

Dual-mode dynamic functional stiffness of articular cartilage

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INTRODUCTION: Dynamic stiffness parameters (elastic modulus, loss angle, Poisson's ratio) determine how poroviscoelastic materials or structures (e.g. cartilage) distribute and dissipate loads. Also, these parameters are highly sensitive to structural changes and thus have diagnostic value. Nutrition processes in cartilage occur at slow loading rates which move water in and out of the tissue. In contrast, gait subjects hip, knee and ankle cartilage to impact loads which severely limit water movement, produce higher modulus values and lower loss angles, indicating energy storage. We hypothesize that evaluating cartilage in dual modes provides a more complete picture of functional stiffness. Also, indentation testing minimizes specimen preparation and is more functionally relevant¹. This study provides initial results.

METHODS: The cartilage source was fresh, healthy cadaver knees from young pigs (9 months old). Specimens were 7.6mm diameter osteochondral plugs from the lateral condyles. Each specimen was evaluated in both test modes, using a steel spherical tip indenter.

"Nutritional" loading was accomplished with a Synergie 100 MTS® programmed to perform a series of single sinusoidal cycles at 1, 0.3 and 0.1 Hz under displacement control to a depth of ~0.1 mm, separated by 50s pauses--shown to be sufficient to allow dimensional recovery. "Gait" loading was accomplished with a single impact micro-indentation (SIMI) device², mounted in a rigid load frame. The SIMI indenter pendulum falls freely, with impact force thus determined by mass and gravity. The mass and indenter dimensions used provided indentation depths of ~0.1 to 0.2 mm in healthy cartilage. (Actual depth depends on specimen stiffness.) An electromagnetic coil captures indenter motion data. The equivalent frequency of SIMI velocity at impact is ~350Hz.

All previous calculations of cartilage modulus from indentation data¹ are compromised by being based on a model which assumes cartilage is an "infinite elastic layer"³. In the resultant indentation equation, modulus values are inversely proportional to a correction factor, κ , which varies with both indenter-radius/cartilage-thickness ratio and Poisson's ratio. Instead, we used the approach of

Kren² which assumes viscoelasticity, does not require specimen thickness measurement and does not require κ . The modulus is calculated from

$$E_{dyn} = (1 - \nu) [P_{\alpha_{max}} / (R^{1/2} \alpha_{max}^{3/2})] \quad (1)$$

Where E_{dyn} = dynamic elastic modulus, ν = Poisson's ratio, α_{max} = maximum displacement, $P_{\alpha_{max}}$ = force at maximum displacement, and R = indenter radius. Literature values of ν for cartilage vary widely¹, and $\nu = 0.44$ was assumed. This does not affect relative magnitudes of E_{dyn} calculated from (1). The loss angle ϕ was read directly from the differences between the sinusoidal force and displacement curves.

RESULTS: See Table 1

Table 1. Nutrition-mode (0.1Hz) and gait-mode stiffness, same specimen: n = 8 in each mode.

Method	Indenter radius [mm]	Mean E_{dyn} [MPa]	S.D. E_{dyn} [MPa]	Mean ϕ [°]	S.D. ϕ [°]
N-mode	1	8.2	0.9	15.7	2.2
G-mode	0.5	14.9	0.8	7.7	0.6

DISCUSSION & CONCLUSIONS: Precision of both test modes was acceptable (worst S.D.=14%). Compared to N-mode, G-mode modulus was ~82% higher, and loss angle was ~51% lower. The data demonstrate the dependence of cartilage stiffness parameters on test mode, and support dual mode tests to evaluate two aspects of cartilage function.

REFERENCES: ¹ R.K. Korhonen, et al (2002) *J Biomech* 35:909. ² A. P. Kren, et al *Determination of viscoelastic characteristics of biological materials by SIMI* (m.s. in preparation). ³ W. C. Hayes (1972) et al. *J Biomech* 5:541.

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