Impact Of Pressure And Fat Thickness On Tissue Biomechanics During Large Suction Deformation

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Abstract

Accurate tissue mechanical properties are essential for simulating medical devices that deform skin under suction, such as devices for the treatment of fat, skin wounds, and vascular skin conditions. While suction-based methods exist for estimating these properties, most rely on small apertures (under 16 mm) and do not account for anatomical variation in fat thickness.

Displacements were measured experimentally using 50 mm, 30 mm, and 16 mm circular suction apertures across a range of applied pressures. These measurements were used to calibrate a 2D axisymmetric transient finite element model of skin, fat, and muscle, implemented in COMSOL Multiphysics (version 6.3). The geometry was participant-specific, with layer thicknesses obtained from ultrasound imaging. Material behavior was modeled using isotropic hyperelastic formulations: the polynomial model for skin, the Mooney-Rivlin model for fat, and the Ogden model for muscle. Two separate inverse studies were conducted using the Optimization Module. One optimized parameters based on displacement at a single pressure level, while the second incorporated displacements from multiple pressure levels to minimize normalized squared error and improve robustness.

The single-pressure inverse method produced accurate displacement predictions for the 50 mm aperture, with errors generally below 10 percent across pressure levels. However, when applied to the 30 mm and 16 mm apertures, this approach led to significantly higher errors, reaching up to 60 percent at the lowest pressure level. In contrast, the multi-pressure optimization reduced these discrepancies and produced more consistent predictions across all apertures and pressure levels, demonstrating improved robustness to nonlinear tissue behavior.

Stress analysis across skin, fat, and muscle layers showed that stress distribution varied with both aperture size and fat thickness. Circumferential and axial stresses dominated in the skin, while the fat layer experienced lower overall stresses due to its low stiffness, especially in shear. In the muscle, participants with thinner fat showed higher stress transmission, emphasizing the role of fat as a mechanical buffer. These results underscore the importance of pressure range, aperture size, and anatomical variability in suction-based modeling.

This study demonstrates that while single-pressure optimization may suffice for large apertures, using multiple pressure levels significantly improves property estimation and displacement prediction, particularly for smaller applicators. Stress analysis revealed that even slight differences in fat thickness significantly alter internal stress distributions, although the axial and circumferential components vary in sensitivity. These results highlight the importance of accounting for anatomical variability and evaluating stress components separately to improve the reliability of computational modeling of soft tissue biomechanics in device development.

Reference

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Figures used in the abstract

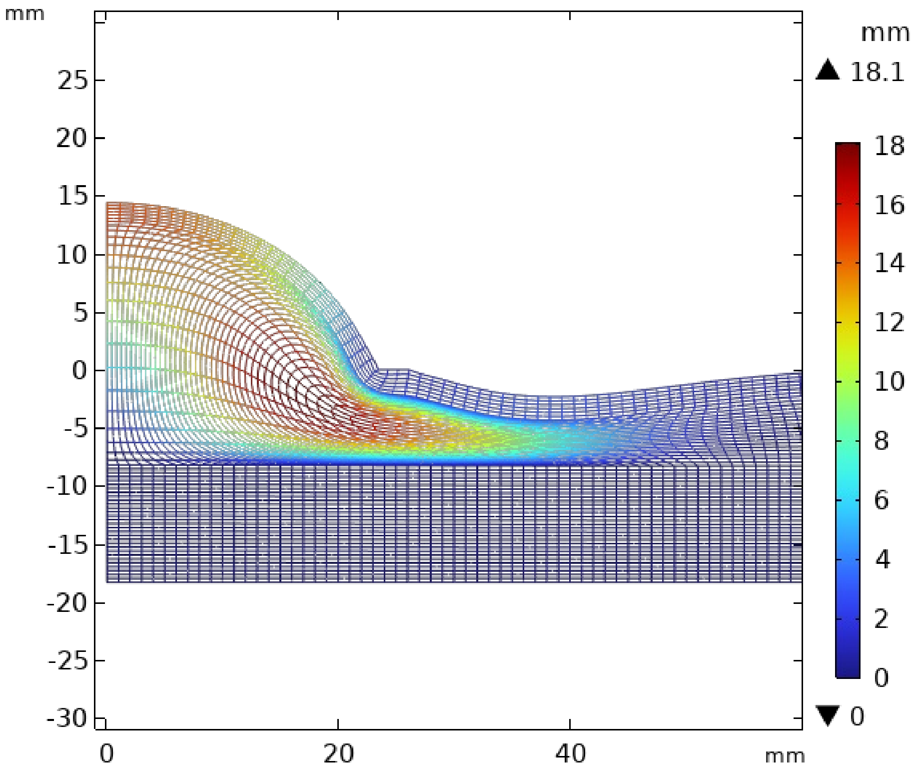

Figure 1 : Numerical displacement of skin (2 mm), fat (6.3 mm), and muscle (10 mm) under a suction pressure of 203.2 mmHg applied over a 25 mm radius aperture in an axisymmetric model. A roller boundary condition was applied at the symmetry axis (r = 0) to restrict

