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Title: Influence of osmotic pressure changes on the opening of existing cracks in two intervertebral disc models

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**Response to reviewers**

**Reviewer #1:**
Thanks for the comments.  
The title is changed to "Influence of osmotic pressure changes on the opening of existing cracks in two intervertebral disc models."

**Reviewer #2:**
Thanks for the compliment.

**Reviewer #3:**
Thanks for the compliment.

**Comment #1:**  
The reviewer is right that true physiologic conditions are different from the situation in the experiment. However, it was not possible to create a crack in the high osmotic pressure stage as was step 2 in the experiments, because it is not possible to access the sample as its volume is constrained. That is why we have not examined the process when the crack is introduced in step 2, as the reviewer suggests.

**Comment #2:**
O.K. We did not have a control group. However, we did trial experiments to test the set-up, in which we found that a crack did not change if the osmotic pressure was not changed. (see manuscript line 77/78 and 117/118)

**Comment #3:**
One extra sentence is added to the introduction in line 60/61 which might clarify the idea better. Furthermore, figure 6 is added to illustrate the hypothesis (line 158) and a comparison is made with an oaken beam (lines 167/168).

**Reviewer #4:**
1. We agree that the analogy with intervertebral disc has limitations. Indeed, this study does not address radial fissures in particular. Disc herniation could also result from delamination, or other types of fissures. Just a general crack in the inner annulus is considered in the models. The reviewer is right that hydrogel is typically isotropic, while annulus tissue is a fiber reinforced anisotropic tissue. It is unlikely that the anisotropy does not affect the damage. We chose on purpose an isotropic material because we wanted to investigate the influence of decreasing osmotic pressure on the behavior of the crack without having to take into account other complicating factors such as fiber direction. (See introduction on lines 58-61 and discussion lines 184-185 and discussion is modified on lines 195-197).

2. We agree that osmotic pressure is essentially different from intradiscal pressure and that in some sentences the distinction is not clearly made. In line 17 "osmotic" is replaced by "internal" and the principle of osmotic pressure is explained better (lines 17-19 and 198-206). See also detailed comment #1.

3. The reviewer is right that a certain amount of hydrostatic pressure inside the nucleus is needed for it to extrude through the annulus and cause a prolapse and he is certainly right that weakening of the annulus is an important factor. Relating to this issue, the distinction between intradiscal and osmotic pressure is crucial (lines 198-206). We attempt to show that exactly a decreasing osmotic pressure that occurs with degeneration is a cause for herniation. See also reaction on detailed comment #4.
Detailed comments:

#1 page 1 lines 11-15: The information in the paragraph covering these lines is indeed too brief. The corrected paragraph (lines 13 - 25) gives a more detailed description of the structures in the disc and a better explanation of the internal and osmotic pressure.

#2 page 2 line 1: It is true that the nucleus loses more hydration than the annulus. However, the water loss in the annulus is significant, especially in the inner annulus (ref. 4, 6 and 7). For the choice of some material parameters, we drew data from the literature for the inner annulus. It is true that the proposed mechanism explains the hamburger discograms. We corrected line 30-32 and 110. We dropped the words 'in the annulus' in line 157 of the discussion.

#3 page 2 line 38: Right. Protrusion is replaced by extrusion (lines 41 and 162).

#4 page 2 lines 45-48: The facts brought up by the reviewers are correct. Cadaver experiments and finite element analyses are consistent with one another. High hydration and high intradiscal pressure are risk factors for herniation. What the manuscript wants to highlight in lines 45-48 (in the revised manuscript 48-51) is that the clinical events do not seem to be consistent with this picture. Herniation typically occurs in a period of life when degeneration progresses. Hence, herniation typically occurs in a period of life during which both hydration and intradiscal pressure is decreasing.

