiffness and compressive stiffness values with independent variables consisting of order of treatment (between subjects) and time (within subjects). Dependent variables were the response of specimens after the initial fatigue trial, after hydrogel injection, after PMMA injection, and after the fatigue trial once both interventions had been performed. A Bonferroni correction was performed on all statistical tests to adjust for multiple comparisons. All statistical tests were performed using SPSS Statistics software version 20 (IBM, Somers, NY, USA).

Table 1
Specimen failure and fracture data

	Failure load (kN)	Fracture type (End plate breach vs. no breach)	End plate cross-sectional area (mm^2)
Specimen 1	7.5	No breach	526
Specimen 2	11.3	No breach	495
Specimen 3	10.0	No breach	618
Specimen 4	9.9	No breach	646
Specimen 5	9.4	Breach	499
Specimen 6	10.5	Breach	594
Specimen 7	12.1	No breach	592
Specimen 8	10.5	Breach	614
Specimen 9	12.2	No breach	609
Specimen 10	11.8	Breach	614
Specimen 11	10.3	Breach	668
Specimen 12	9.7	Breach	614
Specimen 13	14.2	Breach	605
Specimen 14	12.5	Breach	479
Average (SD)	10.8 (1.6)		584 (60)

SD, standard deviation.

Results

Rotational stiffness values were found to be significantly different within subjects over time (p=.00004), whereas there was no interaction between group and time (p=.36). Between-group differences revealed that although the hydrogel was able to restore the rotational stiffness values and change them compared with the initial fatigue condition (−115.7% mean difference, 95% confidence interval=−185.3% to 46.2%, p=.003), it could not maintain this effect after repeated cyclic compression as rotational stiffness values returned to their initial fatigue values (−0.7% mean difference, 95% confidence

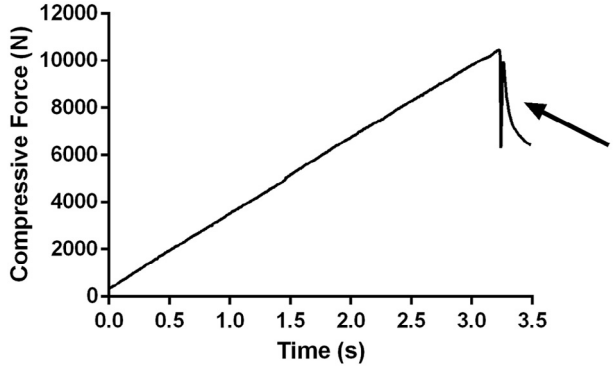

Fig. 3. Sample specimen failure point with arrow pointing to the deflection in the load applied by the hydraulic ram.

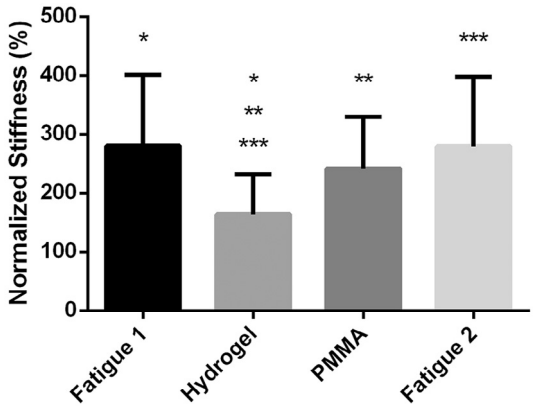

Fig. 4. Normalized rotational stiffness values for both specimen groups. Asterisks denote significance between matching pairs. The hydrogel injection was able to significantly restore rotational stiffness values to near initial values (100%). Following fracture and the first fatigue loading protocol, rotational stiffness increased relative to initial values. After hydrogel injection, rotational stiffness decreased relative to all other stages of testing, but this could not be maintained, and rotational stiffness increased following polymethyl methacrylate (PMMA) injection and a second fatigue loading protocol.

interval=−29.4% to 28.0%, p=.96). Overall, rotational stiffness was found to be influenced over time (Fig. 4); values were restored to 151.5%±81% (Group 1) and 177.2%±54.9% (Group 2) after hydrogel injection. Normalized rotational stiffness values for all specimens throughout the testing stages are presented in Tables 2 and 3. Rotational stiffness was increased after fracture and fatigue, decreased with hydrogel injection, increased (relative to hydrogel injection) after PMMA injection, and greatly increased after further fatigue.

