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Biomechanical Factors Influencing Nuclear Disruption of the Intervertebral Disc

David I. Simunic, BE,* Neil D. Broom, PhD,* and Peter A. Robertson, MD FRACS†

Study Design. A disc model with full anular division was used to investigate how different biomechanical parameters influence the severity of nuclear disruption during compressive loading.

Objective. To quantify the manner in which flexion, hydration, and loading rate contribute to the breakdown in the intrinsic cohesive structure of the nucleus pulposus.

Summary of Background Data. The risk of disc herniation is known to increase when the disc is loaded in flexed positions. However, there is a lack of experimental data showing how a combination of flexion with different loading rates and hydration levels affects the extent of nuclear disruption.

Methods. A reproducible state of full hydration was established for isolated bovine caudal discs. A period of static preloading at an applied stress of 1 MPa was used to obtain a consistent state of partial hydration. Then 96 discs were subjected to a full-thickness division of the anulus fibrosus and compressed while hydration level, degree of flexion, and rate of loading were varied systematically.

Results. A full spectrum of nuclear damage was observed in the tests, ranging from no detectable disruption to sudden sequestration of the entire nucleus. These results were quantified, and a general correlation was established between the severity of disruption and the different loading parameters.

Conclusions. The degree of flexion and the level of hydration were shown to play an important role in influencing the tendency of the nucleus to break loose and extrude through a preexisting anular division. Interestingly, the rate of loading appeared to have only a minor effect on the severity of damage induced in discs that incorporated a full depth anular division. [Key words: disc prolapse, intervertebral disc, spine biomechanics] **Spine 2001;26;1223–1230**

In vitro loading experiments with the intervertebral disc have demonstrated consistently that it is very difficult to induce a prolapse using direct compressive loading. Almost invariably, the vertebral bodies are damaged first, with the anulus remaining largely intact.[3,8,9,33]

Clinically, however, there is substantial evidence linking disc prolapse with sudden loading while the subject's posture is flexed.[18,20] Furthermore, studies have identified high-risk factors for disc prolapse and low back pain when whole body vibration[7,26,34] is combined with flexion, compression, or rotation.[4,16] Epidemiologic studies suggest that people whose work involves repetitive bending and lifting have a 300% to 600% increased risk of acute lumbar disc prolapse.[11] It is thought that bending stretches and thins the posterior anulus fibrosus in the axial direction, thus rendering the disc more vulnerable to prolapse if the hydrostatic pressure in the nucleus pulposus is raised simultaneously.

A randomized prospective study by Snook et al[29] demonstrated that there is a significantly lower risk of back pain if flexion is avoided in the morning when the intervertebral discs are maximally hydrated.[2,30,31] It also is well established that the level of disc hydration strongly influences its mechanical properties.[6,12,24] Furthermore, a very recent study by Race et al[27] demonstrated a strong dependence of the disc's modulus on both loading rate and level of hydration. In their study, loading rates spanning six orders of magnitude were investigated in detail, and the modulus was shown to increase progressively with an increase in the loading rate up to approximately 1 MPa per second, beyond which little further change was observed. The influence of hydration on disc stiffness was more complex. At the lower loading rates, the modulus was low and relatively insensitive to creep-induced dehydration, but with increasing loading rate, the modulus was increasingly sensitive to the level of hydration.

This behavior is generally consistent with that of other heavily hydrated biologic tissues in which deformation under slowly applied external loading proceeds *via* a consolidation-type process.[21] The controlling mechanism in consolidation involves the time-dependent outflow of matrix fluid through an ultra-low permeability structure. As the rate of loading increases, this fluid outflow becomes more difficult, thus increasing the effective dynamic stiffness of the structure.[17,21,22,27,28]

The current study aimed to investigate how the preceding factors, which are known to affect the disc, combine to influence disruption of the nucleus pulposus. The nucleus pulposus is a gel structure that derives its internal strength from a network of poorly differentiated collagen fibers intimately associated with proteoglycan complexes.[10,15] The latter generate the osmotic properties of the nucleus. The fibers from the innermost layers of the anulus fibrosus pass into the nucleus and blend to provide an important element of structural cohesion with little clear demarcation between the inner anulus and the nucleus.

Any degree of disc prolapse will cause the nucleus to move intra-anularly. Whether this results directly from traumatic or from degenerative weakening of the anular

From the *Department of Mechanical Engineering, University of Auckland, and the †Department of Orthopaedic Surgery, Auckland Hospital, New Zealand.
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wall, any movement of nuclear material must involve some degree of breakdown in the internal cohesiveness of the nucleus, or in its attachment to the inner anulus and endplates. There is thus a fundamental reliance of the disc on this cohesive property, which is not directly accessible to experimental quantification.

