Comparison of Mechanical Response of TMJ and Knee Cartilage under Dynamic Loading

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INTRODUCTION: Disorders of the temporomandibular joint (TMJ), the only articulating joint in the human head, affect over 10 million Americans [1]. TMJ condylar cartilage, however, remains an understudied tissue. It has a bilayer structure, distinct from the articular cartilage in knee joints [2]. The top layer is fibrocartilage, with a hyaline layer underneath. The two layers are integrated by type I collagen fiber bundles [3]. We found that the bilayer TMJ cartilage has a similar static compressive stiffness to knee articular cartilage, but the hyaline layer alone is much softer [2]. Most of the loading experienced by the TMJ is dynamic, such as during talking and chewing [4]. In this study, we compare the dynamic compressive properties of knee cartilage to TMJ condylar cartilage. We hypothesize that the bilayer structure of the TMJ endows the cartilage with greater shock absorption capabilities.

METHODS: Cylindrical cartilage samples (2.5 mm diameter) were harvested from the TMJ condyle and knee femoral condyles of young porcine (6-9 months old). Subchondral bone was removed (TMJ h = 1.03±0.15 mm; Knee h = 1.06±0.18 mm, mean ± std), and samples were stored at -80 ºC prior to testing (n = 10). Histological images of the TMJ condyle cartilage were acquired (Fig. 1a). *Dynamic Loading*: Dynamic loading was applied to the samples with an ElectroForce 3230 Test Frame (TA Instruments) using previously described profiles in an unconfined compression setup (Fig. 1b) [5]. A preload of 0.2 N (~ 40.7 kPa) was applied to the knee and TMJ high preload (HPL) samples for 1 hr. to reach equilibrium deformation, with the final reductions in thickness by 14.4±2.7% and 50.9±20.3%, respectively. A second TMJ group had a low applied preload (LPL) of 0.06 N, to decrease the compressive stress to ~12.2 kPa. Compressive modulus was calculated based on the equilibrium strain under preload. Afterwards a sinusoidal waveform with amplitude of 6 N (~1.0 MPa) was applied over the preload, consisting of 20 cycles at 20 Hz, 15 cycles at 15 Hz, 10 cycles at 10 Hz, 5 cycles at 5 Hz, 3 cycles at 3 Hz, 2 cycles at 1 Hz, and 1 cycle at 0.1 Hz (Fig. 2), resting for 5 minutes between each frequency. *Theoretical Analysis*: Equilibrium and dynamic mechanical properties were evaluated using Cauchy normal stress component ($\sigma_{33} = hF/h_oA_o$) versus stretch ratio ($\lambda_3 = h/h_o$), assuming the cartilage was incompressible. Dynamic modulus ($\partial\sigma_{33}/\partial\lambda_3$) as a function of dynamic stress was calculated as the slope of the dynamic stress vs strain curve (Fig. 2a).

RESULTS: Histology staining of the TMJ condylar cartilage illustrated its bilayer structure anchored by type I collagen bundles (Fig. 3). The hyaline layer became highly cellularized ~500 µm into the tissue, with little to no inter-territorial space between cells. Under a 0.2 N preload in unconfined compression, the equilibrium modulus of TMJ HPL cartilage was significantly lower than that of knee cartilage (94.8±45.5 kPa vs 286.9±52.7 kPa, $p < 0.001$) (Fig. 1c). Decreasing the preload to 0.06 N resulted in a significantly lower modulus of the TMJ LPL cartilage (20.3±7.6 kPa, $p < 0.001$) (Fig. 1c), showing the strain-dependent compressive modulus of TMJ cartilage at low strain levels. Representative dynamic stress-strain plots are presented in Fig. 2b. Under the same initial high preloading, at low stresses, the dynamic modulus of TMJ cartilage is lower than knee cartilage (e.g., 8.1±2.5 MPa vs 10.5±2.2 MPa at 3 Hz) (Fig. 4a). When the TMJ cartilage experiences a lower preload, the dynamic modulus is reduced by 50% compared to HPL between 0.1-3 Hz (Fig. 4a). In contrast, at high dynamic stresses, the TMJ has similar dynamic stiffness to knee cartilage under the same initial preload. Moreover, the low TMJ preload has less of an effect reducing TMJ dynamic modulus at high dynamic stresses (Fig. 4b).

DISCUSSION: The TMJ condylar cartilage consists of a high-density of pre-hypertrophic chondrocytes residing in the proteoglycan-rich hyaline matrix, distinct from knee articular cartilage that has a much lower cell density and higher matrix content. This indicates that the tissues' poroelastic and intrinsic viscoelastic properties could be substantially different. The loading profile in this study reflects the physiological loading during TMJ daily functions. During chewing, the TMJ cartilage is under high stress levels at 1-3 Hz [6,7]. Under these conditions, TMJ cartilage has a similar dynamic stiffness to knee cartilage, protecting the tissue from over deformation. When speaking, the TMJ cartilage experiences little to no stress, but moves at a faster frequency of 5-6 Hz [8]. In these loading conditions, the TMJ condylar cartilage has much lower dynamic stiffness than the knee cartilage, indicating better shock absorption capabilities which minimizes forces transmitted through the temporal bone to the brain. **SIGNIFICANCE:** TMJ condylar cartilage has better shock absorption capabilities than knee articular cartilage in TMJ daily functions.