#5 page 4 lines 71-72: Physiological pressures in upright position are indeed much higher than 0.1 MPa. We added the words 'in supine position' on line 74. The present study did not analyse the effect of changing external loads on the cracks. Only the effect of changing osmotic pressures has been investigated, because the effect of external load seems to be pretty well understood, as indicated in the reviewer's detailed comment #4. This study only covers physiological pressures in supine position (see lines 18 and 74) to show the effect of decreasing osmotic pressure irrespective of external loads. See changes on lines 165-169 and 195-197. See also reaction to detailed comment #8.

#6 page 4 line 82: The cations and the anions are defined as separate components. Numbers are added to make this clearer (lines 85-89).

#7 page 5 lines 96-102: The rigid restraint at the top and bottom are an approximation for the swelling constraint caused by the annulus and the vertebrae (lines 101/102). Free fluid flow is allowed at the left side and in the crack (line 103). Only at the right side zero fluid flow is applied because of symmetry reasons: balance must exist between left and right. However, we realize that assuming symmetry might give limitations (lines 189-191). Zero fluid flow at the top and bottom is justified by the fact that no external forces are taken into account.

#8 page 7 line 1: We agree that cracks propagate most easily under tension. In a fluid solid mixture such as the nucleus, it is the effective stress (i.e. the stress minus the hydrostatic pressure) that should be under tension. The total stress can still be compressive, when the effective stress is under tension. This is why hamburger discograms are observed, while indeed the total stress in the nucleus is typically compressive. In a model including Donnan pressure, the hydrostatic pressure can develop from within the disc, without external load, and hence tensile effective stress within the disc without external load. This, we think, is why disc generation is poorly correlated with external load [29]. This study shows that even in an unloaded material stress concentrations at the crack tips occur, and hence a risk of propagation, even without tensile total stresses. Different factors can be involved in the progression of the crack, for example crack direction with respect to the disc geometry, fiber direction and external loading. This is not investigated in this study. See Discussion, lines 165-169 and 195-197.
We agree with the reviewer that it is shown that a degenerated disc shows increased compressive stresses in the annulus. From the measurements of the stress [2], however, it appears that this compressive annulus stress is axially oriented, while the nucleus stress is same in all directions. In a separate study presented at the Davos-meeting in July 2005, our group has spent considerable time comparing the prediction of our finite element model to the experimental data of Adams et al. [2]. In that study, a mesh of the full disc is used including fiber reinforcement. The shift of compressive load from nucleus to annulus is simulated, resulting in axial compressive stress in the annulus. The axial compressive stress being part of the effective stress, does not contribute to the hydrostatic part. Therefore, the observed reduction in hydrostatic pressure in the nucleus continues into the inner annulus. This reduction in hydrostatic pressure is compensated by an increase of axial effective stress in the annulus. In line 159 we refer to ref [2] mentioned by the reviewer.

The comments on blood vessels and nerves are dropped. Instead the issue on the distinction between hydrostatic pressure and osmotic pressure is illustrated in the context of Starling’s law. (lines 198-206)
Influence of osmotic pressure changes on the opening of existing cracks in two intervertebral disc models

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Structured Abstract

Study Design. An experimental hydrogel model and a numerical mixture model were used to investigate why the disc herniates while osmotic pressure is decreasing.

Objectives. To investigate the influence of decreasing osmotic pressure on the opening of cracks in the disc.

Summary of Background Data. In the degeneration process the disc changes structure: cracks occur and osmotic pressure decreases. Disc herniation typically develops when hydration declines, but on the other hand it is said that the annulus of a highly hydrated disc has a high risk of rupture. We hypothesized that disc herniation is preceded by the opening of cracks as a result of decreasing osmotic pressure.

Methods. The osmotic pressure was changed in hydrogel samples with a crack, which was visualized with a Confocal Laser Scanning Microscope. A 2D finite element mixture model simulated a decrease in osmotic pressure around a crack in a swelling material.