The current study is not concerned with prolapse under normal physiologic conditions, but rather with the biomechanical parameters governing nuclear disruption and possible sequestration under defined conditions, in which a potential exit path through the anular wall is already provided. The focus is on the internal cohesiveness of the nucleus and its attachment to the inner anulus and endplates. This report therefore presents a systematic experimental study of how the level of hydration in the disc, combined with loading rate and flexion, affects the process of nuclear disruption.

Methods

Because the current investigation was concerned with the fundamental biomechanical parameters influencing ease of nuclear disruption, an animal model was chosen to ensure a reliable supply of healthy specimens, thus eliminating the complicating factor of disc degeneration. All experiments were conducted on caudal intervertebral discs obtained from approximately 2-year-old bovine animals. The tissue was obtained from the local abattoir within 4 hours of slaughter, wrapped in plastic film, and stored whole at −20 C until needed.

Part A: Hydration Studies.

To control the degree of disc hydration, it was necessary to establish a reproducible level of hydration. Dehydrating the disc fully was not a feasible option because irreversible damage might have occurred in the disc, thus changing its mechanical response. Therefore, the fully hydrated state of the isolated disc was chosen as a standard reference point. Although this fully hydrated state is not experienced *in vivo* because of the normal resistive constraints provided by the surrounding tissues, it does provide a means of comparing disc responses under widely differing, but defined, levels of hydration. A preliminary study therefore was carried out to determine whether a fully hydrated state could be reproduced reliably within a disc, and also to establish what minimum time was required to achieve this fully hydrated state.

Specimen Preparation. The bovine tails were thawed at 4 C, after which the intervertebral discs were isolated completely and the extraneous muscles and ligaments removed. The adjacent vertebral bodies were sawn through a transverse plane, leaving less than 3 mm of bone adjacent to the disc. Using wet carborundum abrasive paper, the vertebral bone at both ends was ground flat and parallel to the midtransverse plane of the disc until approximately 2 mm of bone remained. The surface of the inferior vertebra then was glued to a stainless steel plate with Loctite 454 cyanoacrylate instant adhesive.

Method of Measuring Swelling Profiles. The specimens were submerged in a bath of 0.15 mol/L physiologic saline and allowed to equilibrate at room temperature before any subsequent load was applied. A small amount of sodium azide also

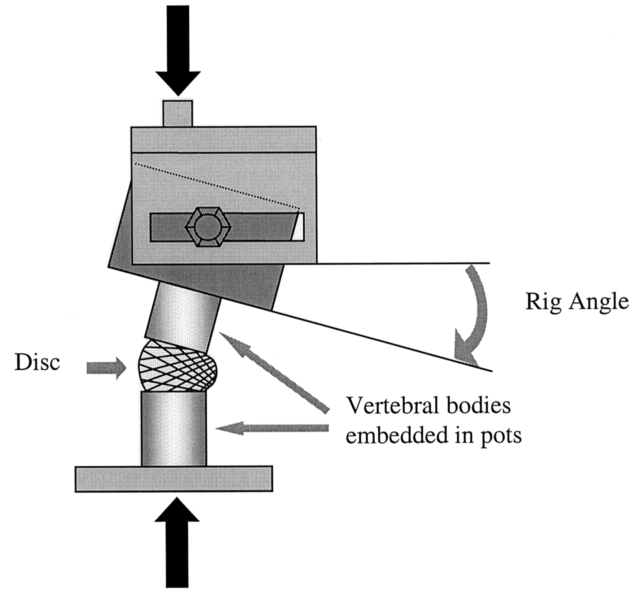

Figure 1. Schematic of the rig used to introduce a component of flexion into the sagittal plane before compression. The required rig angle was determined from radiographs of the whole tails and the orientation of the vertebral bodies within the pots.

was added as an antibacterial agent (0.004% wt/wt) because the monitoring period could extend to several days. To measure the change in disc height, a computer sampled the output from a linear variable differential transformer displacement transducer whose core (<1 g) rested on the disc and moved as the disc swelled. This transducer was calibrated and found to be linear (R^2=0.999) over a range of 0 to 4 mm (±0.08 mm). The disc then was loaded statically at 0.73 MPa for a time and allowed to recover in a saline bath until its initial height was restored. This process then was repeated with reduced durations of loading. Altogether, six discs were used for this hydration study.

Part B: Mechanical Testing.

