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The role of axial torque in disc herniation

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ABSTRACT

Background: Epidemiological studies have found associations between lifting, lifting and twisting and twisting alone with increased incidence of disc herniation. This study investigated the role of repeated dynamic axial torque/twist combined with repeated flexion on the disc herniation mechanism.

Methods: Porcine cervical spines were tested in one of the following four testing protocols: flexion–extension only; axial torque/twist only; flexion–extension followed by axial torque/twist; or axial torque/twist followed by flexion–extension. Plane film radiographs and computed tomography with contrast in the nucleus were obtained at regular intervals during and following the mechanical testing process together with final dissection to determine the disc injury patterns.

Findings: Axial torque/twist in combination with repetitive flexion extension motion, regardless of order, encouraged radial delamination within the annulus (67.5% of specimens). Alternatively, repetitive flexion motion alone encouraged posterior or posterolateral nucleus tracking through the annulus. Axial torque/twist alone was unable to initiate a disc herniation. Both X-ray images with contrast and computed tomography were not good at detecting radial delamination observed during dissection.

Interpretation: The clinical relevance is that twisting may cause more radial delamination while repeated flexion causes more posterior tracking of the nucleus giving guidance for both prevention and rehabilitation decisions. In addition, X-ray images with contrast are not effective at detecting the radial delamination which was exacerbated by combined loading in flexion extension and axial torque/twist.

1. Introduction

Epidemiological studies have found associations between lifting (Kelsey et al., 1984; Mundt et al., 1993), lifting and twisting (Kelsey et al., 1984; Mundt et al., 1993) and twisting alone (Greenough and Fraser, 1994) with increased incidence of disc herniation. While *in vitro* investigations confirmed that repeated flexion motion reliably produced herniations with relatively modest accompanying compressive loads, investigations involving axial rotation and torque have drawn mixed conclusions. This study investigated the role of axial torque/twist in producing disc herniation.

Two pioneering studies set the stage over 25 years ago. Adams and Hutton (1981) found more axial rotation was required to damage the intervertebral disc than that required to damage the facet joints in an acute loading protocol to failure. They concluded that axial rotation, within physiological ranges of motion, was not a major factor in the etiology of disc degeneration or disc prolapse. In contrast, Farfan et al. (1970) reached different conclusions with observations of circumferential tears in the posterolateral outermost annular fibers when spinal segments were exposed to repeated axial rotation and postulated a gradual communication would develop between the nucleus and the outside of the intervertebral disc with repeated axial rotation. Because of this it was his opinion that torsion was a precursor for disc pathology. Gordon et al. (1991) produced herniation with combinations of flexion and twist motion suggesting that twisting and twist torque have an exacerbating role in the herniation mechanism. The need to better understand axial torque/twist mechanics motivated this study.

The purpose of this study was to evaluate the role of axial torque/twist on disc herniation mechanisms. The following hypotheses were tested: (1) no disc herniation would be initiated in specimens loaded under axial torque/twist alone; (2) specimens loaded in repetitive flexion motion followed by axial torque/twist would have a posterior herniation as well as radial delamination; and (3) specimens loaded in axial torque/twist followed by repetitive flexion extension motions would produce posterior herniations with more serious tissue destruction. It is possible that axial torque/twist may predispose a disc when subsequently flexed, or it simply may not matter as long as the specimen is exposed to axial torque/twist at some stage of the loading regimen.

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2. Methods

Porcine cervical spines (mean age 6 months, weight 80 kg) were used for this study as they appear to approximate the failure mechanisms of human lumbar spines and provide control over age, diet, and exercise (Yingling et al., 1999). The spines were sectioned into functional spinal units consisting of the C5/C6 vertebrae and the intervening disc with the facet joints left intact. Only specimens which met Galante's grade one criteria of a normal disc were used for further testing (Galante, 1967). The intervertebral disc was injected through the anterior annulus with a radio-opaque dye mixture consisting of 0.1 mL blue dye (Coomassie brilliant blue Gmix; 0.25% dye, 2.5% MeOH and 97.25% distilled water), 0.2 mL water and 0.2 mL of barium sulphate in order to track the progression of the nucleus pulposus in plane film radiographs. The dye mixture was of a sufficient consistency that it did not diffuse into the annular fibers unless a fissure was present in the annulus (Callaghan and McGill, 2001) and did not track through the injection site.

