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Dynamic characterisation of the temporomandibular joint disc using split Hopkinson pressure bars

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1. Introduction

The temporomandibular joint (TMJ) disc is a fibrocartilaginous intra-articular tissue that connects the skull and mandible, and ensures the correct motion of the jaw (Tappert et al. 2017). Unphysiological mechanical stress and trauma, such as in car crash, sport accidents or whiplash, are well-known causes of permanent TMJ disorders (Pérez del Palomar and Doblaré 2008). To date, the TMJ disc mechanical behavior has been mainly documented under reduced strain (e.g., 10%) and at low strain rates ($<1 \text{ s}^{-1}$), far to be representative of trauma and unphysiological conditions (Fazaeli et al. 2019). The exact aetiology of such trauma-induced disorders is complex and remains largely unresolved as a paucity of investigations exists into TMJ disc high rate behavior. In this study, we investigate the compressive mechanical properties of porcine TMJ discs at strain rates of 1118 ± 56 and $2553 \pm 281 \text{ s}^{-1}$. We used a modified split-Hopkinson pressure bar (SHPB) embedded with quartz crystal transducers to measure the loading forces. The displacements were obtained using digital image correlation (DIC). The experimental data were, then, fitted with established hyperelastic models, and parameters were extracted for 3-dimensional (3-D) finite element (FE) modelling (Pérez del Palomar and Doblaré 2008).

2. Methods

2.1. TMJ disc sample preparation

A total of 6 cylindrical TMJ discs were carved out from three porcine heads by punching the

intermediate zone. The nominal punch diameter was either 5.08 (small) or 7.62 mm (large). The disc samples were directly stored in a -20°C freezer for 7 days at most. On the day of testing, the samples were allowed to thaw in a pre-warmed 39°C water bath, and their actual diameter and thickness were carefully determined on photographs by image analysis (e.g., 5.53 ± 0.25 and $8.53 \pm 0.18 \text{ mm}$ for the small and large diameter, respectively). Just prior to the compressive experiments, any pre-strain due to the setup was determined using a calliper.

2.2. High strain rate compressive loading

The high strain rate compressive experiments were performed on a modified $1/2$ inch SHPB system instrumented with inertia-compensated quartz crystal transducers and a charge amplifier (Sory 2017). The input bar (IB) and output bar (OB) were made of 7068 Al alloy and were 1500 mm and 1000 mm long, respectively. The compressive loadings were generated by impacting the IB at velocities up to $6.40 \pm 0.10 \text{ m.s}^{-1}$ with a 560 mm long projectile. The force at the IB- and OB-sample interfaces, F_{IB} and F_{OB} respectively, were obtained from the quartz transducers using pre-established ‘voltage-force’ calibration relationships, and then processed into average engineering stress-history as:

$$\sigma(t) = \frac{(F_{IB} + F_{OB})/2}{A_s}$$

where A_s is the sample cross-sectional area. The displacements at the IB- and OB-sample interfaces, u_{in} and u_{out} respectively, were recorded on a Phantom camera at 93137 frames per second, and then computed from digital image correlation (Ncorr, MatLab). The sample average engineering strain-history was processed as:

$$\varepsilon(t) = \frac{u_{in} - u_{out}}{L_s}$$

where L_s is the sample length. Even though the sample undergoes compression, the curves are presented with positive values for better reading.

2.3. TMJ disc hyperelasticity modelling

The experimental stress-strain data were fitted with the incompressible uniaxial hyperelastic Mooney-

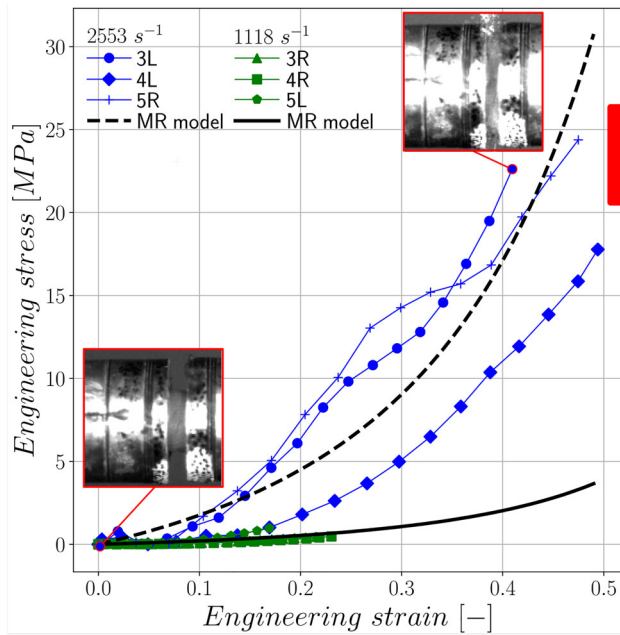


Figure 1. TMJ stress-strain behavior at two strain rate regimes. The photograph inserts depict the compression of a sample prior to and at the end of the testing. A Mooney Rivlin model (MR model) is fitted to the experimental data and average parameters' values allowed plotting trend curves (solid and dashed black lines).