Specimen Preparation. Freshly collected bovine tails were radiographed whole in both their flexed and nonflexed postures before they were wrapped in plastic film and stored whole at −20 C. The angular orientation of each vertebra was determined from the radiographs, then used later to reproduce the angle required for the testing of each individual motion segment. The flexed state was obtained by using a rubber band to apply a small bending force to each end of the intact tail in the sagittal plane. The nonflexed state was defined by inverting the tail so that the dorsal face was downward and the tail straightened under its own weight. These two anatomic positions reflected the maximum and minimum curvatures that could be induced elastically in the tail by applying minimal force.

In preparation for mechanical testing, the tails were thawed at 4 C, after which complete motion segments (consisting of adjacent vertebrae and intervening disc) were excised and prepared as for the hydration studies described earlier, then allowed to hydrate fully. To complete the preparation for testing, the vertebral bodies were set in stainless steel pots using dental plaster, with the disc and pot axes coaxial (Figure 1).

Compression Tests. Compression of the prepared discs was conducted using a computer-controlled servohydraulic testing

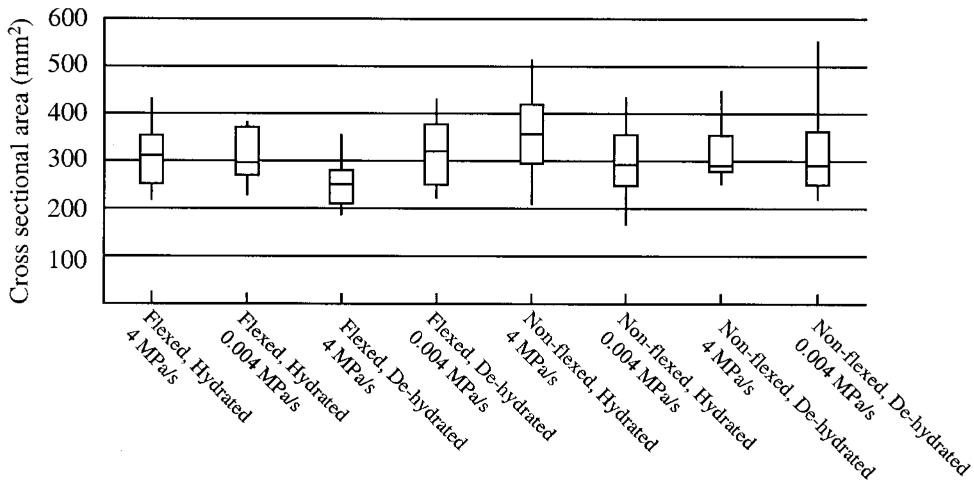

Figure 2. Plot showing distribution of cross-sectional areas in each of the eight testing categories.

machine (MTS Systems Corporation, Minneapolis, Minnesota). Load, displacement, and time were recorded at 0.01-mm increments. All tests were performed at room temperature, and the disc was kept moist with 0.15 mol/L saline to prevent dehydration.[25]

Each of the three variables (*i.e.,* flexion, loading rate, and hydration level) was investigated independently by testing in two contrasting conditions. The states of flexion obtained from the radiograph data (see earlier) were defined as full flexion and no flexion. A specially constructed adjustable rig allowed either of these orientations to be imposed on the potted disc assembly (Figure 1) immediately before the compression began. The rig angle necessary to reproduce the desired flexed or nonflexed orientation during testing was determined by comparing the radiograph data from the intact tail and the potted motion segments.

It was noted that whereas the caudal region of the bovine spine is kyphotic, the human lumbar spine is lordotic. In this study, the caudal discs were flexed such that the posterior anulus was stretched as in a forward-flexed human lumbar disc. It also was noted that the vertebral endplates in the human spine are relatively flat or even slightly concave, whereas the bovine caudal endplates are convex. Therefore, although forward flexion will induce wedging of the disc in both cases, only a qualitative comparison can be made between the two anatomic systems.

In the bovine caudal spine the disc area decreases progressively with each caudal spinal level. To minimize the influence of this variation in the testing program, the full range of disc sizes were spread through each of the eight testing categories (Figure 2). All the force data were normalized to stress values by dividing by the cross-sectional area of each disc, which was calculated by assuming a circular shape and taking the mean of the midsagittal and midcoronal diameters, as measured using vernier callipers. The maximum and minimum loading rates were 4 and 0.004 MPa/second, respectively. Put into a clinical perspective, for a human lumbar disc, a loading rate of 4 MPa/second is approximately equivalent to an applied load of 8.5 body weights per second, based on an average disc area of 1600 mm^2 and an average body weight of 75 kg.