The specimens were secured to steel cups by inserting a screw into the centre of the vertebral body together with 18 gauge galvanized wire looped bilaterally around both the anterior processes and lamina of the vertebral bodies. The cups were filled with non-exothermic dental stone (Denstone®, Miles, South Bend, IN, USA) to further secure the "potted" specimens. To maintain hydration during the testing protocol the specimens were wrapped in a saline soaked cloth and plastic wrap.

The specimens were placed in a servohydraulic dynamic testing system (model 8511, Instron Canada, Burlington, Ontario, Canada) customized to apply flexion motion and axial torque/twist (Fig. 1). The superior cup was fixated to the testing jig while the inferior cup was able to translate freely. This equipment setup enabled the disc to find its own torsion and bending axes. Flexion–extension motions were applied through an electrical brushless servomotor (model BNR3018D, Cleveland Machine Controls, Billerica, MA, USA) and planetary gear head (model 34PL0400, Applied Motion Products, Watsonville, CA, USA) which was controlled by custom software interfaced with an ISA bus motion controller (model DMC1701, Galil Motion Control, Mountain View, CA, USA) (Callaghan and McGill, 2001).

The servohydraulic testing system was also combined with a custom jig which was modified to incorporate a pneumatically driven torsion capability with load-rate control. The pneumatic system loaded the specimens under axial torque generating a first order response to a square wave pulse (upon opening of air valve) with an initial load rate of 24.0 Nm/s and final load rate of 6.2 Nm/s over a 1 s period. The two pneumatically driven pistons were set up in a parallel force couple to cause rotation of the specimens. Force was measured in each piston using two strain gauge force transducers (model MLP-300-C0, Transducer Techniques, Temecula, CA, USA) while linear displacement of the pistons was measured using a linear potentiometer (Novotechnik, Southborough, MA, USA). Angular rotation was calculated from the linear displacement data via the computed arc length.

The specimens were preloaded for 15 min with 300 N of compression to counter any swelling that occurred postmortem (Callaghan and McGill, 2001). A compressive load of 1500 N was used during the remainder of the testing protocol. Then a passive test was performed to find the linear region obtained from the angular displacement versus torque curves to determine the range of flexion and extension motion for subsequent tests. The ranges for testing were 12° (standard deviation 3°) in flexion and 6° (standard deviation 2°) in extension, thus actual ranges were specimen specific. This cyclic motion was conducted at 1 Hz in position control. During the axial torque/twisting protocol specimens were loaded with 17.5 Nm of axial torque to produce axial rotation to the left and 12.5 Nm of axial torque to produce axial rotation to the right. This right–left difference was simply due to pneumatic ram behavior. This right/left reversal of twist was applied at a rate of 0.5 Hz in load control. These levels of axial torque/twist were chosen from pilot work that revealed no visible damage to the facet joints under these loads.

In consideration to the three hypotheses we formed six test groups. The specimens were loaded according to one of the following six protocols: (1) 6000 cycles of repetitive flexion–extension motions followed by 2000 cycles of axial torque/twist; (2) 6000 cycles of repetitive flexion–extension motions followed by 4000 cycles of axial torque/twist; (3) 2000 cycles of axial torque/twist followed by 6000 cycles of repetitive flexion–extension motions; (4) 4000 cycles of axial torque/twist followed by 6000 cycles of repetitive flexion–extension motions; (5) 4000 cycles of axial torque/twist only; or (6) 6000 cycles of repetitive flexion–extension motions only. There were ten specimens in each of the testing groups except the repetitive axial torque/twist only which had five specimens. An X-ray image of the specimen was taken in the sagittal plane following the passive test and prior to dissection. A computed tomography scan of the specimen in the transverse plane was taken pre- and post-testing.

