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CONFINED AND UNCONFINED CARTILAGE MECHANICS: EFFECT OF CREEP TIME ON MATERIAL PROPERTY PREDICTION

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Introduction

Variability in mechanical tissue testing techniques limits meaningful comparisons across studies, impacting the evaluation of healthy and osteoarthritic cartilage, as well as engineered tissue constructs [1]. A recent review recommended creep testing of cartilage to use 1 MPa creep stress with >60-min relaxation [1]. Therefore, this study aims to assess the impact of data quantity on cartilage creep material property predictions, offering guidance for cartilage creep testing.

Methods

Confined and unconfined creep experiments were conducted using bovine cartilage samples (ϕ = 6 mm, n = 16). A preload of 0.05 MPa were used to reach baseline thickness [2] before applying 1 MPa creep load (ramping rate: 0.25 MPa/s) that was maintained for 5 hours. Confined tests used a chamber (ϕ = 6.2 mm) with a porous plate (40 µm) while unconfined tests used an open chamber and a rigid cylindrical piston (ϕ = 12 mm). Two models were fitted to the data including a range of time intervals (30-min, 60, 120, 180, 240 and 300 minutes): a three element Kelvin (Eq. 1) and Burgers model (Eq. 2).

$$\varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{E_2}\left(1 - e^{-\frac{E_2}{\eta_2}t}\right) \qquad \text{(Eq. 1)}$$

$$\varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{E_2}\left(1 - e^{-\frac{E_2}{\eta_2}t}\right) + \frac{\sigma_0}{\eta_1}t \qquad \text{(Eq. 2)}$$

$$\tau_i = \frac{\eta_i}{E_i} \qquad \text{(Eq. 3)}$$

Results

Both models captured cartilage creep accurately using the full (5h) dataset (Figure 1). For shorter time interval, as more data was introduced into the models, the predicted material properties started to converge towards a steady state (Table 1).

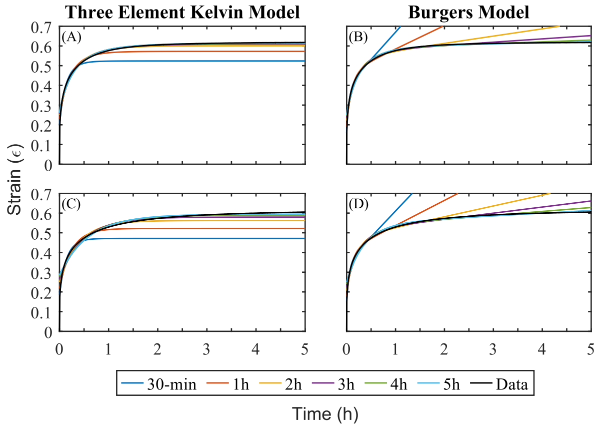

Figure 1: Mean cartilage creep predictions at different time intervals using confined (A-B) and unconfined (C-D) experimental configuration with the two models.

Discussion

Time intervals ≤ 1 hour led to insufficient information to accurately predict material properties; longer creep experiments with ≥ 2 hours appeared to be more appropriate as the estimated viscoelastic properties started to converge. This is concerning as most cartilage creep experiments are performed using ≤ 1 hour [1], resulting in significant errors. Future work will include recovery testing to study if the applied stress is appropriate or if it is concomitant with tissue damage as 0.1 MPa is predominantly used to replicate physiological strain [1].

References

1. Patel et al, Tissue Eng Part C Methods 25: 593-608, 2019.
2. Athanasiou et al. J. Orthop Res 9: 330-340, 1991.

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		Three Element Kelvin Model (Eq. 1)			Burgers Model (Eq. 2)			
	Interval	E_1 (MPa)	E_2 (MPa)	τ_1 (sec)	E_1 (MPa)	E_2 (MPa)	τ_1 (sec)	τ_2 (sec)
Confined	30-min	5.5 ± 1.4	3.3 ± 0.8	515 ± 170	7.0 ± 1.8	4.8 ± 1.5	197 ± 47	2396 ± 2080
	1h	4.7 ± 1.0	3.1 ± 0.6	855 ± 317	5.8 ± 1.5	4.0 ± 1.2	388 ± 140	9005 ± 12764
	2h	4.3 ± 0.8	2.9 ± 0.5	1243 ± 589	4.9 ± 1.2	3.4 ± 1.0	713 ± 285	84286 ± 152540
	3h	4.1 ± 0.8	2.9 ± 0.5	1443 ± 829	4.5 ± 0.9	3.2 ± 0.8	941 ± 351	187706 ± 283711
	4h	4.1 ± 0.8	2.9 ± 0.5	1541 ± 957	4.3 ± 0.9	3.1 ± 0.7	1130 ± 500	287081 ± 380790
	5h	4.0 ± 0.8	2.9 ± 0.5	1594 ± 1024	4.2 ± 0.8	3.0 ± 0.6	1272 ± 658	402929 ± 512482
Unconfined	30-min	5.7 ± 1.3	3.6 ± 0.4	528 ± 83	7.0 ± 1.6	5.3 ± 1.0	208 ± 36	2108 ± 714
	1h	4.9 ± 1.1	3.3 ± 0.4	894 ± 126	6.0 ± 1.3	4.4 ± 0.7	383 ± 68	4981 ± 1273
	2h	4.2 ± 0.9	3.2 ± 0.3	1417 ± 214	5.1 ± 1.1	3.8 ± 0.5	690 ± 109	13717 ± 3452
	3h	3.9 ± 0.8	3.2 ± 0.3	1778 ± 301	4.7 ± 1.0	3.6 ± 0.4	947 ± 142	26889 ± 8003
	4h	3.7 ± 0.7	3.2 ± 0.3	2036 ± 373	4.4 ± 0.9	3.5 ± 0.4	1168 ± 179	45281 ± 15260
	5h	3.6 ± 0.7	3.2 ± 0.3	2228 ± 431	4.2 ± 0.8	3.4 ± 0.4	1354 ± 219	68578 ± 23854

Table 1. Overview of cartilage material properties determined from confined and unconfined experiments.