The levels of hydration tested were fully hydrated (*i.e.,* at least 20 hours in 0.15 mol/L saline bath) and partially hydrated. The partially hydrated state was obtained by applying a 1-MPa static load to a fully hydrated disc for 30 minutes before the actual compression test. This stress roughly equals the load experienced by a lumber disc during light manual labor.[19]

Immediately before compression testing, a division through the full thickness of the posterior anular wall in the midsagittal plane spanning the full height of the disc was made with a scalpel. An upper load limit of 25 MPa was set to protect the testing equipment from accidental overloading. This load limit was high enough to ensure that it was not reached during a normal test. To examine the morphology of a failed disc, it was necessary to stop the test quickly when a failure occurred to prevent the specimen from being totally crushed. If no obvious external failure was observed visually, the compression was continued until endplate contact occurred, as determined previously from radiograph data of pretest endplate separation. At the point of endplate contact, it was assumed that a failure of the disc would not occur before the vertebral bodies were crushed.

After testing, the intervertebral disc was sectioned through its midtransverse plane and photographed. The nucleus pulposus then was examined with a blunt probe for evidence of disruption. A total of 96 discs were tested in this part of the investigation, 12 discs in each of the eight categories.

Results

Results of Preliminary Hydration Study

Representative data showing disc height compared with hydration time are presented in Figure 3. The data shows that the height of the intervertebral disc increases at a decreasing rate as it hydrates.

All six discs tested showed similar hydration profiles, thus indicating that the decrease in disc height, and therefore the hydration level, depends on the duration of the static preload. The disc in Figure 3 was hydrated from its thawed state of unknown hydration level before being loaded at 0.73 MPa for 1.5 hours and then allowed to recover. Once the initial disc height was restored, the process was repeated successfully twice at the same stress, with loading durations of 1 and 0.5 hours, respectively. The results indicate that a static preload can be used to induce varying hydration levels within a disc. This finding concurs with that of earlier studies suggesting the use of a preload to consolidate the disc partially and reduce the level of hydration.[25] The data in Figure 3 also demonstrate that a high degree of repeatability ex-

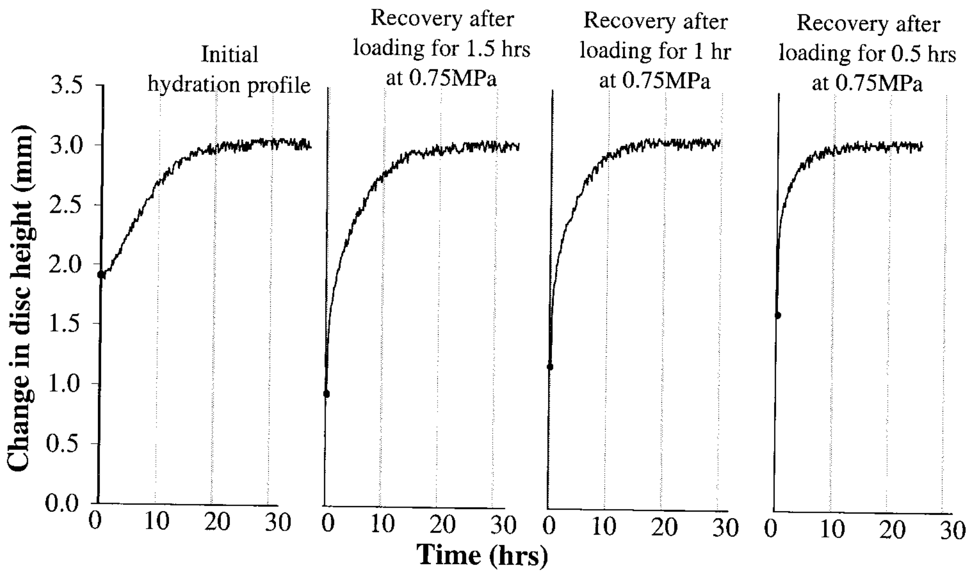

Figure 3. Typical hydration profiles from a disc hydrated fully from its initial thawed state, then loaded and left to rehydrate repeatedly over three such cycles.

ists in the maximum disc height obtained when a disc has been fully hydrated.