Results. Experiments and simulations show that a decrease in osmotic pressure results in the opening of cracks. The simulations show high effective stress concentrations around the crack tip, while the overall stress level decreases, indicating an increased risk of crack growth.

Conclusions. Decreasing osmotic pressure in a degenerating intervertebral disc enhances the opening of existing cracks, despite the concomitant decrease in annular stresses.

Key Words: intervertebral disc, herniated disc, osmotic pressure, crack, finite element analysis, mixture theory, hydrogel
Key Points

- The intervertebral disc typically herniates in a period of life in which osmotic pressure decreases. However, literature shows that the disc is at highest risk of rupture in the fully hydrated state.
- Existing cracks in swelling materials open as a result of decreasing osmotic pressure.
- Degeneration leads to decreased overall levels of fiber prestressing and to increased stress concentrations at crack tips.
- Local stress concentrations at crack tips contribute to increased risk of crack propagation, and hence herniation.
Mini Abstract

Experiments on hydrogel samples and 2D finite element simulations with a four-component mixture model show that cracks in a degenerating intervertebral disc open as a result of decreasing osmotic pressure. This could eventually lead to intervertebral disc herniation, despite the concomitant decrease in tissue stresses.
Introduction

Low back pain is the most common cause of disability in individuals between 20-50 years of age. Disorders associated with low back pain impose an economic burden similar to that of coronary heart disease and greater than that of other major health problems such as diabetes, Alzheimer's disease and kidney diseases [1]. It is still largely unknown from what pathologies low back pain arises, but it is believed that many cases arise from intervertebral disc problems. Two commonly known pathologies are intervertebral disc degeneration and intervertebral disc herniation. The knowledge on the causes and on the exact underlying processes of disc degeneration and herniation is increasing thanks to new imaging and modeling techniques and advances in cell biology and genetics [1]. However, the intervertebral disc seems to be poorly researched, even in comparison with other musculoskeletal systems [1]. Because of the limited knowledge no adequate treatment exists for low back pain arising from disc degeneration or herniation.

The intervertebral disc, which is the primary connection between two subsequent vertebrae, is a complex tissue consisting of different distinct structures: the gelatinous nucleus pulposus in the center, a fibrous outer ring called annulus fibrosis and the cartilaginous end plates that connect the disc to the vertebrae. Both the nucleus and the annulus consist of a dense collagen network embedded in a gel-like hydrophilic material with a high water content of 70-80 wt% on average and a high internal pressure of 0.1 MPa on average in supine position. This pressure is caused by the swelling properties of the proteoglycans being resisted by tension in the annulus fibrosus and ligamentum flavum. The fixed charges in the material cause a difference in ion concentration between the material and the solution, resulting in a Donnan osmotic pressure gradient. This gradient attracts water into the disc, resulting in a high water content [3]. The collagen network, especially that of the annulus, prevents the disc from swelling freely, leading to the high internal pressure and tensile osmotic prestressing of the annulus fibers. The lower the amount of fixed charges and the higher the concentration of the external salt solution, the lower the osmotic pressure and the lower the tensile stresses in the solid material [2]. Intervertebral disc tissue has been successfully modeled as a material consisting of a solid matrix with fixed charges, representing the collagen fibers and proteoglycans, together with interstitial fluid with dissolved ions [2].
The intervertebral disc ages faster than most other tissues, because nutrition is hampered in an avascular tissue. During aging the disc changes its structure and composition \[1,4,5\]. A major structural change that takes place in the process of degeneration is a decrease in water content and in osmotic pressure mainly in the nucleus and the inner annulus \(4, 6, 7\) leading to a loss of pre-stressing of the collagen network in the whole disc. A possible reason for this decreasing hydration could be loss of and changes in distribution of proteoglycans and consequently of fixed charges \[7\].

