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Volumetric Imaging of Skin Deformation with Synchrotron X-ray Microtomography

Thomas Daunizeau[1,2], Matej Mayet[1], Lukas Stracovsky[3], Basil Duvernoy[4], Maxime Rouillard[1], Donatien Doumont[5,6], Guillaume Daniel[7], Jonathan Perrin[7], Timm Weitkamp[7], Benoit P. Delhaye[5,6], and David Gueorguiev[5]

I. Introduction

Even a simple touch elicits complex skin biophysics, from frictional contacts to viscoelastic deformations, which subserves neural coding of grip regulation [1] and texture perception [2]. Despite decades of research supported by imaging techniques such as optical coherence tomography [3] and frustrated internal reflection [4], [5], these processes remain elusive. Current methods have limited penetration depth and require smooth, optically clear surfaces. Here, we introduce a, depth-independent, micrometer-resolution imaging approach based on X-ray microtomography using synchrotron radiation. By scanning live skin biopsies pressed against a variety of textures, it reveals 3D contact and deformation with unprecedented detail, even on rough and opaque matter. These findings offer unique insights into the evolutionary origins of touch in primates, which involved interactions with natural materials such as wood and stone.

II. Materials and Methods

A. X-ray microtomography

Experiments were conducted at the ANATOMIX beamline of the SOLEIL synchrotron [6]. Its highly coherent beam enables in-line phase-contrast X-ray microtomography, revealing skin microstructures invisible to conventional absorption imaging. We captured cylindrical volumes about 2.6 mm in diameter and height (see Fig. 1.C), spanning subcutaneous through epidermal layers and contact regions with a 1.3 µm voxel size. Each scan lasted 3 min at 20 keV photon energy.

B. Textures samples

Five textures were tested, including engineered samples (convex dome, 0.5 mm-diameter pin, 1.0 mm hole) and natural materials (pumice stone, wood bark). They were mostly made of low-Z elements and trimmed into 6 mm-diameter disks.

[1]T. Daunizeau, M. Mayet, M. Rouillard are with the Institute of Intelligent Systems and Robotics, CNRS, Sorbonne University, 75005 Paris, FRANCE.
[2]Current affiliation: École Polytechnique Fédérale de Lausanne (EPFL), 2000 Neuchâtel, SWITZERLAND. e-mail: thomas.daunizeau@epfl.ch
[3]L. Stracovsky is with the Cognitive Robotics Department, Delft University of Technology (TU Delft), 2628 CD Delft, NETHERLANDS.
[4]B. Duvernoy is with the Department of Biomedical and Clinical Sciences, Linköping University, 58183 Linköping, SWEDEN.
[5]D. Doumont, B. P. Delhaye, and D. Gueorguiev are with the Institute of Neuroscience, UCLouvain, 1200 Brussels, BELGIUM.
[6]D. Doumont and B. P. Delhaye are with the Institute of Information and Communication Technologies, Electronics and Applied Mathematics, UCLouvain, 1348 Louvain-la-Neuve, BELGIUM.
[7]G. Daniel, J. Perrin, and T. Weitkamp are with Synchrotron SOLEIL, 91190 Saint-Aubin, FRANCE.

C. Skin samples

Ex vivo human abdominal skin samples were obtained from 36- and 50-year-old female donors (NativeSkin, Genoskin), incubated in culture medium at 37 °C to preserve the cells' biomechanical properties, and punched into 6 mm-diameter disks. Experiments took place within seven days of surgery.

D. In-situ loading apparatus

The compact loading cell shown in Fig. 1.A.B was custom-built to apply sequential, quasi-static normal compression of skin against the textures. Displacement was stepped from 0 mm (non-contact) to 1.50 mm in 0.25 mm increments, then reversed until detachment, yielding 185 scans (9 TB of data).

III. Results

Orthogonal mid-slices from a raw 3D X-ray scan of skin against wood are shown in Fig. 2.A. Close-ups in Fig. 2.B highlight the ability of phase-contrast to resolve minute features such as epidermal folds, dense collagen networks, well-contrasted adipocytes, hair follicles, and the cellulose fibers of the wood. Skin deformation under increasing compression is shown in Figs. 2.E-G for wood, stone, and the pin, respectively. Scans were processed to enhance contrast and tissues were digitally colorized for clarity. Remarkably,

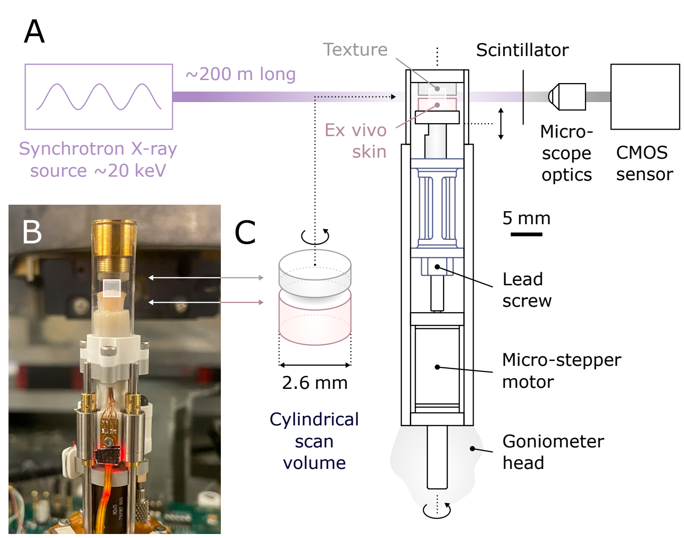

Fig. 1. A) Schematic of the in-situ loading cell compressing human skin samples against various textures. B) Prototype mounted at the ANATOMIX beamline of the SOLEIL synchrotron. C) Cylindrical scan volume.