The change in disc height is not uniform across the disc cross section. Figure 4 shows representative anterior, posterior, lateral, and middle swelling profiles for disc-free swelling in physiologic saline at room temperature. Maximum swelling occurred posteriorly, and minimum swelling anteriorly. Lateral swelling was approximately uniform and occurred between the anterior and posterior magnitudes. This increased swelling of the disc posteriorly, which contributes to the natural curvature of the tail, is analogous to the increased anterior disc height in the human lumbar spine contributing to lumbar lordosis. It can be seen that all height changes stabilized at approximately the same time. Therefore, this study assumed the disc to be hydrated maximally when the central height stabilized, which occurred after approximately 20 hours. Importantly, this finding is in

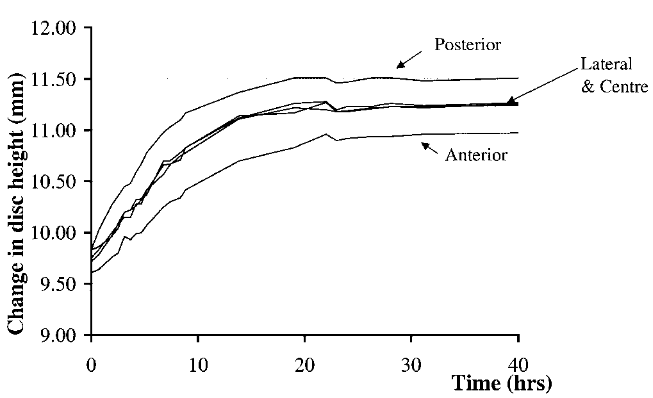

Figure 4. Typical swelling profiles for different positions on the transverse plane of the disc. The disc swells unevenly. Maximum and minimum swelling occurs posteriorly and anteriorly, respectively.

agreement with the hydration study of human discs carried out by Pflaster et al[25]

Mechanical Studies

To quantify the damage caused to the disc nucleus, each specimen was put into one of five categories based on a combination of the following: 1) observation of a sequestered prolapse (sometimes violent) or an intra-anular prolapse during testing, and 2) careful examination of the freshly tested and transected disc with a blunt probe. The categories, ranging from no detectable damage to severe damage, were assigned a weighting value (W) from 0 to 4, reflecting the severity of the damage. The severity of damage was evaluated in terms of cleft area, using a series of graded templates, and expressed as a percentage of total disc area. The values of 2% and 5% were chosen to differentiate, respectively, between moderate and serious disruption in discs with or without some intra-anular movement of nuclear material. Figure 5A to 5E shows representative specimens from each of the five categories described as follows:

W = 0 (no detectable damage to the nucleus)

W = 1 (incipient cleft formation in which the measured cleft area is less than 2% of the total disc area)

W = 2 (overt cleft formation, including nondisplaced nuclear separation, in which the measured cleft area is greater than 2% of the total disc area)

W = 3 (intra-anular nuclear displacement, either partially attached or free, in which the measured area of the cleft is less than 5% of the total disc area, as well as sequestered nuclear prolapse, in which the cleft area is less than 5% of the total disc area)

W = 4 (intra-anular nuclear displacement, either partially attached or free, in which the cleft area is greater than 5% of the total disc area, as well as sequestered