A more localized form of an intervertebral disc pathology is intervertebral disc herniation. Intervertebral disc herniation typically is a problem in individuals of age 30-50, which is the period of life where degeneration already has taken place to some extent, but where the remodeling process to withstand the altered stresses probably has not had effect yet. This implies that the underlying mechanisms of disc herniation and disc degeneration may be linked.

Tears, fissures or cracks in the annulus are observed in degenerated discs \[4,8,9\]. Annular tears must play a major role in the damage mechanism of disc herniation. These tears could be a precursor for herniation, followed by extrusion of a fragment of nuclear material through the fissure as was suggested by others \[10,11\]. One of the important questions is how such annular tears develop into full grown cracks, eventually leading to disc herniation.

It follows that both decreasing osmotic pressure and annular tears are important factors in disc degeneration. Moreover, disc degeneration likely precedes disc herniation. This indicates that a relation could exist between osmotic pressure or hydration, annular tears and disc herniation. The influence of hydration on the propensity of a disc to prolapse was investigated before by others \[12-14\]. These studies suggest that the intervertebral disc has a higher risk of herniation when it is fully hydrated. The outcome of these studies seems contradictory to the clinical facts, as it is known that disc herniation usually occurs in intervertebral discs that, considering the age of occurrence, must be degenerated to some extent. Hence, their hydration should be decreasing.

Therefore, the objective of the present study is to elucidate the apparent paradox of, on the one hand, experimental and conceptual evidence that the annulus of a highly hydrated disc is more likely to rupture than a less hydrated disc and, on the other hand, that disc herniation typically develops in a period of life in which the hydration declines. We hypothesize that the opening and propagation of cracks results from
Decreasing hydration. The influence of decreasing osmotic pressure on the opening behavior of existing cracks is investigated using both an experimental hydrogel model and a numerical four-component mixture model. The hydrogel model material is preferred above native intervertebral disc tissue 1) because hydrogel mimics the swelling propensity of the disc [15,16], while the complicating properties of disc tissue, such as its anisotropy, non-homogeneity, specimen-to-specimen variability, limiting viability and proteoglycan leakage are excluded, and 2) because of the transparency of the hydrogel.
Materials and Methods

Experimental set-up

Experiments are performed on HEMA – Sodium Metacrylate hydrogel samples. This hydrogel consists of negatively charged polymer chains, water and free ions. The charged polymer chains mimic the proteoglycan content of disc tissue [14]. Thin, cylindrically shaped hydrogel samples are stored in a NaCl solution of 0.4 M in which they have a diameter of 14 mm and a thickness of 1.3 mm. A crack of 3 to 6 mm long is generated in the middle of each sample by cutting through its depth with a scalpel knife, after which the sample is colored with the fluorescent dye Procion Red (Zijdelings, Tilburg, The Netherlands).

Six samples are placed in a 6-wells culture plate together with a 0.4 M NaCl salt solution and a system to prevent the sample from changing volume when swelling (figure 1). The decreasing osmotic pressure in the degenerating intervertebral disc is simulated in the hydrogel samples by increasing the concentration of the external salt solution.

The osmotic pressure in the sample is first brought to a physiological level in supine position of approximately 0.1 MPa [16] by decreasing the external salt concentration from 0.4 M to 0.2 M and finally to 0.15 M. This process is reversed again (from 0.15 M to 0.2 M and back to 0.4 M) to achieve a decrease in osmotic pressure. After each replacement the samples are left to equilibrate overnight. Trial experiments are performed to test the set-up.

The 6-wells plate is placed under a Confocal Laser Scanning Microscope (CLSM) (Zeiss, Göttingen, Germany) to visualize the crack. Images of the crack are collected when in equilibrium with an external salt concentration of 0.4 M (t ≈ 0), 0.2 M (t ≈ 1 day), 0.15 M (t ≈ 2 days), 0.2 M (t ≈ 3 days) and 0.4 M (t ≈ 7 days). With these experiments the opening behavior of the crack in the hydrogel sample as a result of changing osmotic pressure is determined.