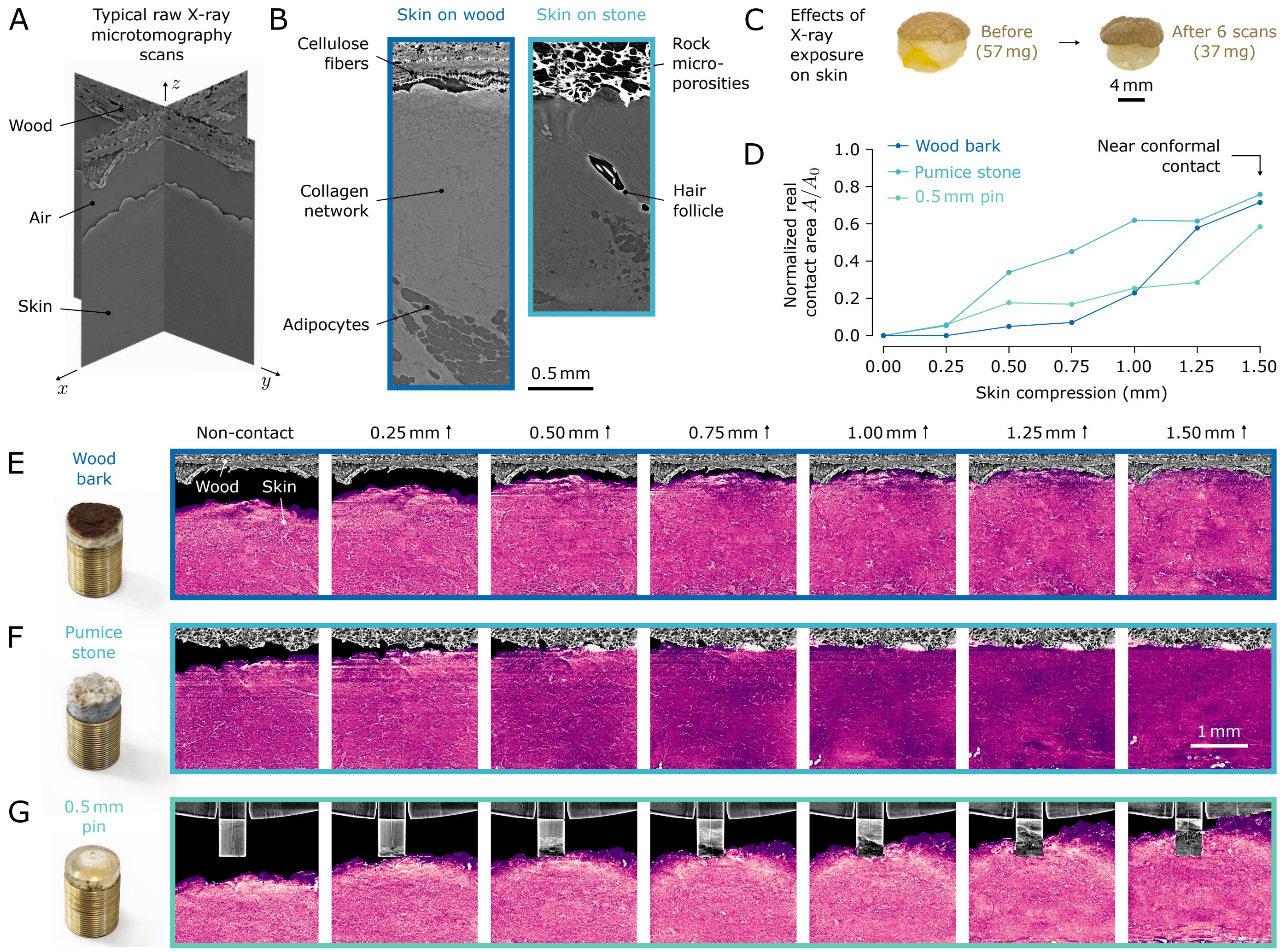

Fig. 2. A) Orthogonal mid-slices from a raw X-ray scan of skin against wood. B) Close-up views showing the high resolving power of phase-contrast X-ray microtomography. C) Examples of skin biopsies before and after an 18 min X-ray exposure. D) Normalized real contact area. E) On the left, wood bark used in the experiment, facing up for visualization. On the right, sequential X-ray scans of skin being compressed upward against wood bark, with skin digitally colored for clarity. F) Same sequence for the pumice stone. Skin samples were replaced between each loading cycle. G) Same sequence for the plastic pin.

the outermost skin layer, i.e. the stratum corneum, conforms to rough natural substrate down to individual skin cells, yielding a ratio A/A_0 of asperities in intimate contact (here defined as closer than 2 voxels) of up to 70%, as shown in Fig. 2.D. These preliminary findings indicate substantial skin plasticization. Sharp geometries like the pin can even cause epidermal punctures. Skin samples pre and post X-ray exposure are depicted in Fig. 2.C. The water loss (-35%) indicates a radiation-induced drying and stiffening of skin.

IV. Discussion

On flat surfaces, skin exhibits high adhesive friction modulated by interfacial moisture. Extending this to rough natural surfaces, we observed for the first time how skin flows within microscale asperities, even under light loading, providing numerous interlocking sites. This would have provided primates with a decisive evolutionary advantage for gripping and climbing. We also observed skin deformation and diffusion at the mechanoreceptor level (yet to be found through post-processing), which could shed new light on mechanotransduction and tactile coding. To that end, our preliminary 2D study will be extended to native 3D methods.

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