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A first poro-mechanical characterization of temporomandibular joint disc tissue undergoing spherical compression

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1. Introduction

The temporomandibular joint (TMJ) disc is a fibrocartilaginous soft biological tissue, whose main objective is ensuring effort distribution during jaw movements (Wu et al. 2017). The disc is composed mainly of water, contained inside pores within a fibrous extracellular matrix (ECM) (Wu et al. 2017). The fluid motion within the material influences its mechanical response and fluid pressurization composes part of the stress developed during loadings. Viability of TMJ disc cells relies on fluid renewing and physiological mechanical loads. Therefore, mastering its poro-mechanical behaviour is a keystone for predictive modeling of healthy and pathological TMJ discs (Ortún-Terrazas et al. 2020). Spherical compression tests allow to keep the integrity of the tissue and may be performed in different regions of the sample, by compressing it with a sphere and preserving natural fluid flow within the disc (Tappert et al. 2020). The force and displacement may be then recorded and used to estimate non-uniaxial stress/strain state through analytical models (Tappert et al. 2020).

The use of a biphasic law to describe the behaviour of the TMJ disc through spherical compression has not yet been explored in literature. This study aims to identify poro-mechanical properties of a pig TMJ disc based on material parameters suggested in the literature. To tackle the complexity of analytically

treating spherical compression of non-linear materials, the behavior laws were implemented on a finite element (FE) model to be compared and fitted to experimental data from Tappert et al. (2020).

2. Methods

2.1 Experimental data

Cyclic spherical compression tests were performed on porcine TMJ discs measuring approximately 15.52mm mediolaterally, 29.65mm anteroposteriorly and 2.75mm on thickness (Tappert et al. 2020). A test with a spherical tool of 0.875mm radius compressing the samples at 0.01Hz with 0.373mm total displacement was chosen.

2.2 Finite element model

An axisymmetric finite element model was built in Abaqus/CAE 2022[®]. A rigid semi-sphere of 0.875mm radius applied compression on a deformable disc meshed with CAX4PH type elements in a coupled pore fluid diffusion and stress analysis.

The disc was 2.75mm thick with an 8mm radius. The contact in between the support, the disc and the compression tool was frictionless due to disc high hydration. The compression tool, displacement controlled to match the experimental data, penetrated the material at a 0.01Hz rate. Fluid flow was free on all sample borders by imposing zero pore pressure.

2.3 Model parameters definition

A biphasic homogeneous isotropic behaviour with constant permeability was adopted for all simulations. Ortún-Terrazas et al. (2020) proposed the use of hyperfoam constitutive law for the behaviour of TMJ discs under unconfined compression. A first simulation based on their mean parameters (shear modulus μ , coefficient α and Poisson ratio ν), was performed (Model 1). Then, experimental results from Tappert et al. (2020) provided material parameters for a monophasic Ogden law, that were associated to the permeability (k) value from Wu et al. (2017) to define material properties for another biphasic hyperfoam simulation (Model 2). The material parameters in Table 1 show a large difference in orders of magnitude, pointing out the lack of knowledge and the necessity to combine experimental and numerical approaches.

A dichotomy approach was used in between these two simulations to identify new properties fitting the experimental data from Tappert et al. (2020) (Model 3).

3. Results and discussion

The simulation results and the experimental curve are superimposed in Figure 1.

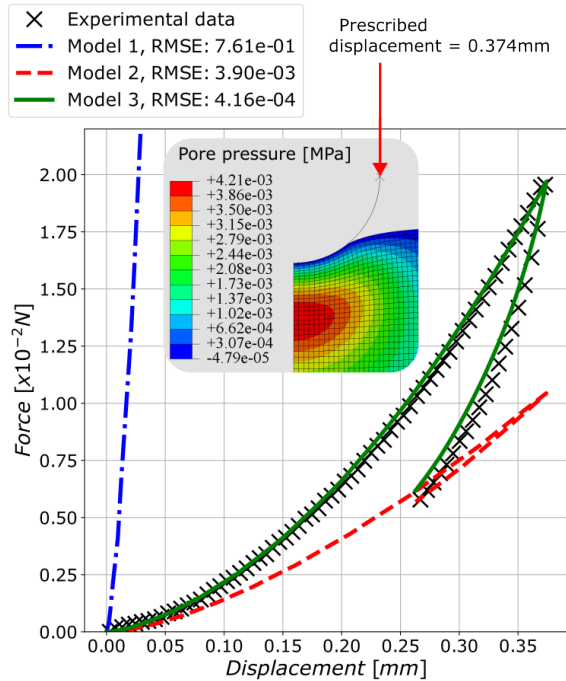


Figure 1. Simulations results compared to experimental force/displacement curve with root mean square errors (RMSE). Parameters from: Model 1) Ortún-Terrazas et al. (2020), Model 2) Tappert et al. (2020) + Wu et al. (2020) and Model 3) present study. Pore pressure is illustrated for Model 3 in the FE caption.
credit: C de Oliveira Cafiero

One can observe the non-linearity caused by the contact radius development and the hyperelastic response of the TMJ disc tissue. Fluid pressurization (Figure 1) is the main contributor to the material's compressive response (Wu et al. 2017). Fluid loss during the compression phase may explain the lower force obtained during the unloading phase. The force at the end does not return to zero since the original experiment starts the following cycle from a non-zero deformation to stay in contact with the sample. The mechanical parameters of Model 2, despite obtained from experimental data, were not the best fit since they had not been identified for a biphasic model. Nevertheless, Model 2 was still more accurate (RMSE = 3.9E-3) than Model 1 (RMSE = 7.61E-1), which presented higher stiffness and reached a maximal force of 1.41N for 0.374mm prescribed displacement. Therefore, material parameters from Ortún-Terrazas et al. (2020) were not adapted to spherical compression. By varying the material parameters, Model 3 gives a better fitting of the experiments (RMSE = 4.16E-4).

Table 1. Material parameters for the models
credit: C de Oliveira Cafiero

Model	k (m ⁴ /Ns)	μ (MPa)	α	ν
1	9.96E-12	2.16	76	0.167
2	8.80E-16	0.00979	6.21	0.125
3	5.65E-14	0.029	49	0.125

The presented approach adopts simplifications such as constant strain-independent permeability, isotropy and homogeneous ECM. The chosen boundary conditions do not consider the flow impediment caused by contact between sample and the compression tool as well as with the support.

4. Conclusions

It was possible to define material parameters to reproduce in a FE model a spherical compression test on a TMJ disc. The adequacy of a porous hyperfoam law to reproduce the tissue behaviour was confirmed, corroborating the idea presented in Ortún-Terrazas et al. (2020).

Although, due to the complexity of the analysed material and lack of data in the literature, it was necessary to adjust the parameters to achieve a good fit in the observed context.

The present work opens the possibility to analyse the influence of loading frequency and compression tool dimensions on the tissue. Indeed, the compression of the disc with bigger diameter spheres allows the access to deeper regions of the tissue (Tappert et al. 2020). Furthermore, varying loading velocity allows strain-rate dependent permeability identification.

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Conflict of Interest Statement

None.

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