Numerical simulations

The finite deformation of the swelling material around a crack is simulated with a four-component mixture model [18]. The simulated material consists of four different components: 1) a solid matrix with fixed charges (representing either the collagen fibers with the proteoglycans in intervertebral disc tissue or the
charged polymer chains in hydrogel), 2) fluid (representing either the interstitial fluid or water), 3) monovalent cations and 4) anions dissolved in the fluid. The four components interact with each other resulting in chemical, mechanical and electrical forces. The mixture model is implemented in the Finite Element package SEPRAN [19] and it is validated for intervertebral disc tissue [2]. As a result of changing external salt concentration, fixed charge density or loading conditions, the material deforms by swelling or shrinking.

The model material is assumed isotropic and homogeneous to limit the number of material parameters. A hyperelastic, compressible Neo-Hookean constitutive relation is used. Both the osmotic coefficients of the material and the surrounding solution are taken into account in the model. The input and material parameters [20,21] of the model are given in Table 1. The deformation, electrical potential, electrochemical potentials, hydrostatic pressure, stresses and strains throughout the material are calculated.

The left half of a rectangular sample of 2 by 0.5 mm with a 1 mm long crack in the center is modeled (figure 2). The bottom and top are fixed in both directions to model the swelling restraint caused by the annulus fibers in the disc and the adjacent vertebral bodies. Both the left side of the sample and the crack are allowed to move freely, while in contact with an external salt solution and free fluid flow is allowed. For symmetry reasons, the right side of the sample is disallowed to move in the horizontal direction and no fluid flow between the material and the exterior is allowed. The crack is assumed to be closed at an external salt concentration of 0.15 M and a fixed charge density of -0.2 moleq/l.

Two types of simulations with a decrease in osmotic pressure are performed: 1) the external salt concentration at the left side of the material is increased at the start of the simulation from 0.15 to 0.2 M, which is consistent with the design of the hydrogel experiment, 2) the fixed charge density is decreased from -0.2 to -0.15 moleq/l, which is consistent with degeneration of the inner annulus of an intervertebral disc [6]. The material is left to equilibrate for 1000 seconds. By performing both types of simulations, the effect of an increase in external salt concentration is compared with the effect of a decrease in fixed charge density.
Results

Experiments

The geometry of the crack in the hydrogel samples is visualized at different external salt concentrations [0.4 M, 0.2 M, 0.15 M, 0.2 M, 0.4 M] using the CLSM. The trial experiments showed that the cracks did not change when the osmotic pressure was not changed. Figure 3 shows the results of one of the samples. At the start of the experiments the external salt concentration is 0.4 M and the crack is open. The diameter of the crack in figure 3 is about 0.2 mm and the length of the crack is 5.8 mm. After equilibrating the sample with a 0.2 M NaCl solution, the crack is almost closed. However, at 0.15 M the crack is even more closed. After returning to a salt solution of 0.4 M and waiting for several days, the crack opens again to the same extent as in the beginning of the experiment. Pictures are also taken every hour in the period after changing the salt solution from 0.2 M to 0.4 M, showing a steady increase in the diameter of the crack (figure 4). The five other samples had a crack width ranging from 35 to 90 µm at an external concentration of 0.4 M and were also closed at 0.15 M.

The experimental results show that a crack closes as a result of a decrease in external salt concentration and reopens as a result of an increase in external salt concentration, i.e. a decreasing osmotic pressure.

Numerical simulations

Simulations are run with an increase in external salt concentration and a decrease in fixed charge density. Both methods decrease the osmotic pressure. They both result in opening of the crack. In the simulation with an increase in external salt concentration the crack has opened to a maximum width of 0.75 µm. Decreasing the fixed charge density results in a crack width of 20 µm. Hence, both an increase in external salt concentration from 0.15 to 0.2 M and a decrease in fixed charge density from -0.2 to -0.15 moleq/l result in opening of the crack. The decrease in fixed charge density has a larger effect on the crack than the increase in external salt concentration.