As with rotational stiffness, there was a significant influence of time for compressive stiffness values within subjects (p=.001) although there was no interaction between group and time (p=.63). Between-group differences revealed that PMMA injection could significantly alter the compressive stiffness value of a specimen compared with the fatigue condition (−16.7% mean difference, 95% confidence interval=−27.4% to −6.0%, p=.005). Similarly, this effect could not be maintained with repeated cyclic compression as the compressive stiffness returned to its initial fatigue value (6.6% mean difference, 95% confidence interval=−8.0% to 21.2%, p=.344). Overall, the compressive stiffness was found to be influenced over time (Fig. 5); values were restored to 89.3%±29.3% (Group 1) and 81%±27.9% (Group 2) after PMMA injection. Normalized compressive stiffness values for all specimens throughout the testing stages are presented in Tables 4 and 5. Changes in values are evident within specimens where fracture decreased compressive stiffness, fatigue loading increased stiffness (above 100% values), PMMA injection decreased compressive stiffness, hydrogel injection further decreased compressive stiffness, and further fatigue greatly increased stiffness.

Over testing, there was no observed containment issue between the hydrogel and the initial injection site at the anterior of the disc; however, two types of end plate fracture occurred during testing. The first was a breach-type fracture, where the cortical bone of the end plate was ruptured and the underlying cancellous bone within the adjacent vertebra was exposed (Fig. 6). Upon dissection, no evidence of hydrogel was present in these discs with open cracks, implying that the hydrogel had migrated out of the disc and

Table 2
Specimen Group 1 normalized rotational stiffness values throughout testing trials

	Initial (%)	Fracture (%)	Fatigue loading (%)	Hydrogel injection (%)	PMMA injection (%)	Fatigue loading (%)
Specimen 1	100	205.8	289.2	107.6	231.3	270.1
Specimen 2	100	102.8	212.8	67.4	201.2	262.3
Specimen 3	100	501.5	555.5	118.2	373.4	583.4
Specimen 4	100	456.6	485.7	266.8	427.6	487.6
Specimen 5	100	172.5	271.2	252.1	312.4	282.6
Specimen 6	100	81.4	103.8	77.5	98.3	132.4
Specimen 7	100	161.2	190.1	170.8	154.5	166.3
Average (SD)	100	240.3 (168.9)	301.2 (162.7)	151.5 (81.0)	257.0 (119.1)	312.1 (164.9)

PMMA, polymethyl methacrylate; SD, standard deviation.

Table 3
Specimen Group 2 normalized rotational stiffness values throughout testing trials

	Initial (%)	Fracture (%)	Fatigue loading (%)	PMMA injection (%)	Hydrogel injection (%)	Fatigue loading (%)
Specimen 8	100	166.7	277.2	246.7	100.4	294.5
Specimen 9	100	170.9	244.3	231.1	189.6	236.5
Specimen 10	100	227.4	216.9	210.6	216.3	230.6
Specimen 11	100	156.9	193.3	160.4	133.3	248.6
Specimen 12	100	233.3	368.7	279.6	261.1	227.1
Specimen 13	100	244.0	318.2	277.7	143.3	274.9
Specimen 14	100	176.0	194.2	177.3	196.6	214.4
Average (SD)	100	196.5 (36.8)	259.0 (66.3)	226.2 (46.4)	177.2 (54.9)	246.7 (28.5)

PMMA, polymethyl methacrylate; SD, standard deviation.

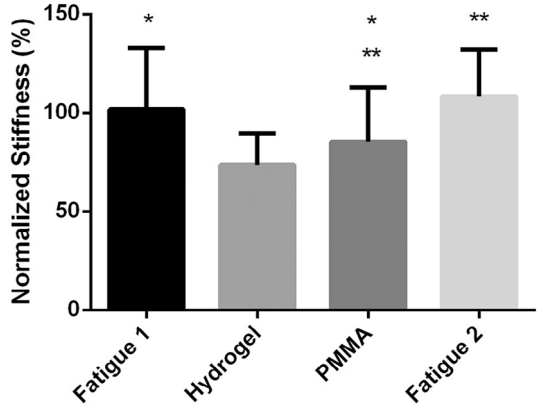

Fig. 5. Normalized compressive stiffness values for both specimen groups. Asterisks denote significance between matching pairs. Polymethyl methacrylate (PMMA) injection was able to significantly affect compressive stiffness values compared with fatigue trials. Following fracture and the first fatigue loading protocol, compressive stiffness was generally observed to increase relative to initial values. Hydrogel injection decreased compressive stiffness lower than initial values and made specimens more compliant. Polymethyl methacrylate injection was found to return compressive stiffness to levels close to initial values, but the influence of this intervention could not be maintained after a second fatigue loading protocol.