The following variables were recorded: endplate area; resulting flexion angle; resulting extension angle; injury pattern observed from dissection; and concordance between the dissection and the computed tomography scan and X-ray images. The endplate area was calculated as the average of the two exposed endplates using the formula for the surface area of an ellipse, $\pi/4 \times A \times B$, where A was the medial–lateral length of the exposed endplate and B was the anterior–posterior length of the exposed endplate (Tampier

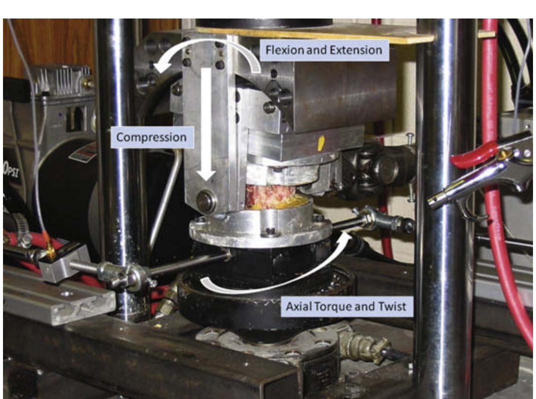

Fig. 1. The servohydraulic dynamic testing system customized to apply flexion motion and axial torque/twist.

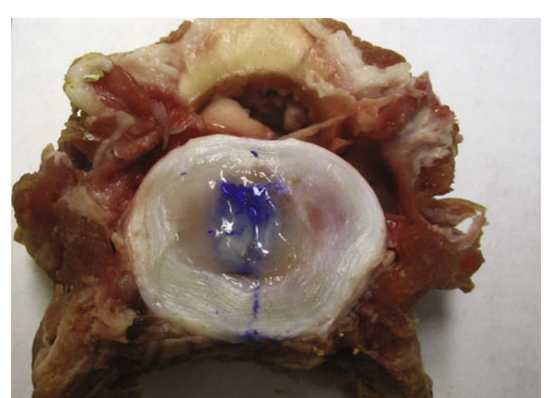

Fig. 2A. A dissected intervertebral disc with no herniation.

et al., 2007). The specimens were classified into one of the following three injury patterns: (1) no herniation (Fig. 2A); (2) posterior or posterolateral herniation (Fig. 2B); or (3) posterior herniation with radial delamination (Fig. 2C). The concordance was classified into one of the following three categories: (1) no match with the dissected specimen; (2) partial match with the dissected specimen; or (3) complete match with the dissected specimen. The concordance was considered partial if a herniation was evident in the X-ray image or computed tomography scan, however, dissection also revealed radial delamination. The following variables were calculated from the axial torque portion of the study: axial torque stiffness during axial rotation to the left; axial torque stiffness during axial rotation to the right; axial rotation to the left from neutral; and axial rotation to the right from neutral. Axial torque stiffness was taken as the slope of the angular displacement versus axial torque curve at between 15–17 Nm during axial rotation to the left and 10–12 Nm during axial rotation to the right (at the end range of motion). These variables were calculated after 100, 1000, and 2000 cycles of axial torque.

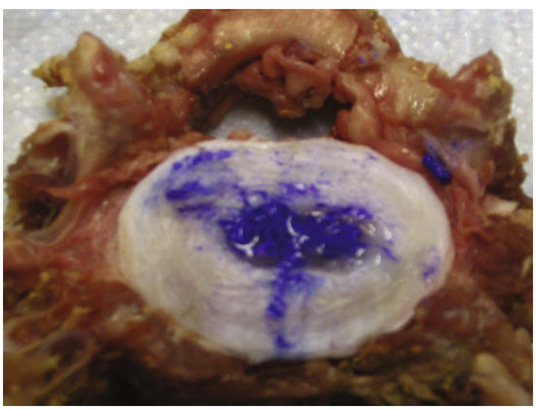

Fig. 2B. A dissected intervertebral disc with a posterior herniation.