A decrease in fixed charge density transforms the initial uniform effective stress distribution into a distribution with a high concentration of effective stress around the crack tip (figure 5) The average effective stress level in the material decreases from $\sigma_{11}^e = \sigma_{22}^e = 0.136$ MPa in the state with high fixed
charge density to ± 0.1 MPa in the state with low fixed charge density. The stresses around the crack tip are more than three times as high as in the rest of the material. The simulations with increase in external salt concentration show similar results.

The largest strains are found in the simulations with a decrease in fixed charge density. These strain values show that the model is able to describe relatively large deformations with strains up to 0.37. In both simulations the initial strain was 0.11.
Discussion

Both an experimental hydrogel model and a numerical four-component mixture model show that a decrease in osmotic pressure results in the opening of an existing crack in swelling materials. The simulations further show that this conclusion holds irrespectively of the method of achieving the decrease in osmotic pressure, i.e. by means of decrease in fixed charge density or increase in external salt concentration. Around the crack tip in the simulations a high peak of effective stress is observed, while the overall effective stress has decreased significantly.

Translating this to the intervertebral disc, these findings imply that the decreasing proteoglycan content that is associated with degeneration, results in decreased osmotic pressure and decreased overall levels of fiber prestressing, while through the very same mechanism the crack tips in the disc are exposed to increased stress concentrations. We hypothesize that the vulnerability of the degenerating disc to herniation is caused by these local stress concentrations, because it contributes to increased risk of propagation of the cracks, and hence herniation (figure 6). The importance of localized stresses in the development of intervertebral disc herniation is confirmed by other studies [22-25] and the fact that it appeared difficult to experimentally produce a disc prolapse in the past [26-28] may substantiate our hypothesis. In addition, the opening of cracks increases the risk of fragments of nucleus material extruding through the crack, which may contribute to further opening of the cracks [10,11]. Hence, this paper proposes a new paradigm in the understanding of disc herniation: that of increased stress concentration around crack tips in a surrounding of decreased annular stresses.

The experiments and the simulations were performed without the presence of external forces. Hence, the proposed hypothesis implies that cracks open and stress concentrations occur without explicit contribution from external mechanical load. This is comparable to an ageing oak beam that develops cracks because of loss of turgor, even if it remains unloaded. Furthermore, this finding is consistent with the clinical observation that disc degeneration is poorly correlated with mechanical load [29].

