Experimental and numerical investigations on engineering tissue enhanced by mechanical simulation

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Motivation and aim

- Replacement of human articular cartilage by **condensed cellular collagen gel**.
- Development of a viscoelastic-diffusion and remodeling model for cellular material.
- Theoretical and experimental study of remodeling effects.
Contents

1. Bioreactor
2. Theoretical model
3. Finite element model
4. Compression tests
5. Theoretical / Experimental comparison
6. Conclusions
1. Bioreactor

- Cyclic mechanical stimulation in a bioreactor.
Histological evaluations

Unstimulated control sample

Stimulated bioreactor sample

newly produced collagen fibers
Phenomenon in bioreactor

Initial configuration

current configuration

stimulation
In bioreactor

weight function

cell

remodeling effect
due to synthesized fiber

σ^r

σ^e, σ^ve, σ^d

condensed
collagen gel

stimulation

no remodeling effect
2. Theoretical model

Cauchy stress rate tensor: \[ \dot{\sigma} = \dot{\sigma}^e + \dot{\sigma}^{ve} + \dot{\sigma}^d + \dot{\sigma}^r \]

Elastic part: \[ \sigma^e = C : \varepsilon \]

Viscoelastic part: \[ \dot{\sigma}^{ve} = \tilde{C} : \dot{\varepsilon} \]

Diffusive part: \[ \dot{\sigma}^d = -D\sigma \]

Remodeling part: \[ \dot{\sigma}^r = C^r : \dot{\varepsilon} \]
Diffusion

Diffusive part:

\[ \dot{\sigma}^d = -D\sigma \]

\[ \rightarrow \quad \dot{\sigma}_1^d = \dot{\sigma}_3^d = -D\sigma_1 \quad (\dot{\sigma}_4^d = \dot{\sigma}_5^d = \dot{\sigma}_6^d = 0) \]

with \[ D(\varepsilon_v) = D_0 + D_1 \varepsilon_v \] (\( \varepsilon_v \) - volumetric strain)
Remodeling

Remodeling part:

\[ \dot{\sigma}^r = C^r : \dot{\varepsilon} \]

Evolution equation:

\[ \dot{C}^r = \Phi k \sqrt{\Psi} (C^r_{\text{crit}} - C^r) \]

\[ \rightarrow \dot{C}^r_{11} = \dot{C}^r_{33} = \Phi(x_2) k \sqrt{\Psi} (C^r_{11,\text{crit}} - C^r_{11}) \]

with

- weight function of cell distribution
- remodeling velocity parameter
- limit value of stiffness component
- stiffness change due to remodeling effect
Free energy

\[ \psi = \frac{1}{2} \lambda \ln^2 J + \frac{1}{2} \mu (F^T F : I - 3) - \mu \ln J + \int \sigma^r : d\varepsilon \]

Isotropic Neo-Hookean-type free-energy function

Deformation energy due to newly synthesized collagen fiber

\[ \rightarrow \psi = \frac{1}{2} \lambda \ln^2 J + \frac{1}{2} \mu (F^T F : I - 3) - \mu \ln J + \int \sigma_{11}^r d\varepsilon_{11} + \int \sigma_{33}^r d\varepsilon_{33} \]

With \[ J = \text{det} (F) \] and \[ \lambda, \mu \] - Lamé constants
3. Finite element model

- Stress increment in user defined subroutine Umat in Abaqus:

\[ \Delta \sigma_{ij} = C_{ijkl} \Delta \varepsilon_{kl} + \tilde{C}_{ijkl} \Delta \varepsilon_{kl} + \Delta \sigma_{ij} + C_{ijkl}^r \Delta \varepsilon_{kl} \]

short time scale / sec  long time scale / week

- Gradient material (Linear distribution of stiffness):

\[ C_{11}(x_2) = C_{11,i} + \frac{C_{11,a} - C_{11,i}}{h} \cdot x_2 \]
4. Compression tests

- MTS Material testing machine
5. Theoretical / Experimental comparison

Before stimulation in bioreactor

\[ E_{11} = E_{22} = 0.8 \text{ MPa} \]
\[ D_0 = 2.58 \text{ 1/s} \]
\[ D_1 = 2.7 \text{ 1/s} \]

After stimulation in bioreactor

\[ E_{11} = 1.2, E_{22} = 0.8 \text{ MPa} \]
\[ D_0 = 26.1 \text{ 1/s} \]
\[ D_1 = 22 \text{ 1/s} \]
Remodeling of stiffness

initial state

after 4 days

after 9 days

after 14 days

after 18 days

after 23 days

after 28 days

\[ C_{11} + C^{r}_{11} \]

or

\[ C_{33} + C^{r}_{33} \]
6. Conclusions

• A remodeling phenomenon in bioreactor was investigated and a constitutive model was proposed.

• The replacement material exhibits high strength that is experimentally and theoretically studied.

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