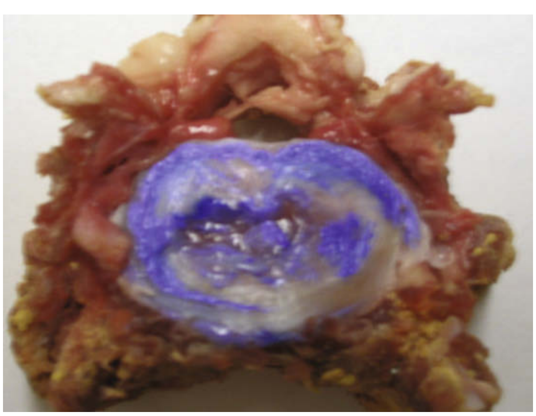

Fig. 2C. A dissected intervertebral disc with a posterior herniation as well as radial delamination.

Differences in the values of the resulting flexion angle, resulting extension angle, and endplate areas were assessed with a one-way ANOVA. A three-way ANOVA evaluating the effects of axial torque cycles, order and time assessed differences due to axial rotation to the left, axial rotation to the right, axial torque stiffness during axial rotation to the left, and axial torque stiffness during axial rotation to the right. The least significant differences post hoc test was used to assess differences found during both the one-way ANOVA and three-way ANOVA. A chi-square approach assessed differences due to injury patterns observed post dissection, and the concordance found between the X-ray images or the computed tomography scan with the post dissection injury pattern.

3. Results

There were no differences between the groups in either the resulting flexion angles, resulting extension angles or the endplate areas of the specimens suggesting homogenous test groups.

Axial torque/twist with flexion–extension motions increased damage over simply flexion–extension alone. Whether axial torque/twist proceeded the flexion cycles, or followed the flexion cycles, there were no differences in injury patterns between the two ($P = 0.5296$). Therefore, these four groups were collapsed into one group (combined group) and compared with the injury patterns of the flexion-extension only group. Differences were found between the injury patterns of the combined group (exposed to axial torque/twist) compared to the flexion-extension only group ($P = 0.0139$). The combined group had more specimens with a posterior herniation as well as radial delamination while the flexion-extension only group had more specimens with only posterior or posterolateral herniations (Table 1). None of the specimens exposed to axial torque/twist alone herniated after 4000 cycles of axial torque/twist and therefore were not included in these analyses.

No differences were found in the concordance between the X-ray images and dissection or the computed tomography scan and dissection ($P = 0.9661$) (Table 2). However, it was worthy to note that five of the computed tomography scans were able to detect some radial delamination while zero of the X-ray images were able to detect radial delamination.

There was an increase in stiffness ($P < 0.0001$) at the final end ranges of axial torque/twist with increasing cycles of axial torque/twist.

4. Discussion

The first hypothesis was supported as the specimens loaded in axial torque/twist alone did not herniate after 4000 cycles of axial torque/twist. The results from the present study compared well to previous research which also found axial torque alone was not able to initiate disc herniations (Adams and Hutton, 1981). The second hypothesis was also supported in that specimens loaded in repetitive flexion–extension motions followed by axial torque/twist encouraged a posterior herniation as well as radial delamination. In this way, Farfan's (1970) impressions appear to have merit as not only did axial torque/twist exacerbate damage but the tendency for radial delamination between layers of the annulus appeared to be more on the outer annulus. The third hypothesis

Table 1
A table comparing the injury patterns of the combined group and the flexion–extension only group in order to identify differences between their injury patterns.

	Total number of specimens	No herniation		Posterior or posterolateral herniation		Posterior herniation and radial delamination	
		Number	Percent	Number	Percent	Number	Percent
Combined group	$n = 40$	9	22.5	4	10	27	67.5
Flexion–extension only	$n = 10$	4	40	4	40	2	20

Table 2
Concordance between the X-ray images or computed tomography scan and post dissection injury pattern.

