Reproducing Soft Tissue Viscoelasticity by Silicone 3D Printing [1]

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Introduction

Patient-specific anatomical models are increasingly used for teaching, patient education, surgical planning, and training. While geometry can be reproduced accurately, matching the **haptic (viscoelastic)** behavior of soft tissues remains challenging, (Fig. 1), [2].

In this work, **soft-tissue-like infill microstructures from 3D-printed silicone** were created using a two-phase strategy: stiffness was adjusted via **infill density**, and viscous dissipation was increased by post-printing **injection of high-viscosity silicone oil**. This approach addresses the persistent gap where printed materials are either too stiff or insufficiently damped to mimic real organs.

Fig 1: Soft tissue viscoelastic properties are among the main factors for a realistic haptic sensation of anatomical models.

Materials & Methods

Specimens: A total of **72 cylindrical silicone specimens** (Sista F101 silicone) with gyroid infill ρ_{infill} of **20, 30, 40 %** (n=24 each; diameter = 50 mm, height = 12.6 mm) and **10 bulk (100 %)** specimens were produced on a self-built **direct ink writing (DIW) 3D printer**, (Fig. 2).

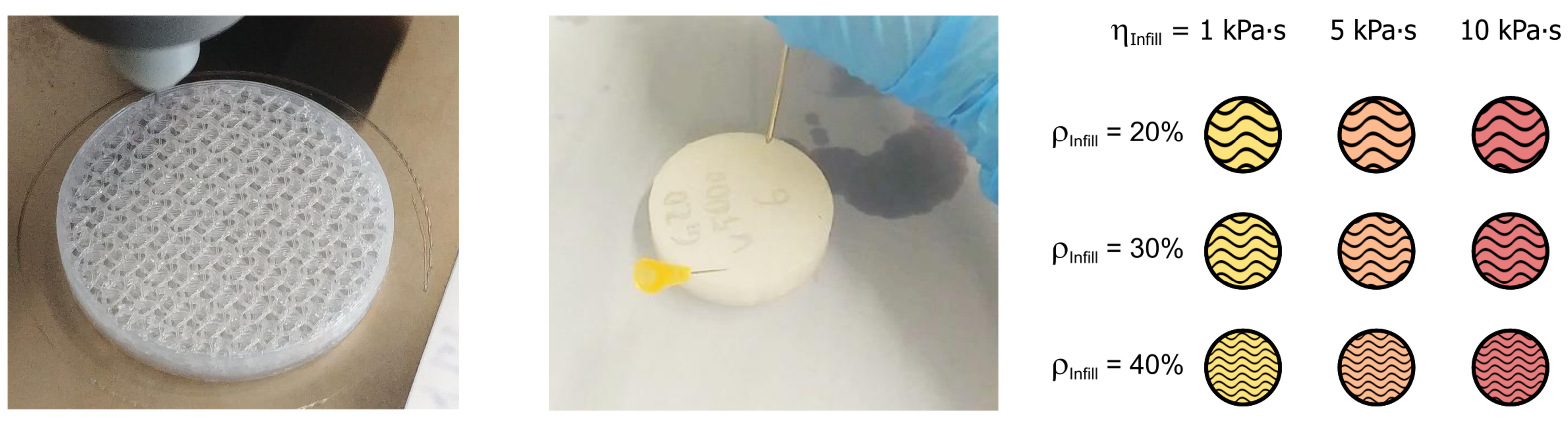

Fig. 2: (left) 3d printing of silicone specimen showing the gyroid infill pattern, (center) post-printing silicone oil injection, (right) overview of sample combinations: three different infill densities ρ_{infill} and three different oil viscosities η_{infill}

Viscoelastic mechanical testing: All samples underwent **stress-relaxation compression** with a step displacement to **ε_0=12 %** and a holding time of 300s, (Fig. 3). After baseline testing, each printed specimen was **injected** from the top with **silicone oil.** The oil had a dynamic viscosity η_{infill} of either **1.0, 5.0 or 10.0 kPa·s.** All samples were then retested, (Fig. 2).