into the cancellous bone of the vertebral body. The second was a no-breach-type fracture, where no rupture of the cortical bone occurred and the disc was not exposed to the underlying cancellous bone of the adjacent vertebra. A small deformation could be felt on the otherwise smooth end plate surface using a probe, which could indicate failure of the underlying cancellous bone. Specimens without breaches in the

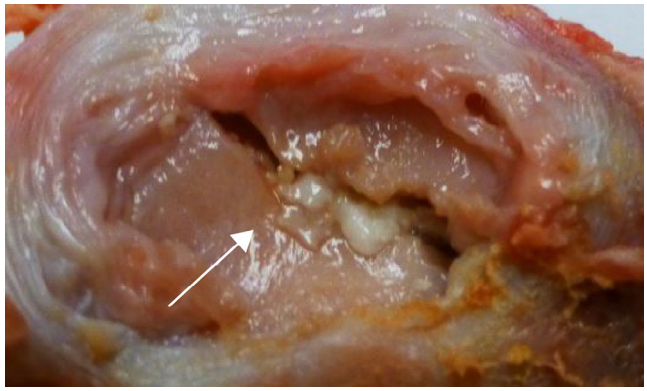

Fig. 6. Large cracks in the end plate (arrow) could not contain the hydrogel while the disc was under compression.

end plate still contained hydrogel (Fig. 7). Because specimens had returned to room temperature during dissection, the hydrogel had returned to its liquid state, but was easily distinguished from nucleus pulposus, given its comparatively lower viscosity at room temperature. Specimen height values were tracked throughout testing and expressed relative to their initial height; these values are presented in Tables 6 and 7.

Discussion

The hypothesis that hydrogel injection would alter rotational stiffness from the compressively fatigued state was supported. Hydrogel injection was observed to lower the normalized rotational stiffness levels close to their initial values.

Table 4
Specimen Group 1 normalized compressive stiffness values throughout testing trials

	Initial (%)	Fracture (%)	Fatigue loading (%)	Hydrogel injection (%)	PMMA injection (%)	Fatigue loading (%)
Specimen 1	100	124.0	113.6	83.8	124.0	134.5
Specimen 2	100	110.1	143.9	71.3	112.4	144.6
Specimen 3	100	80.0	103.6	89.8	109.3	139.5
Specimen 4	100	74.8	113.9	94.5	99.7	118.3
Specimen 5	100	58.3	81.9	69.4	57.3	81.5
Specimen 6	100	68.4	76.1	75.0	49.3	75.2
Specimen 7	100	42.7	74.2	85.1	73.1	80.3
Average (SD)	100	79.8 (25.2)	101.0 (25.4)	81.3 (9.6)	89.3 (29.3)	110.6 (30.7)

PMMA, polymethyl methacrylate; SD, standard deviation.

Table 5
Specimen Group 2 normalized compressive stiffness values throughout testing trials

	Initial (%)	Fracture (%)	Fatigue loading (%)	PMMA injection (%)	Hydrogel injection (%)	Fatigue loading (%)
Specimen 8	100	88.5	132.7	96.4	70.3	116.4
Specimen 9	100	84.1	150.8	127.4	46.8	112.1
Specimen 10	100	43.6	61.1	40.5	47.9	84.4
Specimen 11	100	39.8	67.4	63.4	47.8	121.0
Specimen 12	100	102.3	136.7	93.3	84.4	125.3
Specimen 13	100	53.9	65.4	77.5	89.6	95.9
Specimen 14	100	47.9	104.1	68.4	74.0	89.1
Average (SD)	100	65.7 (25.2)	102.6 (38.2)	81.0 (27.9)	89.3 (29.3)	106.3 (16.3)

PMMA, polymethyl methacrylate; SD, standard deviation.

