Mechanical characterisation of skin using suction experiments, modelling and machine learning

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Introduction: There is a need for more quantitative and detailed criteria for the assessment of lymphoedema. Previously, we developed a 3D camera-based assessment of lymphoedema which allowed us to identify localised swelling patterns for patients with unilateral lymphoedema. Furthermore, we quantified the variability of sub-garment pressures across scanned arms and questioned the validity of the Laplace assumptions for real arm shapes through a computational modelling approach. However, beyond geometric considerations we should also consider skin material properties for optimal patient treatment strategies. Therefore, a framework is developed that mechanically characterises skin through suction experiments combined with state-of-the-art computational modelling and machine learning.

Method: A cutometer with probes of 2mm and 8mm diameter is used to capture skin displacement versus time curves, which are indirect measures for skin stiffness and skin permeability to fluid flow. This device is used on a group of 18 volunteers to generate baseline responses for each probe, which will aid the development of multi-layered skin phantoms. Poly (vinyl-alcohol) (PVA) hydrogels are created to fabricate 2-layered skin samples representing the stiffer dermal and less stiff subcutaneous layers. The mechanical material properties of the individual hydrogel layers are tested using mechanical compression tests and tuned to values found in literature.

To aid the interpretation of the experimental data a computational framework is developed. At the basis is a computational model that simulates the cutometer experiment. Poro-viscoelastic material models are used that represent the porous fluid-filled properties of skin across each of the two layers. The material properties are given as inputs to the model whilst the transient displacement signals are calculated based on the fundamental laws of mechanics. By choosing a large range of material properties combinations a virtual data base can be created with thousands of samples. This database is then used to train a machine learning model that takes displacement curves as an input and predicts skin material properties.

Results: Successful hydrogel phantoms are created that show similar behaviour to that measured on volunteers. The cutometer signals on these well-characterised hydrogel samples can provide validation for the computational models. Hyperparameter tuning of the machine learning models allowed us to obtain a 90%+ accurate prediction of the material parameters in the different layers of the skin based on the cutometer signals. Future work is needed to refine the current framework and characterise the skin of lymphoedema patients and gain a further quantitative understanding of their skin changes.