The positive correlation between stress and hydration as found in this study confirms the experimental findings of Simunic et al. [13,14] that the disc is at greater risk of disruption in the fully hydrated state, i.e. in the state of maximal osmotic pressure. However, the involvement of decreasing osmotic pressure in
disc herniation seems contradictory to their findings. The difference in results could suggest that the
process of initiation of disc herniation (as is investigated by Simunic et al.) is different from the process of
growing of cracks (as is investigated in the present study). Lu et al. [12] also concluded that disc prolapse
is more likely to occur if the disc is fully hydrated. They found with their simulations that higher hydration
gives higher tensile stresses in the fibers. This agrees well with the findings of the present study.
The lower average effective stress found in the present study seems contradictory to the numerical
findings of Iatridis et al. [7], who report increase in matrix stresses and strains with changes in fixed
charge density from a healthy to a degenerate distribution. The increase in matrix stresses in their study,
however, are an increase in compressive axial stresses in the nucleus, whereas in the present study the
tensile effective stresses that balance the hydrostatic pressure are considered.
The conclusions in this study are based on results from models. One could question whether the models
are suitable to investigate the physiological problem of disc herniation. Hydrogel is chosen because of its
resemblance with disc tissue [15,16], while it excludes the complicating factors of disc tissue. The four-
component mixture model [18,19] is preferred above other computational models [7,30-37], because it
describes the full mechano-electrochemical behavior of swelling materials in time, including the electrical
potential, for finite deformations. Furthermore, this model was verified to describe the 1D behavior of
canine intervertebral disc tissue reasonably well [2]. We realize that the symmetry assumption applied in
the simulated sample might not be justified and may have given limitations. However, it has not affected
the results significantly.
In the experimental as well as in the numerical model, no fibers are taken into account. This is justified by
the fact that we solely wanted to look at the influence of osmotic pressure on the opening of a crack,
without having to consider other influences. Of course, fibers could largely influence the orientational
behavior of a crack. Also the presence of external loads and hence higher internal pressures in the disc
would influence the orientational behavior of the crack. Depending on the direction of the crack, this will
either help opening or prevent opening of the crack.
The sensitivity of the opening behaviour of cracks to osmotic pressure is qualitatively well understood in
the context of Starling's law, one of the key ingredients of the mechano-electrochemical model discussed
above. This law states that the driving force of fluid flow from the crack to the medium is governed by the
gradient of the chemical potential of the water. The chemical potential is the hydrostatic pressure minus the osmotic pressure. At constant osmotic pressure fluid flows from high hydrostatic pressure to low hydrostatic pressure. At constant hydrostatic pressure, fluid flows from low osmotic pressure to high osmotic pressure. A crack in a healthy young disc is surrounded by high osmotic pressure tissue, causing the fluid to leave the crack and the crack to close. The degeneration of the tissue causes the osmotic pressure of the tissue to decrease, leading the fluid into the crack. Hence the crack opens.
Figure 1. A schematic representation of the experimental set-up: a cross-section through one well indicating the colored sample (ø14 mm), the NaCl solution and the system to prevent the sample from swelling: a porous glass filter surrounding the sample, a glass plate and a PVC plate on top and a PVC lid with screw.

Figure 2. The sample used in the finite element simulations. The left side of the sample and the crack are in contact with a salt solution of concentration $c_{ex}$. The right side is a symmetry plane. The crack is indicated in red.

Figure 3. CLSM pictures of the crack in a hydrogel sample at different external salt concentrations: 0.4 M, 0.2 M, 0.15 M and 0.4 M. The white lines each represent 1 mm. The length of the crack is 5.8 mm and the width at 0.4 M is approximately 0.2 mm.

Figure 4. CLSM pictures of the crack in a hydrogel sample, in the period after changing the salt solution from 0.2 M to 0.4 M. The white line represents 0.1 mm. The moment of changing the salt solution is defined as $t = 0$. The pictures are taken at $t = 1h$, $t = 9h$, $t = 10h$, $t = 11h$, $t = 14h$, $t = 16h$, $t = 18$, $t = 21h$ and $t = 3$ days.

Figure 5. Simulated normal effective stress distribution ($\sigma_{22}^e$, in MPa) after a decrease in fixed charge density, in the full sample as well as zoomed in at the crack tip. The color bar belongs to both figures. The effective stress at the start of the simulation was $\sigma_{22}^e = 0.136$ MPa.

Figure 6. A degenerating disc is vulnerable to herniation because as a result of decreasing fixed charge density and hence decreasing osmotic pressure closed cracks open and stress concentrations occur at the crack tips. The stress concentrations contribute to increased risk of propagation of the cracks, and hence intervertebral disc herniation.
References


Figure 4
Click here to download high resolution image
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* The material parameters are derived from different studies [18,19] and standard books. $D^{+}$ and $D^{-}$ are the diffusion coefficients in a free solution. $r$ is the hindrance factor, accounting for the deceleration of diffusion due to the presence of a solid. $K_{11}$ denotes the permeability of the porous solid in a Darcy experiment. The molar volumes and the osmotic coefficients are taken constant throughout the simulation. For simplicity reasons, the external osmotic coefficient ($\Gamma_{ex}$) is taken equal to the internal osmotic coefficient ($\Gamma_{in}$).