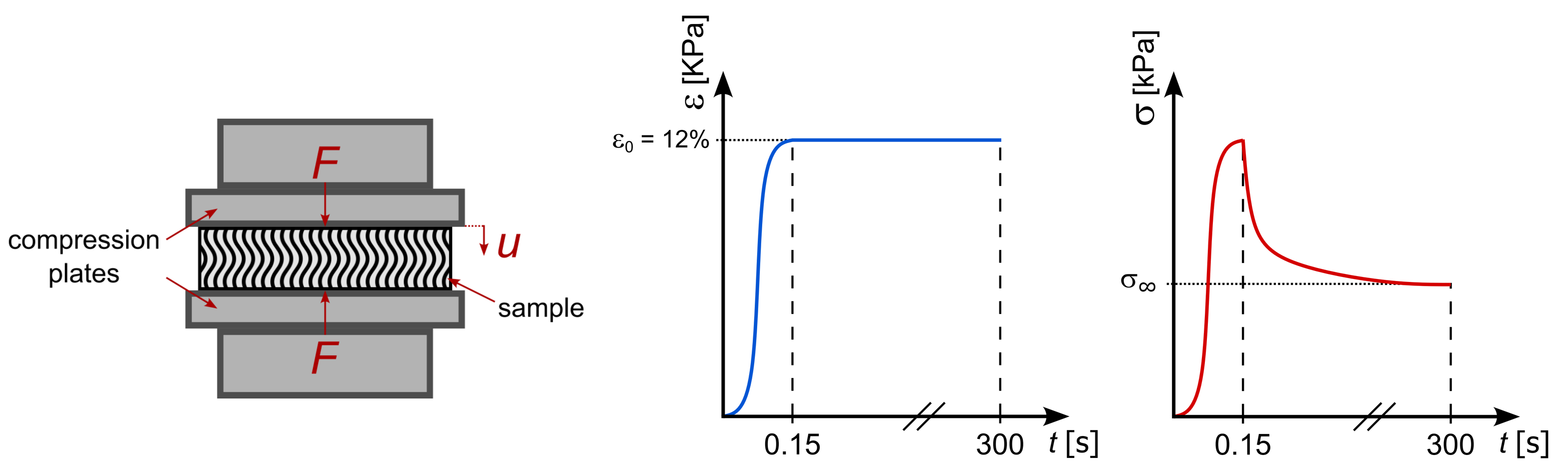

Fig 3: (left) schematics of the compression relaxation test, (center) applied strain step, (right) typical stress response of the relaxation test

Parameter identification: To infer the infill's viscoelastic properties, the relaxation tests were reproduced in a **FEM simulation**, (Fig. 4). The perimeter was modeled as bulk silicone, and the core as the unknown infill material. In an **optimization loop**, the **infill storage- and loss moduli E', E'' were identified,** so that the global behavior fits the experiments best. The loss factor **tan** δ, the ratio of E''/E', was calculated as a metric for **energy dissipation.**

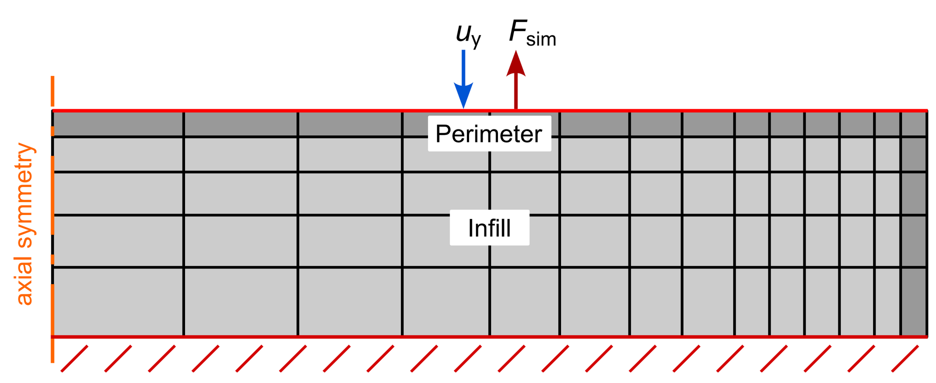

Fig 4: Axisymmetric FEM model for the identification of the infill viscoelastic parameters E' and E'' (light gray) by numerical optimization. The perimeter was modelled as bulk silicone (dark gray).

