2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

An Optimised Lattice-reinforced Dynamic Liver Phantom with Realistic Tactile Properties for Palpation Training

Yiting Mo[1] and Fernando Bello[1,2]

I. Introduction

Haptic cues play a critical role in conveying tissue properties such as stiffness, texture, and temperature, which are crucial in routine physical examination of patients through palpation. Physycal simulators offering realistic tactile information have shown to be valuable for palpation training [1].

Amongst abdominal organs, the liver is a large organ with crucial physiological functions, prominent anatomical location, and interaction with surrounding tissues. Chronic liver disease often leads to progressive histological changes, altering tissue stiffness. Whilst various techniques have been developed to detect stiffness abnormalities, liver palpation remains relevant and routinely performed. However, most existing liver phantoms are static, lacking the dynamic behaviour required to replicate realistic tissue compliance and deformation. This limitation reduces haptic fidelity and training effectiveness in palpation-based scenarios [2].

Achieving tactile realism with a tunable stiffness range remains a major challenge, due to the range of normal and abnormal stiffness values, as well as morphometric and shape changes resulting from benign and malignant conditions. To address these issues, this work in progress presents an optimised internal lattice structure that can dynamically replicate the liver's stiffness properties, while maintaining tactile fidelity. The resulting liver phantom is designed to better recreate in-vivo conditions for use in palpation-based medical training simulators.

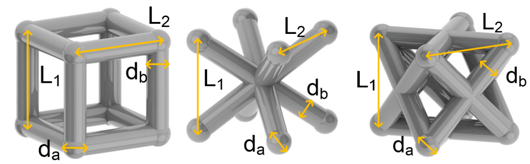
II. Lattice-reinforced design of liver phantom

Aiming to recreate liver mechanical properties, Estermann et al. compared nine different materials in terms of tactility for improving material selection in anatomical models [3]. Results showed silicone rubber Ecoflex 00-30 (Smooth-On Inc., USA) has the most similar mechanical properties to normal liver tissue. Pneumatic actuation provides simpler control, faster response, and greater adaptability, making it suitable for applications requiring dynamic behaviour. By adopting a chamber structure and pneumatic actuation, the liver phantom can achieve tunable stiffness. However, the ultra-soft nature of Ecoflex 00-30 limits the achievable stiffness range while maintaining the original liver shape. We propose using an internal lattice reinforcement for the liver phantom to balance these conflicting requirements.

*Research supported by Duke-NUS Medical School

[1]Department of Technology Enhanced Learning and Innovation, Office of Education, Duke-NUS Medical School, National University of Singapore, Singapore. e-mail:yt.mo@duke-nus.edu.sg, f.bello@duke-nus.edu.sg

[2]Department of Surgery and Cancer, Imperial College, London, UK.



(a) Cubic (b) BCC (c) FCC

Fig. 1: Lattice structures and geometry parameters, L_1: length of cell vertical side, L_2: length of cell horizontal side, d_a: joint diameter, d_b: beam diameter.

A. Lattice design

Lattice structures composed of periodic unit cells have been widely used in fields such as aerospace, military, and engineering for their excellent energy absorption capabilities, exhibiting pressure-resistant stability, which enhances structural integrity under varying load conditions. Three classic lattice unit cell patterns were used in the optimization of mechanical performance: Cubic, Body-Centred Cubic (BCC), and Face-Centred Cubic (FCC). The lattice structure design and the corresponding geometric parameters are shown in Figure 1. For better durability and manufacturability, the geometric parameters of the cubic unit cell were set as $L_1 = L_2 = 20$ mm, $d_a = 6$ mm. In addition to the conventional cubic unit cell, the tetragonal cell, which uses a cuboid with a square base as the unit cell, was also considered. The geometric parameters for this configuration were $L_1 = 40$ mm and $L_2 = 20$ mm.

B. Liver phantom design

The mechanical design of the lattice unit cells, as well as the liver model, was performed using SolidWorks 2023. For better durability and manufacturability, the thickness of the liver model was set to 5 mm. Instead of automatically generating the lattice structure within the liver model, a uniform lattice array with predefined dimensions of 100×120×140 mm was employed to manually fill the chamber of the liver model. The inner wall surface of the liver model was used as a cutting reference to trim the lattice structure array, resulting in a liver phantom with uniform lattice-reinforced design.

III. Finite element analysis stiffness optimization

A. FEA simulation setup

Considering the highly non-linear and time-independent characteristics of silicone materials, a finite element analysis (FEA) on hyperelasticity simulation was conducted to simulate the deformation and stiffness of the liver model to ensure that the optimised design achieves an acceptable trade-off between the initial softness, the liver shape, and the stiffness variation. To compare the performance of the different geometric properties of the lattice structure, d_b was set to 2.4 mm and 4.8 mm, respectively. Different boundary conditions were set for the deformation and stiffness of the liver model.

Shape deformation was quantitatively evaluated by considering changes in anatomical directions. The largest distance measured in the cranial-caudal direction is denoted as L_{cc}, while the maximum distance in the anteroposterior direction is defined as L_{ap}. Dimensional changes in these two directions are then expressed as Δ_{cc} and Δ_{ap}. A simulated indentation test was conducted to demonstrate the range of achievable stiffness.

