The triphasic mechanics of the intervertebral disc : a theoretical, numerical and experimental analysis

7.1 Summary

In the industrial world low back pain is one of the important causes of absence and incapacity for work. Besides the financial loss there is the personal loss of quality of life. Epidemiological research relates low back pain to the mechanical loading of the spinal column. During lifetime the biochemical and structural composition of the intervertebral disc changes, often referred to as degeneration. In order to analyze the chemo-mechanical interaction a theoretical model is needed, which takes into account the structural and chemical composition of intervertebral disc tissue.

The presented framework in this thesis is based on the theory of mixtures. Starting with the kinematic relationships and the general balance laws constitutive restrictions based on the entropy principle are derived. The constitutive restrictions may depend on the local chemical composition and the local deformation. The model includes: (1) large deformations of the solid component, (2) relative fluid flow caused by gradients in the chemical potential of the fluid and diffusible ions, (3) non-ideal Donnan osmosis and electro neutrality, (4) convection-diffusion of the small ions. The model is capable of describing the equilibrium results in the physiological range of a confined compression test reasonably well. It also shows that the apparent dependence of the elastic constants on the local ion concentration originates from the Donnan osmotic pressure.

The equations describing the chemo-mechanical behaviour of intervertebral disc tissue are three coupled partial differential equations in which geometric and physical non-linearities occur. To solve them for an arbitrary geometry and arbitrary boundary conditions we use the Finite Element Method. A Total Lagrange (Newton-Raphson iteration scheme, Houbolt third order time integration scheme) formulation based on the Galerkin method is implemented in the commercial FE-package DIANA (DIANA Analysis B.V., Delft, the Netherlands). For the numerical studies iso-parametric elements of the serendipity family are used. Two dimensional (plane strain and plane stress), three dimensional and axisymmetric elements have been developed. The interpolation functions are the same for displacements, pressures and concentrations and can be either linear or parabolic.

In order to test whether the proposed model is realistic one dimensional confined compression experiments on canine samples are performed. The samples are taken from the canine anulus fibrosus. Two orientations of the specimen with respect to the spinal axis are used: perpendicular and parallel. The loading protocol consists of a combination of mechanical and chemical loading. The experimental data is successfully fitted to the proposed model. Triphasic evaluation of obtained data shows that swelling behaviour is caused by Donnan osmosis. The experimental data does call for the introduction of salt dependent elastic constant and so-called chemical expansion stress. The aggregate modulus and the permeability are deformation dependent. The permeability and aggregate modulus differ significantly for the axial and radial specimen.

The consequences of modelling a motion segment bi- or triphasically is studied by analysing the mechanical behaviour in axial compression of a human lumbar motion segment without the facet joints (posterior elements). The calculated deformation and fluid

flow versus time agree reasonably well with experimental observations reported in the literature. Donnan osmosis is shown to affect the anulus fibre and ground matrix stresses and the fluid flow through the intervertebral disc.

In conclusion, the present model for the chemo-mechanical behaviour of intervertebral disc tissue is capable of describing the response of the tissue to both a chemical and/or mechanical load.

7.2 Conclusions

The mechanical function of the different components in intervertebral disc tissue has been investigated. The role of swelling and/or osmotic effects has been emphasized. Based on generally accepted thermodynamic principles the chemo-mechanical behaviour of the tissue is derived. Despite the large number of simplifications and suppositions, the presented frame work is capable of describing the experimentally observed deformation of isolated specimen and motion segments under changing chemical and mechanical loads.

7.2.1 Conclusions concerning the presented theory

- A theoretical framework based on the theory of mixtures which takes into account the biochemical and structural composition of the tissue has been derived:
  finite deformation of the groundsubstance and fibre network
  relative fluid flow
  osmosis
  diffusion of small ions into a charged matrix.
- Compressive forces are counter balanced by forces due to deformation of the ground substance and the osmotic pressure due to gradients in the proteoglycan concentration. During the deformation process the load is transferred from the fluid component to the solid component. In contrast with a biphasic approach the fluid ultimately bears a part of the load due to the osmotic pressure. As fluid is expelled from the tissue and the proteoglycan concentration increases, the contribution of the osmotic pressure to the load transmission increases.
- Within the physiological range the presented framework is qualitatively in agreement with the confined compression equilibrium response of a chemically and/or mechanically loaded specimen as measured by Urban and Maroudas (1980).
- The model predictions for non physiological hydrations can not be improved by adding a chemical expansion stress as proposed by Mow et al. (199)) and Lai et al. (1991) to the Donnan osmotic pressure. Introducing a deformation and/or ion concentration dependent stress-strain relation (Mow and Schoonbeck, 1984, Eisenberg and Grodzinsky, 1985, 1987, Myers et al., 1984) also gives no improvement.
- The apparent dependence of the elastic constants of the stress-strain relation on the local salt concentration (Mow and Schoonbeck, 1984, Eisenberg and Grodzinsky, 1985, Myers et al., 1984) originates from the Donnan osmotic pressure.

7.2.2 Conclusions concerning the experimental method and data

- The specimen preparation, the experimental set-up and the experimental protocol yields reproducible results.
- The evaluated material parameters lie within the physiological range except the diffusion coefficient of NaCl.
- Triphasic evaluation of the data shows that both the stress-strain relation and the permeability of the canine anulus fibrosus are deformation dependent, even for linear strains less then 10%. Specimen to specimen variability of the aggregate modulus and the permeability are correlated with each other.
- The swelling behaviour is caused by Donnan osmosis. The experimental results show no need for introducing a chemical expansion stress as has been done by Lai et al. (1991).
- While in contact with a 0.2 M NaCl solution, and increasing the external load from 0.08 MPa to 0.2 MPa, the osmotic pressure contributes for only 15% to the mechanical load, 85% is counterbalanced by tissue deformation.
- The transport coefficient and aggregate modulus, as roughly evaluated by applying the linear biphasic theory to the 1-D consolidation data, differ significantly for the axial and radial specimen.
- The deformation averaged triphasic material properties differ from the deformation averaged biphasic material properties. Therefore, use of the biphasic theory for quantification of the permeability and aggregate modulus from consolidation data should be avoided, particular when large strains are involved.