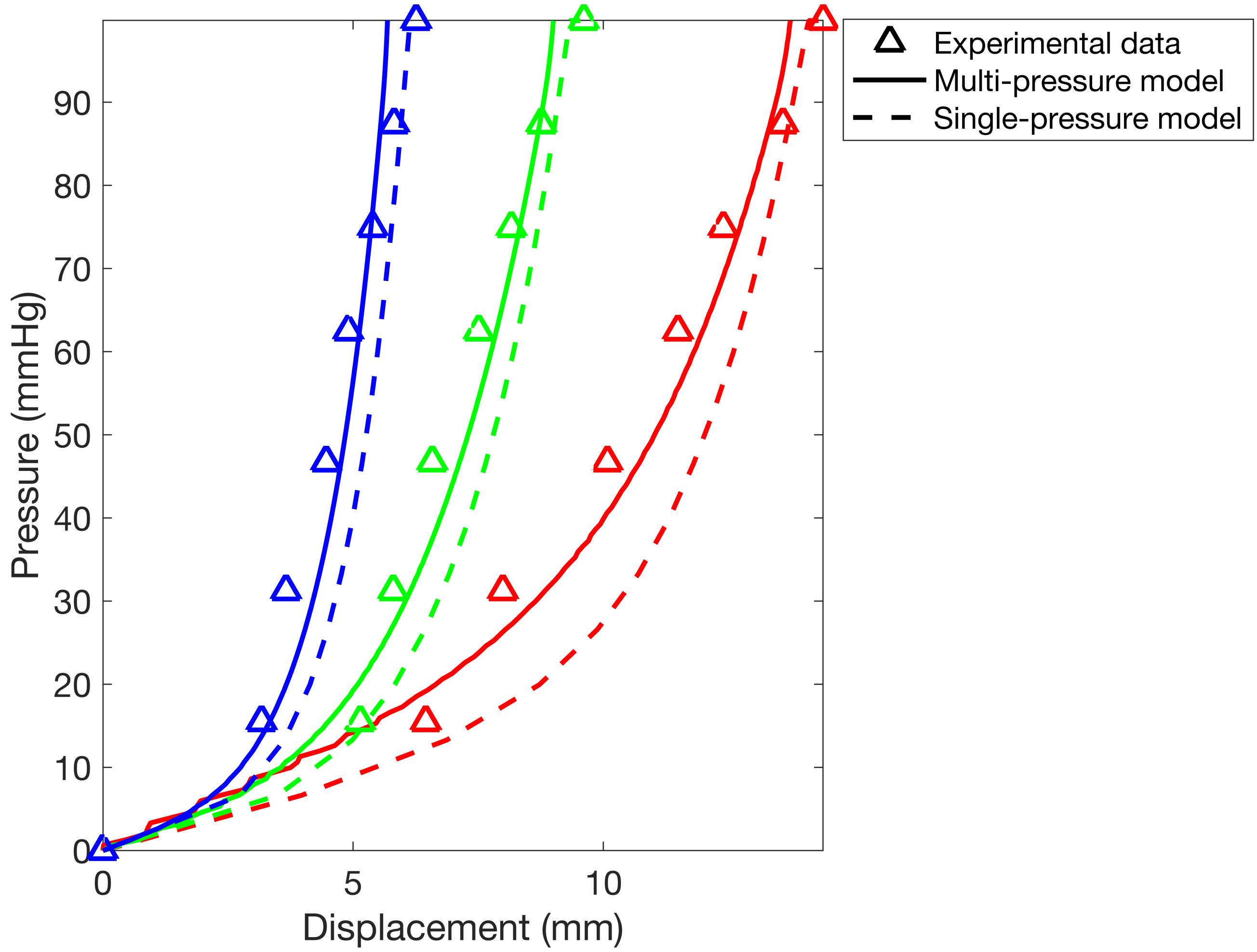

Figure 2 : Experimentally measured and simulated pressure-displacement curves for one participant using 50 mm (red), 30 mm (green), and 16 mm (blue) apertures. Simulations were performed using material parameters estimated by minimizing the error at a pressure of 20

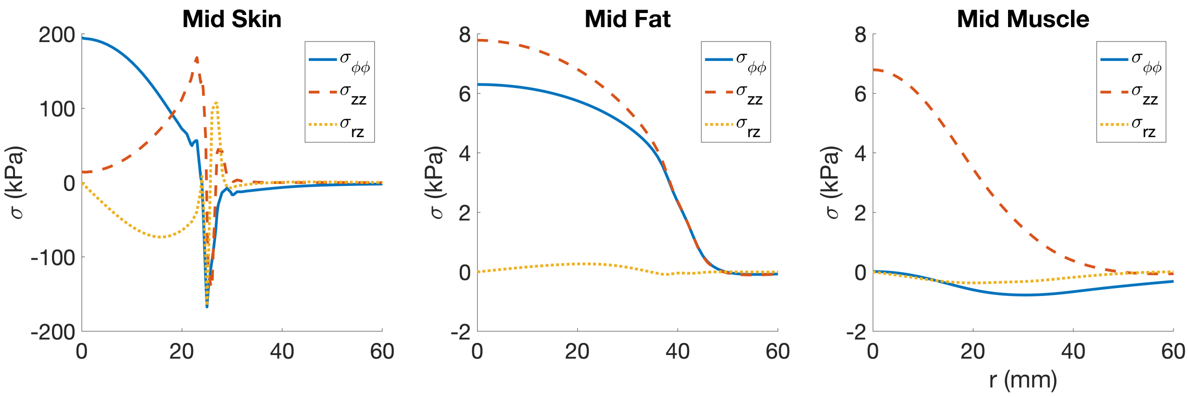

Figure 3 : Circumferential (blue), axial (orange), and shear (yellow) stress distributions at the mid-depth of the skin, fat, and muscle layers at a pressure of 203.2 mmHg.