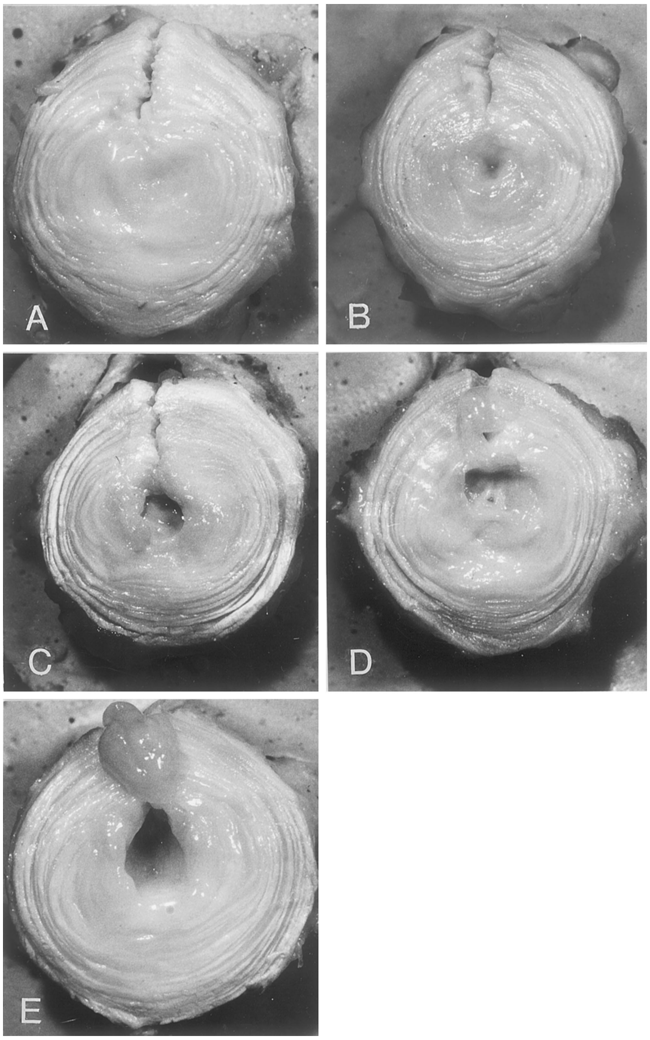

Figure 5. Photographs of representative discs illustrating each of the five categories used to quantify the degree of disruption resulting from compressive testing. **A,** W = 0 (no detectable damage to nucleus). **B,** W = 1 (incipient cleft formation: cleft area less than 2% of the total). **C,** W = 2 (overt cleft formation, including nondisplaced nuclear separation: cleft area more than 2% of the total). **D,** W = 3 (intra-anular nuclear displacement or sequestered nuclear prolapse: cleft area less than 5% of the total). **E,** W = 4 (intra-anular nuclear displacement or sequestered nuclear prolapse: cleft area more than 5% of the total).

nuclear fragments, in which the cleft area is greater than 5% of the total disc area).

The choice of a 2% cleft area to differentiate between moderate and serious disruption in discs with no intra-anular movement of nucleus appears to be justified if a visual comparison is made between Figure 5B and 5C. Similarly, using the value of 5% to differentiate between moderate and serious disruption in discs that experienced intra-anular movement of nuclear material seems to be justified by a visual comparison of Figure 5D and 5E.

Given that each of the three biomechanical parameters (flexion, hydration level, and rate of loading) were investigated in two contrasting states, eight combinations of test conditions were applied. For each group of discs tested with the same biomechanical parameters, an average damage weighting (ADW) value was calculated using the following method.

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where k is the total number of categories, w_i is the weighting for category i, x_i is the number of specimens in category i, and n is the total number of specimens.

Fully Flexed and Fully Hydrated

Examination of all 24 discs showed damage to some degree involving nuclear sequestration, cleft formation, or both. The ADW for the discs tested at 4 MPa/second was 3.33, and that for the discs tested at 0.004 MPa/second was 3.25.

Fully Flexed and Partially Hydrated

All 24 discs in this category experienced some damage, although the degree of damage generally was less severe than in the fully flexed and fully hydrated category. The ADWs for the discs tested at 4 and 0.004 MPa/second were 3.08 and 2.67, respectively.

Nonflexed and Fully Hydrated

The ADW for the discs tested at 4 MPa/second was 2.25, and that for the discs tested at 0.004 MPa/second was 2.17.

Nonflexed and Reduced Hydration Level

The ADW for the discs tested at 4 MPa/second was 1.50, whereas the ADW for the discs tested at 0.004 MPa/second was 1.42.

Analysis of Variance

A three-way analysis of variance (ANOVA) was performed on the ADW data in Table 1. The results show that both the degree of flexion and the degree of hydration are highly significant ($P < 0.001$ and $P < 0.003$, respectively). By contrast there is no significant contribution to nuclear disruption from loading rate ($P = 0.37$). The ANOVA also demonstrated that all the interaction terms were negligible ($P > 0.37$).

■ Discussion

The hydration investigation demonstrated that a reproducible physicochemical reference point of full hydration can be established for the intervertebral disc by equilibrating in physiologic saline for a period of at least 20 hours. Furthermore, by applying a known static stress for a defined period, a reproducible state of partial hydration can be induced.

The fully divided anular wall model demonstrates that prolapse can be induced consistently in the healthy disc by using high levels of hydration and flexion. Thus, these two parameters are biomechanically important in determining whether the cohesive strength of the nucleus or that of the nucleus/anulus/endplate interconnectivity is degraded during compressive loading. By contrast, the loading rate would appear to have no significant role in the fully divided anular wall model.

The ability to induce nuclear extrusion in this study contrasts strongly with the study of Brinckmann,[8] who similarly used a nearly complete division of the anular

Table 1. Number of Discs in Each Damage-Weighting Category and the Average Damage-Weighting Value for Each Group

Test Parameters	Load Rate MPa/sec	Damage-Weighting Value (W) 0	1	2	3	4	Average Damage Weighting (ADW)
Fully flexed and fully hydrated	4	—	—	1	6	5	3.33
	0.004	—	—	—	9	3	3.25
Fully flexed and hydration reduced	4	—	—	—	11	1	3.08
	0.004	—	1	3	7	1	2.67
Nonflexed and fully hydrated	4	1	1	5	4	1	2.25
	0.004	1	3	1	7	—	2.17
Nonflexed and hydration reduced	4	4	1	4	3	—	1.50
	0.004	3	4	2	3	—	1.42