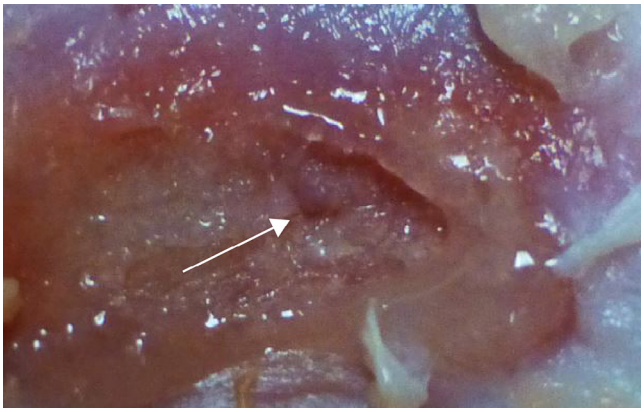

Fig. 7. Smaller fractures (arrow) that did not produce a breach in the end plate were able to contain the hydrogel.

This indicates that disc height has a significant effect on the rotational stiffness of a motion segment, but the integrity of the vertebral body also plays a role. The hypothesis that PMMA injection would alter compressive stiffness levels from the compressively fatigued state was also supported. In some specimens, compressive fatigue increased the normalized stiffness relative to the initial value, whereas in other specimens it was decreased. In general, PMMA injection was found to reduce the compressive stiffness, which meant that some specimens became more compliant than their initial values, whereas others returned closer to baseline.

Although the rotational stiffness measurements were clear in all cases, the hydrogel caused some confounding effects for the compressive stiffness measurements. With hydrogel injection, disc height was restored and stiffness decreased for all specimens. This indicates that although disc height could be restored, the disc could not regain the same hydrostatic pressure and resulted in greater deformation of the specimen under a compressive load. Although it was anticipated that PMMA would help to contain the hydrogel within the disc space, this proved to be a challenge in some specimens with large cracks in the end plate. It is posited that the hydrogel was able to migrate out of the disc space and into the cancellous bone of the vertebral body when axial compression was applied to specimens. Further, a trade-off must be made in terms of PMMA injection to prevent cement leakage into the disc. PMMA was injected above the fracture site at a level that would prevent cement leakage into the disc through the large cracks present in some specimens. If this had not been a concern, the cement could have been injected much closer, and containment of the hydrogel may have been enhanced by providing a more robust barrier between the disc and the cancellous bone of the vertebral body.

The results of this study agree with findings by Landham and colleagues [11] who found that vertebroplasty made a compressively injured spine specimen more compliant than initial values. They also found increased specimen compliance after repetitive loading injury, which is in contrast to the results from this study. There were slight differences, however,

Table 6
Specimen Group 1 height values throughout testing as given by the position of the hydraulic ram (negative indicates height loss)

	Initial (mm)	Fracture (mm)	Fatigue loading (mm)	Hydrogel injection (mm)	PMMA injection (mm)	Fatigue loading (mm)
Specimen 1	0.0	−2.1	−3.2	−0.6	−2.4	−3.2
Specimen 2	0.0	−1.8	−3.0	−0.3	−2.7	−3.9
Specimen 3	0.0	−3.2	−4.0	−2.0	−3.3	−4.7
Specimen 4	0.0	−4.2	−6.0	−3.6	−5.3	−6.2
Specimen 5	0.0	−5.0	−7.5	−5.1	−6.9	−8.3
Specimen 6	0.0	−5.2	−8.1	−5.3	−3.7	−7.9
Specimen 7	0.0	−10.1	−12.7	−11.6	−11.1	−12.9
Average (SD)	0.0	−4.5 (2.8)	−6.4 (3.4)	−4.1 (3.9)	−5.1 (3.1)	−6.8 (3.4)

PMMA, polymethyl methacrylate; SD, standard deviation.

All values were relative the initial height. Specimens lost height between the hydrogel injection and the PMMA injection stages owing to axial creep that occurred during the cement consolidation phase of PMMA injection.

Table 7
Specimen Group 2 height values throughout testing as given by the position of the hydraulic ram (negative indicates height loss)

	Initial (mm)	Fracture (mm)	Fatigue loading (mm)	PMMA Injection (mm)	Hydrogel injection (mm)	Fatigue loading (mm)
Specimen 8	0.0	−1.2	−2.3	−1.9	0.5	−2.5
Specimen 9	0.0	−3.1	−4.4	−4.4	−1.9	−4.5
Specimen 10	0.0	−3.5	−5.2	−3.7	−2.8	−5.8
Specimen 11	0.0	−4.7	−6.3	−6.3	−4.0	−7.6
Specimen 12	0.0	−4.2	−6.2	−5.6	−3.2	−6.2
Specimen 13	0.0	−3.3	−4.0	−4.7	−2.3	−6.0
Specimen 14	0.0	−5.5	−7.4	−5.1	−4.8	−7.3
Average (SD)	0.0	−3.6 (1.4)	−5.1 (1.7)	−4.5 (1.4)	−2.7 (1.7)	−5.7 (1.7)

PMMA, polymethyl methacrylate; SD, standard deviation.