B. FEA simulation results

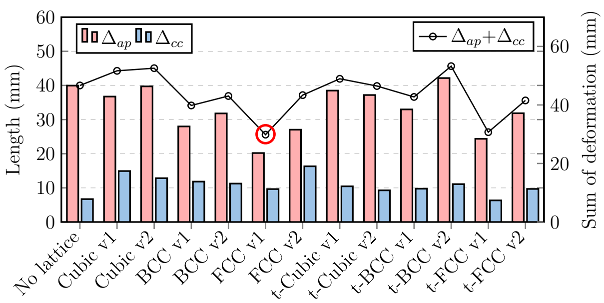


Fig. 2: Deformation simulation results. Note that v1 presents d_b = 4.8 mm while v2 presents d_b = 2.4 mm. t- prefix means lattice reinforcement with tetragonal cell unit.

Δ_{cc} and Δ_{ap} under different configurations were measured as illustrated in Fig. 2. The liver phantom with a tetragonal lattice was tested under an internal simulated pressure of 4 kPa, while the cubic lattice models were evaluated at an internal simulated pressure of 6 kPa. Overall, the FCC lattice demonstrated superior performance compared to both simple cubic and BCC structures, effectively better resisting shape deformation under identical geometric and simulation conditions. In contrast, the tetragonal cell structure showed reduced effectiveness in retaining the original liver shape. Additionally, increased beam diameter led to improved reinforcement performance. Among the twelve configurations, the FCC lattice with 4.8 mm beam diameter exhibited the best deformation response by better retaining morphological shape. Hence, it was adopted for the stiffness simulation.

The stiffness simulation and the corresponding diagram of the simulated indentation test are shown in Fig. 3. Based on the lumped stiffness method, the estimated liver stiffness under different internal pressure is shown in Fig. 4. The relationship between the liver stiffness E and the pressure p follows a linear regression, described by $E = 67.3p + 412$, with $R^2 = 0.994$. This linear correlation suggests that liver stiffness can be reliably tuned from the applied internal pressure. According to in-vivo indentation tests by Carter

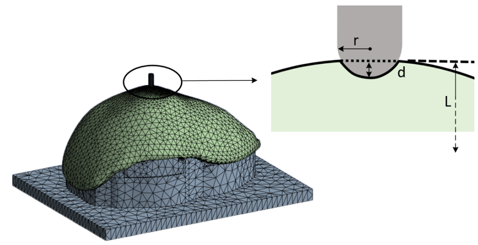


Fig. 3: Schematic diagram for liver stiffness analysis through an indentation simulation. The FEA was performed in Ansys Workbench (ANSYS Inc., USA).

et al. [4], the stiffness of healthy and diseased in-vivo liver ranges from 270 kPa to 740 kPa. Given that a healthy liver is typically not palpable during a physical examination, the simulated stiffness values can effectively replicate the real mechanical behaviour across a wide stiffness range.

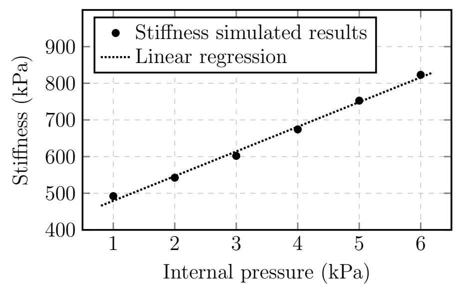


Fig. 4: Stiffness simulation results under various internal air pressure.

IV. Liver Phantom Fabrication

The designed liver phantom was fabricated using silicone Ecoflex 00-30. A real-world indentation test was conducted using a force test stand and digital caliper to measure stiffness under varying internal pressures. The experimental stiffness values aligned well with the FEA simulation results, showing a maximum deviation of 7.6% and a minimum of 0.7%, thereby validating the reliability of the physical phantom. Notably, its tunable stiffness range effectively replicates real mechanical behaviour, as demonstrated in Carter's study [4].

Future work will focus on conducting a user study in an abdominal palpation scenario to subjectively evaluate the tactile feedback conveyed by the liver phantom to participants.

References

[1] Maglio, S., et al. "High-fidelity physical organ simulators: From artificial to bio-hybrid solutions." IEEE Transactions on Medical Robotics and Bionics 3.2 (2021): 349-361.

[2] Tian, Yingjun, et al. "Soft robotic mannequin: Design and algorithm for deformation control." IEEE/ASME Transactions on Mechatronics 27.4 (2022): 1820-1828.

[3] Estermann, Sarah-Jane, Dieter H. Pahr, and Andreas Reisinger. "Quantifying tactile properties of liver tissue, silicone elastomers, and a 3D printed polymer for manufacturing realistic organ models." Journal of the Mechanical Behavior of Biomedical Materials 104 (2020): 103630.

[4] Carter, Fiona J., et al. "Measurements and modelling of the compliance of human and porcine organs." Medical image analysis 5.4 (2001): 231-236.