MPa = megapascal.

wall and found that extrusion could not be induced before vertebral collapse occurred. He concluded that a radial division of the anulus is not sufficient to produce a clinically relevant disc herniation. Brinckmann[8] argued that further prerequisites are a fragmentation of the disc material and a separation from the endplates, which occur in the degenerate and dehydrated nucleus. However, the systematic varying of the flexion, hydration, and loading rate in the current study clearly demonstrates that a full range of nuclear disruption can be achieved during compression testing of healthy discs with a preexisting anular division. Specifically, healthy discs compressed while fully flexed and fully hydrated are highly susceptible to intra-anular prolapse through an existing anular division. In the current study, all but one disc experienced intra-anular prolapse (*i.e.,* ADW = 3 or 4) when compressed in the flexed state while fully hydrated.

The ADW values shown in Table 1 provide a means of quantifying the relative influence of all three biomechanical parameters by inducing nuclear disruption in the healthy disc. When the influence of full flexion was compared with that of no flexion while the fully hydrated condition was maintained, the ADW dropped from 3.33 to 2.25 at the high loading rate. A similar trend was observed at the low loading rate (*i.e.,* 3.25 down to 2.17). With partial dehydration, the same trend was observed at both loading rates, but with overall lower values of ADW. That is, for full *versus* no flexion, they dropped from 3.08 to 1.50 at the high loading rate and 2.67 to 1.42 at the low rate. In the flexed mode, a proportionately large number of discs (43 of 48) exhibited some degree of nuclear displacement during testing (*i.e.,* ADW = 3 or 4 as shown in Figure 5D and E). By contrast, in the nonflexed mode, only 18 of 48 discs displaced nuclear material. Thus, flexion is a primary risk factor in disruption of the healthy disc nucleus. This finding is consistent with the established literature concerning the problem of prolapse in the human intervertebral disc.[3,5,19]

Combined flexion and compressive loading causes a wedge effect that tends to displace nuclear material from the narrow to the open end of the wedge as a result of the Poisson effect. The schematic in Figure 6 shows the axial displacement caused by the combined modes of flexion and compressive loading. If the stress is sufficient to break down the internal structure of the nucleus, the

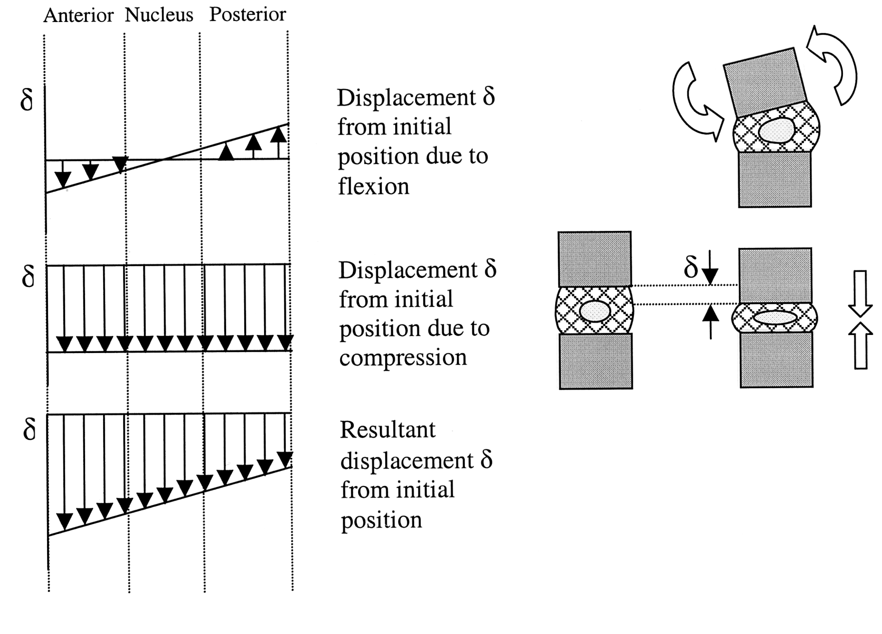

Figure 6. Schematic illustrating displacement of disc caused by combined modes of flexion and compressive loading.