REFERENCES: [1] Murphy+, 2013. [2] Zimmerman+, 2015. [3] Ruggiero+, 2015. [4] Tanaka, 2021. [5] Park+, 2004. [6] Tanaka+, 2006. [7] Gallo+, 2000. [8] Ostry and Flanagan, 1989.

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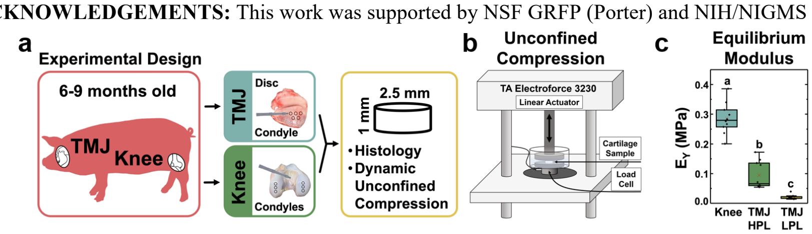

Figure 1. (a) Cylindrical cartilage samples were harvested from the TMJ and femoral condyles of young porcine. (b) Unconfined compression mechanical testing setup. (c) Equilibrium modulus of knee and TMJ high preload (HPL) samples (0.2 N preload) and TMJ low preload (LPL) samples (0.06 N preload). Different letters indicate significant differences between groups ($p < 0.05$).

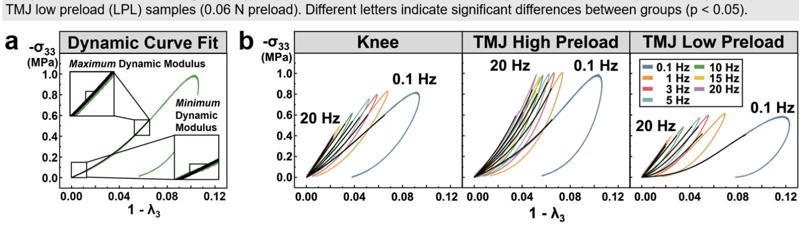

Figure 2. (a) Minimum versus maximum dynamic modulus calculated based on slope of the stress strain curve. (b) Dynamic stress-strain responses of typical knee, TMJ high preload, and TMJ low preload specimens. Exponential curve fits are shown in black.

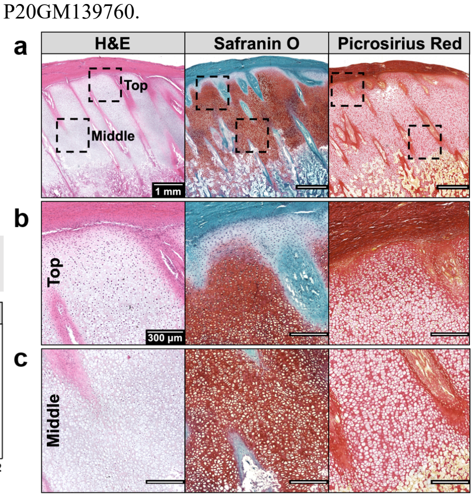

Figure 3. Histological staining of (a) full thickness TMJ condylar cartilage, (b) fibrous and top hyaline layer, and (c) deep hyaline layer.

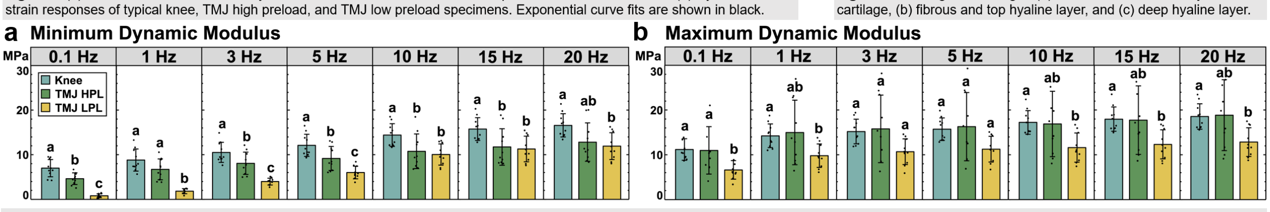

Figure 4. Minimum (a) and maximum (b) stress-dependent dynamic moduli for knee articular cartilage and TMJ cartilage at either a high preload (HPL) or a low preload (LPL). (a) At low stress levels, TMJ condylar cartilage is much softer than knee articular cartilage. (b) At higher stress levels, TMJ and knee cartilage have similar equilibrium moduli.