OPTICAL COHERENCE TOMOGRAPHY BASED MICROELASTOGRAPHY FOR BIOMECHANICAL ASSESSMENT OF NATURAL AND ARTIFICIAL CARTILAGE

Maxim Vovchenko (1, 2), Marnix Gielen (2), Zoë De Vrij (1), Rocío Castro Viñuelas (3, 4), Seyed Ali Elahi (1, 3), Ilse Jonkers (3), Hans Van Oosterwyck (1, 5), Christ Glorieux (2)

1. Biomechanics Section, Dept. of Mechanical Engineering, KU Leuven, Belgium; 2. Laboratory for Soft Matter and Biophysics, Dept. of Physics and Astronomy, KU Leuven, Belgium; 3. Human Movement Biomechanics Research Group, Dept. of Movement Sciences, KU Leuven, Belgium; 4. Laboratory for Tissue Homeostasis and Disease, Dept. of Development and Regeneration, Skeletal Biology and Engineering Research Center, KU Leuven, Belgium; 5. Prometheus Division of Skeletal Tissue Engineering, KU Leuven, Belgium;

Introduction

Osteoarthritis (OA) is the most common chronic joint disease. During disease progression, cartilage degeneration occurs, with associated changes in all other joint tissues. To date, OA is the leading cause of disability among elderly, and no known cure or proven strategy exists for reducing progression from early to end-stage OA. Mechanical loading plays a crucial role in cartilage homeostasis. By adjusting metabolic activity in response to joint loading changes, chondrocytes preserve the extracellular matrix (ECM) balance and maintain cartilage mechanical properties. However, early OA disrupts these processes and jeopardizes cartilage stability. The response of OA-impacted chondrocytes to loading remains an underexplored subject. This work describes the development of a technique for using Optical Coherence Tomography (OCT) in combination with controlled loading to extract spatially resolved information about the mechanical properties of a sample, namely cartilage and cell-seeded hydrogel.

Methods

OCT is based on the principle of low-coherence interferometry, using reflected or backscattered light reflected from a sample to study its optical structure. Having the central wavelength typically within near-infrared range, it achieves an imaging depth of several millimeters, which makes it convenient for cartilage explants. This non-invasive method can provide a spatial resolution in the 1-100 μm range and has various imaging advantages, including high-speed 3D imaging of optically turbid materials and in vivo capabilities. OCT is also highly sensitive to tissue motion: axial sample displacements less than 1 nm cause measurable changes in the phase of the complex OCT signal [1].

In this work, we have used phase-sensitive spectral domain OCT, as opposed to the common amplitude-based OCT application. First, raw phase information was obtained for every 2D OCT image. After moderate smoothing of the complex pixel values, phase difference values were converted into displacements, from which the axial strain map was then calculated by taking the spatial derivative in the depth direction. By simultaneously measuring the uniform force applied and the contact area, the elastic modulus map of the sample was obtained. The force value was derived from the deformation of a reference layer of known stiffness sandwiched together with the specimen of interest between an optical window and the movable piston that was used to impose deformations.

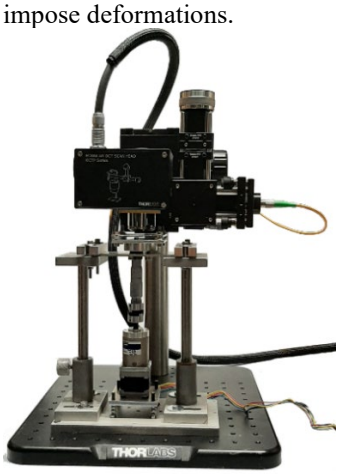

Figure 1: OCT scanning system including a stage with a sample subject to uniform compressive loading exerted by a stepping motor controlled micrometer piston.

Results and discussion

The OCT based elastography approach was applied to natural cartilage as well as to hydrogel filled with cartilage cells, chondrocytes. These cells create a local pericellular matrix (PCM) area [2] that influences the global mechanical properties of the entire hydrogel system. With this preliminary results we were able to create elastic modulus maps with an uncertainty about 20% for a spatial resolution of 50 μm. The approach was validated using finite element simulations in Abaqus as well as calculations based on singular value decomposition. The next step will be to combine the method with protein expression analysis to study both mechanical and metabolic changes in healthy and OA chondrocytes to understand their impact on the chondrocyte mechanical environment.

References

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2. Guilak et al, Osteoarthritis Cartilage, 7(1):59-70, 1999.

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