	No match		Partial match		Full match	
	Number	Percent	Number	Percent	Number	Percent
Computed tomography scan	6	15	23	57.8	11	27.5
X-ray image	6	15	24	60	10	25

was not supported as there was no difference in the injury patterns of the specimens exposed to axial torque/twist either preceded or followed by flexion–extension motions. Therefore, the order of twist exposure does not appear to matter, but rather twist exposure at any point during loading appears to encourage radial delamination.

The observation of the combination of repetitive flexion–extension motions and axial torque/twist encouraging posterior herniations with radial delamination extends the literature. Gordon et al. (1991) also found lumbar motion segments failed by nuclear extrusion and annular protrusion when loaded repetitively in flexion, rotation, and compression; however, the authors did not discuss if radial delamination was present. The repetitive flexion–extension motions only observed in the present study encouraged posterior or posterolateral disc herniations when taken to 6000 cycles. Therefore, axial torque/twist in combination with repetitive flexion–extension motion appeared to play a role in the progression of the nucleus pulposus through the annular layers by encouraging radial delamination.

Contrary to the hypothesis made by the pioneering work of Adams and Hutton (1981), the intervertebral disc was compromised by repetitive axial torque/twist without damaging the articular facet joints. Perhaps the number of cycles in this study made a difference since Adams studied acute loading to failure. Perhaps radial delamination is a more subtle injury mechanism. Farfan et al. (1970) hypothesis that disc damage is initiated by twist may only be partially true since the order of twist and flexion exposure did not seem to matter in this study. Certainly axial torque/twist alone did not lead to intervertebral disc herniations when taken to 4000 cycles of axial torque/twist. Only the combination of both axial torque/twist and repetitive flexion–extension motions led to disc herniation. Interestingly, Haughton et al. (2000) compared the response of cadaveric lumbar motion segments with normal discs to those with transverse tears and radial tears generated using axial torque. The authors found the axial rotation of the normal intervertebral discs (1–1.2°) was significantly smaller compared to the intervertebral discs with transverse tears (2.5–2.7°) or radial tears (2.5–2.6°) suggesting more extensive annulus damage.

Both X-ray images (with contrast) and computed tomography scans are used to diagnose intervertebral disc herniations (Mundt et al., 1993; Gordon et al., 1991; Butler et al., 1990). In the present study no differences were found in the ability to detect herniation damage using the X-ray images versus the computed tomography scans. However, only the computed tomography scan was able to detect radial delamination in a small percentage of cases. X-ray images, even with contrast, were not able to detect this type of damage.

The main limitation of this study was the inability to prevent possible loosening of the mounted specimens in the cups during the twisting fatigue test. However, since the twisting torque was constant as it was pneumatically applied, the injury process should be unaffected. Another limitation of the current study was using an animal model to determine the effect of axial torque on disc herniation mechanisms. However, previous work has shown the porcine cervical spines were a good approximation to the human lumbar spine functionally (Tampier et al., 2007), geometrically and anatomically in terms of annulus and facet structure (Yingling et al., 1999) and most closely resemble the lumbar spine of a human adolescent (Oxland et al., 1991). The porcine intervertebral disc has also been found to be microscopically and macroscopically similar to the disc of human lumbar spines (Tampier, 2006).

5. Conclusions

In summary, axial torque/twist in combination with repetitive flexion–extension motions, regardless of order, encouraged radial delamination within the annulus. Alternatively, repetitive flexion motions alone encouraged posterior or posterolateral tracking through the annulus. The clinical implication is that prevention and rehabilitation approaches for disc herniations should minimize loading of the spine in axial torque/twist. In addition, X-ray images are not effective at detecting the radial delamination which was exacerbated by combined loading in flexion extension and axial torque/twist.

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