XVII International Symposium on Computer Simulation in Biomechanics
July 28th – 30th 2019, Alberta, Canada

A NOVEL CONTACT MODEL FOR THE COMPUTATIONAL INVESTIGATION OF SYNOVIAL JOINTS WITH A CARTILAGINOUS DISC

Beneditk Sagl[1], Colin Smith[2], Martina Schmid-Schwap[1], Eva Piehslinger[1], Michael Kundi[1], John Lloyd[3] and Ian Stavness[4]

[1]Medical University of Vienna, Austria [2]ETH Zurich, Switzerland [3]University of British Columbia, Canada [4]University of Saskatchewan, Canada

Email: benedikt.sagl@meduniwien.ac.at

INTRODUCTION

The representation of joints is an integral part of computer models of the human body. Rigid body joints have proven to be a valuable tool for investigating dynamic movements. These simplified joints enable muscle force optimizations to be performed with reasonable simulation times.

One major drawback of these simple joint models lies in their limited capability for the detailed examination of joint load distributions. Joint load investigations are mostly performed using models created using the finite element method (FEM). This method allows detailed analysis of articular contact mechanics but requires comparably high computational resources and consequently long simulation times, limiting their applicability to mostly static or quasi-static investigations.

Additionally, only limited experimental data exist on material properties of many cartilaginous tissues. Using a full FEM approach and a sophisticated FEM material without accurate material properties will drastically increase the simulation time but yield limited additional benefit due to the uncertainty in the results.

Simulations of larger dynamic movements, such as a full gait or chewing cycle, require a high number of time steps and hence differences in computational speed become more drastic. To make biomechanical simulations relevant for clinical practice and enable large-scale sensitivity analyses, it is of utmost importance to minimize simulation times.

Synovial joints with cartilaginous discs (e.g. knee and temporomandibular) pose a special challenge for musculoskeletal simulations of movement. While elastic foundation (EF) models provide reasonable approximations for articular cartilage as a thin elastic layer bonded to a rigid substrate [1], they are not well suited for cartilaginous discs that deform in multiple dimensions. However, the loading of such discs is important clinically due to the difficulty of repair and their importance to the development of osteoarthritis [2]. Thus, improved computational methods are necessary to enable FEM representations of the discs in muscle driven simulations of dynamic movements.

Hence, this project proposes an efficient contact model that combines a FEM model for the cartilaginous disc and elastic foundation (EF) of the opposing contact surfaces. The intention is to enable biomechanical researchers to simultaneously fulfill the goal of reasonable simulation times and detailed analysis of cartilaginous disc load during dynamic movements of synovial joints.

METHODS

To showcase our approach, we will present three simulation scenarios:

- A simple test case consisting of idealized contact shapes and surfaces;
- A model of the masticatory system; and
- A model of the human knee.

All simulations were performed using the ArtiSynth modeling toolkit (www.artisynth.org). Bony structures are modeled as rigid bodies and muscles are represented using a Hill-type approach. Articular cartilage is modelled as an Elastic Foundation Contact Model [3]. Contact pressure p between the surface mesh of the cartilaginous disc (CD) and the articular cartilage (AC) mesh is computed using:

$$\mathrm{p}(d) = \mathrm{K}\ln\left(1-\frac{d}{h}\right),\ \mathrm{K} \equiv \frac{-(1-\nu)E}{(1+\nu)(1-2\nu)} \qquad (1)$$

,where E is the elastic modulus, ν is the Poisson's ratio, d represents the depth of penetration and h is the cartilage thickness.

The CD is modeled using an FEM model, with the material depending on the respective joint. Contact between the CD and the AC is determined by finding the FEM nodes of the CD which penetrate the AC mesh. Each of these then defines a contact, with a penetration depth d and normal direction $\boldsymbol{n}$. Equation (1) is then used to determine the appropriate nodal response force $\mathbf{f}$, according to

$$\mathbf{f} = p(d)A\,\boldsymbol{n},$$

where A is the surface area associated with the contact (estimated by dividing the total mesh penetration area by the number of penetrating vertices).

Since the contact forces are very stiff, stable simulation requires the use of either extremely small time steps, or an implicit integrator. For additional stability, we actually use a constraint regularization scheme, in which contact is not simulated directly with forces, but rather by using constraints, based on the contact normal directions, which the force behavior is then used to regularize, or "soften". Full details are given in [4].

RESULTS AND DISCUSSION

Idealized simulations using the test case model verified correct implementation of the elastic contact model. Moreover, the test model demonstrated expected results for the interaction between EF-based articular cartilage and the FEM-based cartilaginous disc.

Preliminary simulations with the jaw model yield reasonable TMJ loads as well as movement patterns of the mandible that are consistent with experimental findings. Detailed results for the test case, temporomandibular joint, and knee joint will be presented at the symposium.

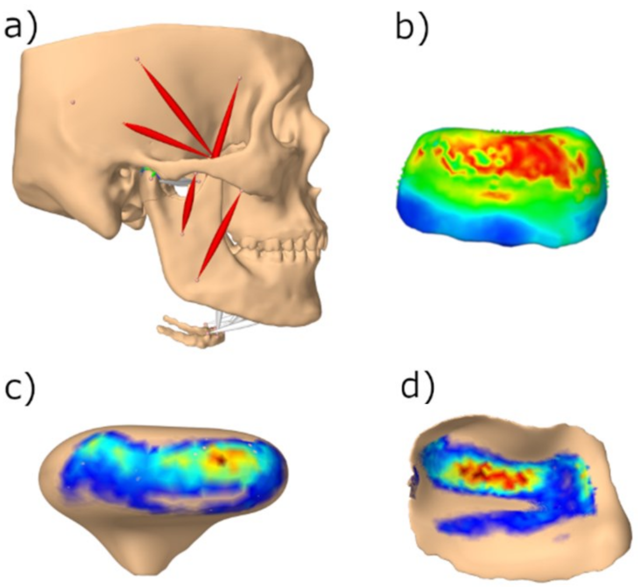

Fig 1: Clenching simulation example; a) model side view; b) TMJ disc loading from top view; c) condylar cartilage contact pressure from top view; d) fossa articularis cartilage contact pressure from bottom view

This project introduces a novel approach for the modeling of synovial joints with a cartilaginous disc. The new method enables muscle driven simulations of dynamic movements that include finite element representations of the deformable discs. We showcased these capabilities using a simple test case and two joints of the human body: the knee joint and the TMJ.

This novel methodology has important implications for both clinical and simulation research. Clinically, meniscal and TMJ disc tears and degeneration are important problems in modern medicine and detailed investigations in the onset of such pathologies might help developing new prevention as well as treatment strategies. Our accelerated simulation framework will help to translate high fidelity simulations into the clinic and enable large-scale sensitivity studies to investigate the uncertainty in predictions due to limited knowledge of soft tissue material properties.

REFERENCES

1. Bei Y, et al. Med Eng Phys **26**:777–789, 2004.
2. Lohmander, L S, et al. Am J Sports Med **35**: 1756-1769, 2007
3. Blankevoort L, et al. J Biomech **24**: 1019–1031, 1991
4. Servin M, et al. Proc SIGRAD Conf: 22–32, 2006