All values were relative the initial height.

in the nature of the injuries produced between the two studies, which could explain the apparent difference. In terms of compressive stiffness, this study also agrees with work by Luo and colleagues [8,18] with regard to the pattern of compressive stiffness changes seen. One potential explanation for these results is the phenomenon of unloaded recovery on the part of the specimens. During PMMA injection, specimens are unloaded while undergoing needle placement and allowing the cement to properly set. Although they are reloaded during cement consolidation, it is possible that specimens are able to recover during this unloaded phase. What the cement provides is protection from further creep deformity [19].

This study shows that disc repair is a difficult proposition. Previous work on herniated discs has shown that the hydrogel is able to restore rotational stiffness characteristics and last through further cyclic flexion-extension motions [7]. This work reveals that end plate fractures make the situation much more complicated, with containment issues and the variety of injuries that can occur. Although the hydrogel was able to restore the rotational stiffness of each specimen to a degree, it could not fully bring back the initial stiffness characteristics in most cases. This would suggest that compressively fractured vertebral bodies play a role in the rotational characteristics of a spine motion segment.

Disc repair is a difficult endeavor, and there are currently many strategies in practice and research that attempt to accomplish it: from trying to promote cellular repair through stem cell injection [20], to total disc replacement [21], to the use of hydrogels [22], and preformed nuclear implants [23]. Ideally, disc repair would fully maintain the anatomical structures and restore their mechanical characteristics and cellular microenvironments. Current strategies seem to accomplish only some of these criteria, but continued work will bring full disc repair closer to reality. The strategy employed in this study attempted to maintain the disc's anatomical structures and restore the mechanical environment of the disc. Vertebroplasty could potentially disrupt nutrient delivery to the disc, at least in the end plate regions where it has coverage. There are works that suggest that vertebroplasty can initiate further degenerative changes in younger subjects [24,25], so caution should be exercised. Further work is also required to develop a more robust containment strategy for the hydrogel regardless of the injury. Kyphoplasty may offer a possible solution, with its ability to create space and restore height to a fractured vertebra [11], potentially allowing for greater cement distribution. This study is the first to attempt such a repair of a motion segment with the given strategy and offers valuable information for future attempts at mechanical repair of the injured disc.

Following further cyclic compressive loading, specimens returned to their injured mechanical profile. It is important, regardless of the repair strategy, that patients are trained and coached in proper movement strategies that do not replicate the mechanism of their injury. No repair strategy can sustain continued repetition of the conditions that caused the injury, as every material is prone to failure at some point. It is therefore imperative that patient education along with active monitoring and coaching on the part of the clinician be performed to prevent injury reoccurrence.

Limitations of this study include its use of a juvenile porcine model. Despite this, the porcine cervical spine has been shown to be a suitable analog for the human lumbar spine with respect to anatomy, geometry [26], and function [27] to discern injury mechanisms. This study also employed a crossover design to better understand the mechanical influence of both hydrogel and vertebroplasty interventions. Each of the interventions in this study would be performed simultaneously in a clinical setting and could potentially lead to better hydrogel containment in some cases. Despite this, the work presented here provides proof of principle evidence for the individual influence of hydrogel and vertebroplasty procedures to an injured spine segment under both axial compression and sagittal plane motions. This will aid in the selection of interventions for future repair attempts that may have increased complexity.

The present study has found that PMMA and hydrogel injections can improve the mechanical profile of a compressively injured spine segment. This is the first study to evaluate a combination of these procedures and assess the mechanical outcomes. The data from this work reveal that compressive injury produces a variety of fracture types that are not always simple to repair using a single strategy. In discs with large cracks in the end plate, containment for the hydrogel becomes an issue that needs to be addressed, as hydrogel is able to migrate into the cancellous bone of the vertebral body. Future work needs to develop more robust containment strategies for the hydrogel in the disc to facilitate its repressurization and enhance outcomes.

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