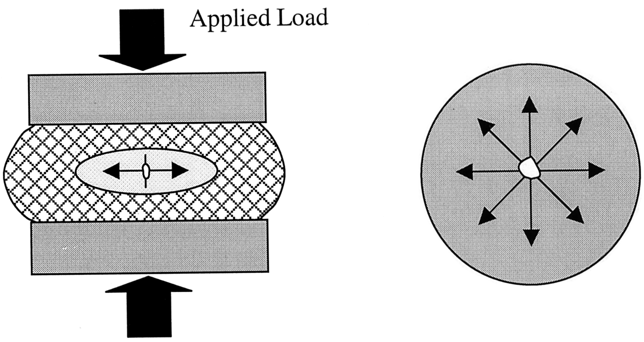

Figure 7. Schematic illustrating cleft formation in nucleus caused by radial stress (arrows).

wedge effect will extrude nuclear material through the preexisting port in the posterior part of the anulus. Without the component of flexion, the compressive load will generate a more uniform pattern of radial stress. This may be sufficient to disrupt the internal structure of the nucleus and form clefts, but the nuclear material will be less likely to migrate through the division in the anular wall because of symmetry in loading. The more symmetrical clefts visible in Figure 5B and 5C most likely resulted from the pattern of radial stress induced in the nucleus of the nonflexed disc as it bulged under direct compressive loading. This effect is illustrated schematically in Figure 7.

Comparing the influence of full and partial hydration with the fully flexed state maintained, the ADW values drop from 3.33 to 3.08 at the high loading rate and from 3.25 to 2.67 at the low loading rate. With the nonflexed state, a similar influence of full *versus* partial hydration was observed: The ADW values dropped from 2.25 to 1.5 at the high rate and from 2.17 to 1.42 at the low rate. Therefore, as with flexion, full hydration also is a primary risk factor in nuclear disruption. Consequently, any rigorous investigation of disc prolapse must consider the important influence of high hydration levels associated with diurnal changes.[2,29,30]

A recent study investigating the consolidation behavior of the intervertebral disc has suggested a mechanism by which the level of hydration might influence the response of the nucleus to compressive loading.[22] Resistance to an applied compressive load is shared between the disc nucleus and the anulus. As loading continues, a pore pressure is developed within the nucleus of the disc. This pressure reaches a maximum and then decays slowly as the fluid is expelled through the ultra-low permeability structure of the disc. The maximum pore pressure developed in healthy discs is 30% to 90% greater than the nominal applied stress.[17,22] Initially, therefore, the major fraction of the applied stress is carried by the hydrated nucleus. Over time, as the nucleus consolidates, the bulk of the applied load is transferred progressively to the anulus. Therefore, the resistance to the applied load provided by the nucleus for a partially hydrated disc will be significantly lowered, thus reducing the risk of nuclear disruption.

Somewhat surprisingly, the current study demonstrated a negligible influence of loading rate on disruption in the fully divided anular wall model. Considering the relatively large increase in stiffness of the disc with increasing loading rate[27] it might have been expected that the nucleus would be more vulnerable to faster loading rates. However, the ANOVA showed that the small increase in ADW values for discs tested at the highest loading rate is statistically insignificant ($P = 0.37$). By dividing the anulus, the disc's resistance to intra-anular displacement of the nucleus was significantly decreased. This may have contributed to the lack of any apparent rate affect. A fully flexed, fully hydrated and divided disc may be at risk of prolapse regardless of the loading rate because of the relative ease with which an intra-anular prolapse can be achieved through a preexisting division.

Furthermore, at the fastest loading rate investigated in this study (4 MPa/second), the duration of loading was approximately 2 seconds, which is considerably slower than the loading time associated with a clinically relevant impact. Therefore, it is possible that similar studies extending into the impact range may well show a significant rate effect.

The idea that disc prolapse is a result of a degenerative process that increases the disc's vulnerability to mechanical stress is challenged by the findings of the current study.[1,32] Although it is well established that dehydration of the nucleus is a symptom of degeneration,[10,23] the current study suggests that the healthy nucleus, when maximally hydrated, is more susceptible to nuclear or nuclear/anular disruption. This supports the hypothesis that the histologically abnormal and degenerate nuclear material removed at surgery[13] may well have attained this state through the cascade of biomechanical and biochemical change that occurred in the disc after rather than before the prolapse event.[14,23]

Conclusions

The current investigation clearly demonstrated that in the fully divided anular wall model of the disc, the nucleus is at greatest risk of disruption in the fully flexed and fully hydrated state, irrespective of loading rate. If careful attention is given to the control of flexion and hydration, then varying degrees of mechanically induced disruption and prolapse can be achieved in discs that incorporate a full anular division.

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Address reprint requests to

Neil Broom, PhD
Biomechanics Laboratory
Department of Mechanical Engineering
University of Auckland
Private Bag 92019
Auckland
New Zealand
E-mail: nd.broom@auckland.ac.nz