Rivlin model with the engineering stress σ defined as:

$$\sigma = 2 \left(C_1 + \frac{C_2}{\lambda} \right) (\lambda - \lambda^{-2})$$

where λ is the stretch while C_1 and C_2 are parameters related to the shear modulus such as: $\mu = 2(C_1 + C_2)$.

The parameter least square optimization has been done with a custom-made Python script through Scipy library on complete loading curves.

3. Results and discussion

Our results are indicative of testing up to 20% and 40% strain at strain rate regimes around $1118 \pm 56 \text{ s}^{-1}$ and $2553 \pm 281 \text{ s}^{-1}$, respectively (Figure 1). The experimental data showed a consistent material response characterized by a J-shaped, monotonically upward, non-linear stress-strain behavior (Tappert et al. 2017). This increasingly marked J-shaped behavior with increased testing strain rate is consistent with previous findings, as it confirms the strong strain-hardening and strain rate sensitivity characteristics of the TMJ disc material. Depending on the sample, our results suggested a 6- to 20-fold increase in strength at 20% strain, when the strain rate increased from 1118 ± 56 to $2553 \pm 281 \text{ s}^{-1}$.

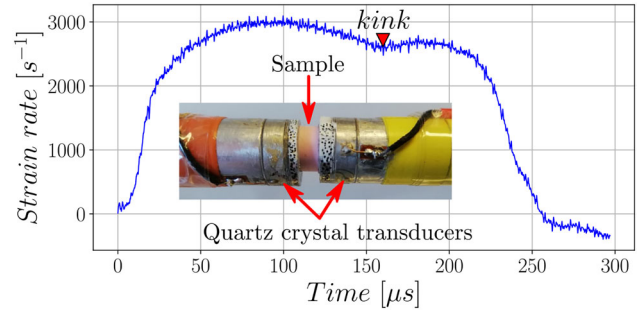


Figure 2. Strain rate history for sample 5R with the moment of partial failure ('kink') as well as a workbench picture focused on the sample.

Our results also showed the presence of a 'kink' (e.g., a sudden decrease in stiffness followed by a recovery) at $\sim 25\%$ strain in the 3L and 5R stress-strain responses (Figure 1). As opposed to the high strain rate data, the low strain rate curves did not show 'kink' ($20.5 \pm 0.3\%$ maximum average strain).

Based on their strain rate history (Figure 2), we hypothesized that this was an indicator of partial failure inception and permanent damage upon compression beyond 25% strain. Further histology and microstructure analysis post-loading are required to confirm our hypothesis. The hyperelastic model fitting highlights the consistency of the Mooney Rivlin model (Figure 1). Interestingly the parameters values were lower as compared to already reported data in previous high rate FE models (Pérez del Palomar and Doblaré 2008). The shear moduli obtained were $4.73 \pm 1.41 \text{ MPa}$ for the $2553 \pm 281 \text{ s}^{-1}$ strain rate and $0.56 \pm 0.31 \text{ MPa}$ for the $1118 \pm 56 \text{ s}^{-1}$ one. Considering an incompressible material with a Poisson's ratio of 0.5, these results lead to a Young's modulus ranged between 1.68 and 14.22 MPa. Being in the literature range, these values appeared higher than recorded in quasi-static testing (Tappert et al. 2017) owing to the visco-elastic characteristics of the tissue (Fazaeli et al. 2019).

4. Conclusions

For the first time, our study introduces the mechanical stress-strain behavior of TMJ discs at high strain rates. Based on experimental data, we computed initial hyperelastic model parameter values to be used in simulation taking also into account the material viscous behavior. Further *ex vivo* testing is warranted on TMJ discs preserved in the jaw in order to further characterize its mechanical properties along with any tissue damages and changes in microstructure upon impact. This proof of concept opens a new window to

address fundamental questions regarding the actual behavior and modeling of TMJ discs in trauma.

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