Results

Non-injected (empty) specimens showed increasing stiffness with infill density ρ_{infill}, (Fig. 5a). After oil injection, **E''** and **tan δ** increased with oil viscosity, (Fig. 5bc). The injection of **10 kPa·s-oil** produced the largest rise in damping, moving loss factors into soft-tissue-like ranges.

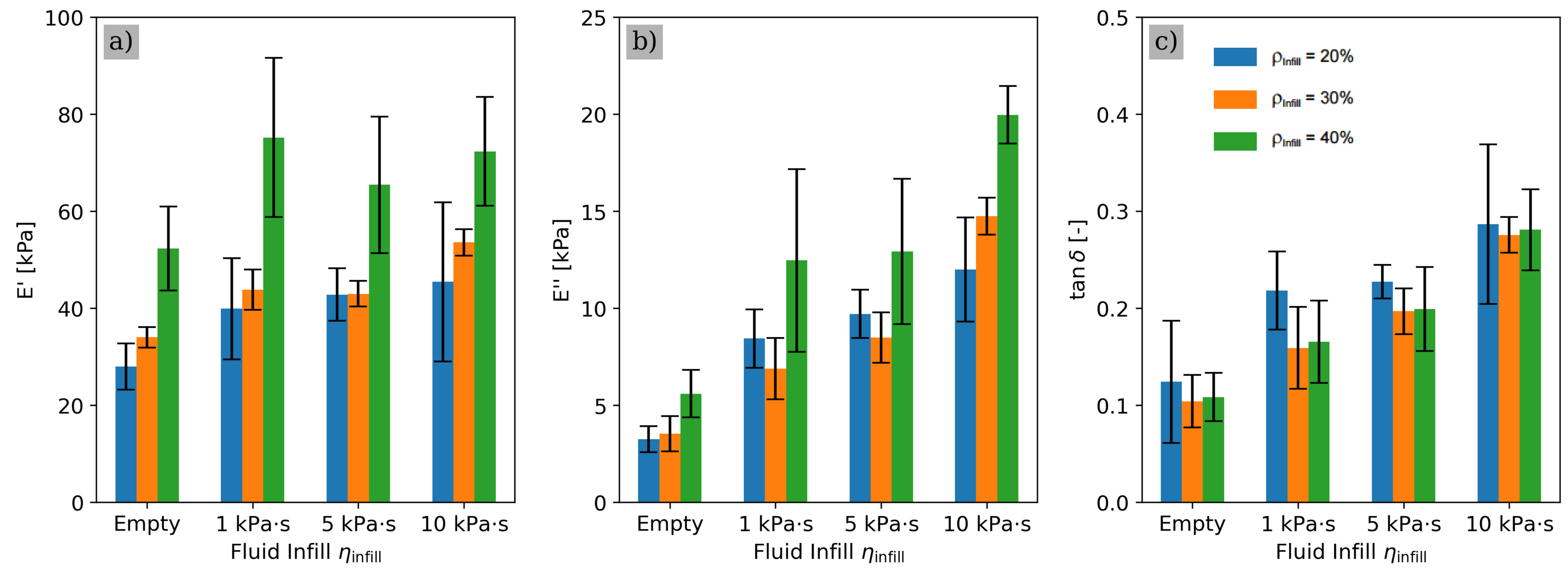

Fig 5: Identified infill viscoelastic properties in terms of storage modulus E' (left), loss modulus E'' (center) and loss factor tan δ (right) at 1Hz.

In general, **E'** scaled primarily with **infill density**, while **tan δ** was governed predominantly by **oil viscosity,** (Fig. 5c). Specific density–viscosity combinations reproduced ranges reported for tissues such as **liver** and **cervix.** In contrast, low-density, non-injected conditions approximated **myocardium,** (Fig. 6), [3,4].