7.2.3 Conclusions concerning the numerical simulations

- Geometrically (linear strain of 25%) and physically (deformation dependent aggregate modulus and the permeability) non-linear biphasic simulation of the confined compression experiment on articular cartilage (Holmes, 1986) shows that:
  1: the response immediately after load application is still linear in the square root of time.
  2: the shift to longer consolidation times due to the deformation dependent permeability is almost fully compensated by the shift to smaller consolidation times due to the stiffening stress-strain relation.
- Geometrically and physically non-linear biphasic versus triphasic simulation of the axial compression of a motion segment shows that:
  1: the triphasic model holds on to more water although the triphasic fluid pressure gradients are larger.
  2: the anulus tensile fibre stress are higher in the triphasic simulation. Therefore, a biphasic model overestimates the load bearing capacity at a given fibre yield stress.
  3: the maximum stress is reached immediately after load application.
  3: the triphasic motion segment reaches equilibrium earlier.
  4: the nucleus pressure / external load ratio for the triphasic simulation is in agreement with the results of Berkson et al. (1979). The biphasic is not.
  5: the axial displacement of the vertebral bone and the radial bulge are qualitatively in agreement with experimental results for both the triphasic and biphasic simulations.

Samenvatting

Lage rugpijn is een van de belangrijkste redenen voor werkverzuim en arbeidsongeschiktheid. Naast de financiële gevolgen is er sprake van een verlies van kwaliteit van leven voor de direct betrokkenen. Epidemiologisch onderzoek heeft een duidelijk verband aangetoond tussen lage rugpijn en de mechanische belasting op wervelkolom. Gedurende het ouder worden treden biochemische- en structurele veranderingen op in de tussenwervelschijf. Deze veranderingen hangen vaak samen met veroudering. Een theoretisch model is nodig om de complexe chemische en mechanische interactie te bestuderen. Het model dient rekening te houden met de chemische en structurele samenstelling van het weefsel.

Het model zoals beschreven in dit proefschrift is gebaseerd op de mengseltheorie: het weefsel is opgebouwd uit drie componenten: vaste stof, vloeistof en kleine ionen. Op basis van kinematische relaties, algemene behoudswetten en de tweede hoofdwet van de thermodynamica worden constitutieve verbanden afgeleid. Deze relaties zijn afhankelijk van zowel de lokale deformatie als de lokale chemische samenstelling van het weefsel. Het model is gebaseerd op: (1) eindige vervormingen van de vaste stof, (2) relatieve vloeistofstroming veroorzaakt door gradienten van de chemische potentiaal van de vloeistof en de ionen, (3) niet-ideale Donnan osmose en electroneutraliteit, (4) convectie-diffusie van de kleine ionen. Het model beschrijft de evenwichtsresultaten van een confined compression experiment in het fysiologische gebied voldoende nauwkeurig. Het model laat ook zien dat de schijnbare afhankelijkheid van de elastische constanten veroorzaakt wordt door Donnan osmose.

De vergelijkingen die het chemo-mechanische gedrag van tussenwervelschijf weefsel beschrijven, zijn drie gekoppelde partiële differentiaal vergelijkingen. Om deze op te lossen voor een willekeurige geometrie en willekeurige randvoorwaarden is gebruik gemaakt van de eindige elementen methode. Een total Lagrange (Newton-Raphson iteratie schema, derde orde Houbolt tijdintegratie) formulering is geïmplementeerd in het commerciële pakket DIANA (DIANA Analysis B.V., Delft). Voor de numerieke studies worden iso-parametrische serendipity elementen gebruikt. Twee dimensionale vlakke rek, axiaal-symmetrische en drie dimensionale elementen zijn ontwikkeld. De interpolatie functies zijn gelijk voor de verplaatsing, druk en ionconcentratie. De orde van de interpolatie functies varieert van lineair tot cubisch.

Voor de experimentele validatie van het model is gebruik gemaakt van de een dimensionale confined compression test. De proefstukjes zijn verkregen uit de anulus fibrosus van herderachtige honden. De oriëntatie van de proefstukjes is evenwijdig of loodrechtten opzichte van de wervelkolom. Het belastingsprotocol bestaat uit een combinatie van chemische- en mechanische belasting. De experimentele data kan gefit worden op het model. Het zwel gedrag wordt veroorzaakt door Donnan osmose. De experimentele resultaten geven geen aanleiding tot het invoeren van een zout afhankelijke elasticiteitsmodulus of een chemische uitzettingscoëfficiënt. De elasticiteitsmodulus and de permeabiliteit zijn vervormingsafhankelijk. Zowel de elasticiteitsmodulus als de permeabiliteit verschillen significant voor de axiale en radiale proefstukjes.

De gevolgen van het twee of drie fasen modelleren is bestudeerd aan de hand van axiale compressie van een bewegingssegment zonder facet gewrichten. De berekende vervormingen en vloeistof stroming als funktie van de tijd zijn in overeenstemming met gerapporteerde experimentele resultaten. Donnan osmose beinvloed de spanningen in de vezels en de grondmatrix, en de vloeistof stroming door het bewegingssegment.

Het gepresenteerde model voor het chemo-mechanisch gedrag van tussenwervelschijf weefsel is in staat om de respons van het weefsel op een chemische en/of mechanische belasting te beschrijven.