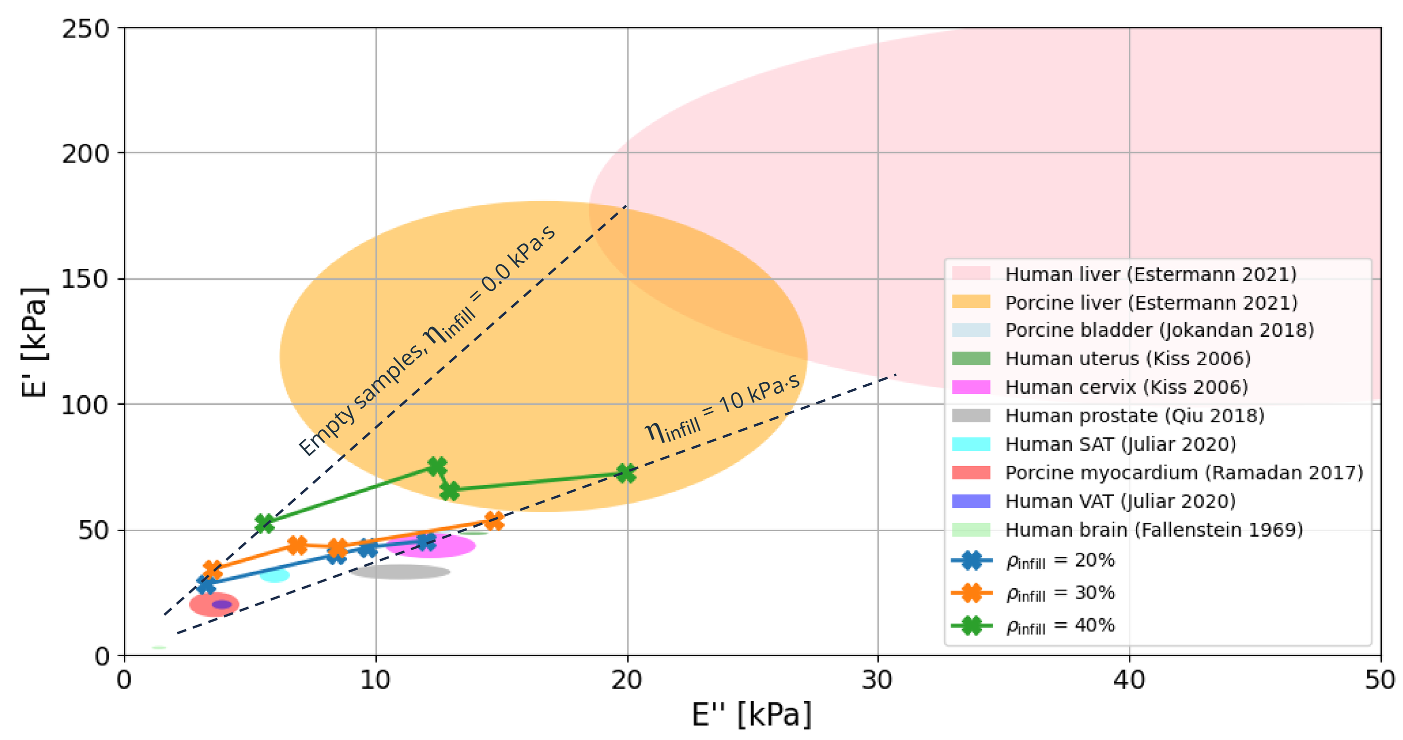

Fig 6: Viscoelastic properties of 3D printed infill patterns (lines) compared to soft tissue (ellipses). The first point of each line indicates the empty specimens, the second one the specimens with η_{infill} = 1.0 kPa·s, the third one specimens with η_{infill} = 5 kPa·s and the last one specimens with η_{infill} = 10 kPa·s.

Discussion

Decoupled stiffness and viscosity: By adjusting **infill density**, elastic stiffness (**E'**) was scaled with minimal change in loss factor, while **post-printing oil injection** elevated viscous dissipation **(tan δ)** to tissue-like values. In combination, this workflow enabled targeted matching of different organs' viscoelastic behavior.

Benefit of 3D Printing: It was demonstrated that silicone 3D-printing allows for the production of soft and complex microstructures where conventional methods, such as casting/molding, would not provide comparable architectures at the needed feature scale.

Outlook: Expanding to **softer base silicones** and refining **infill–viscosity tuning** is expected to widen the achievable design space. The method shows promise for **haptically realistic** patient-specific models for teaching and surgical rehearsal.

References

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