Supplementary methods

Optical coherence tomography

Optical palpation was performed using a Fourier-domain optical coherence tomography (OCT) system [1, 2] described in detail in [3] and briefly here. The system operates by illuminating a sample with a wide optical bandwidth, weakly focused beam of light, with a central wavelength of 845 nm. It is non-ionising and low power (~6 mW). The light backscattered from inside the compliant layer and sample is captured, and the time-delay information between the locations in the sample and the reference reflection, as provided by low-coherence interferometry, is used to reconstruct a depth profile of the compliant layer and sample microstructure. OCT is conceptually similar to ultrasound, however, achieves much higher resolution, which is traded off with lower penetration depth. The system possesses experimentally measured axial and lateral resolutions of 7.8 and 11 μm, respectively, with an imaging depth of up to 1-3 mm, depending on the optical scattering and absorption in the sample.

The OCT system operates using a common-path interferometer configuration, in which the window/compliant layer surface serves as the reference reflector in the OCT system, meaning that, axially, the interface of the window and the compliant layer will always be positioned in the first pixel of the reconstructed image, as seen in figure 1(b).

Using OCT, not only the amplitude (which makes up the structural OCT images presented in this paper), but also the phase of the back-scattered light at varying depths in the compliant layer, can be calculated. If OCT images of the compliant layer in an unloaded and loaded state are captured, then the difference in phase between each co-located pixel in the unloaded and loaded image can be linearly related to the local axial displacement. This method is termed phase-sensitive OCT [4], and is, in fact, fundamental to many OCT-based mechanical and flow measurement techniques [5]. This method can provide a three-dimensional field of local axial displacement in the compliant layer, in contrast to just the thickness observed from the OCT structure. It is sensitive on the sub-nanometre scale of displacement [3]; however, its use in optical palpation is heavily limited in practice, as it requires the displacement of local microstructure to be kept roughly below 1 μm between acquisitions, to avoid significant error introduced by phase wrapping or phase decorrelation [6]. This method is used to estimate friction in this paper (section 4).

Compliant layer fabrication

The compliant layer and the experimental validation samples were fabricated from room-temperature vulcanizing (RTV) silicone rubber (Elastosil® P7676, Wacker, Germany). For the validation samples and the compliant layers used for friction measurement, additional optical scattering was introduced by adding titanium dioxide particles to the rubber. The refractive index was estimated to be 1.4 for silicone rubber and 2.5 for the TiO_2 particles. The refractive index was used to scale the depth of OCT images; OCT intrinsically measures the product of the group refractive index and physical depth. Fabrication of silicone samples for OCT is described in detail [7]. Briefly, silicone rubber is composed of two parts: silicone compound (A) and cross-linker (B). Parts A and B can be mixed with different ratios to attain variable mechanical stiffness. For all experiments, A and B were mixed with a one-to-one ratio. Compliant layers were fabricated to a thickness of 0.5 mm, and width of 5 by 5 mm, which was confirmed by measurement using OCT.

Finite-element analysis

Computation in optical palpation was performed using the Abaqus/Explicit FEA solver (Dassault Systèmes, France). The possibility of high strains induced in the compliant layer made it preferable to use the explicit formulation, both in terms of speed of computation and robustness (lower likelihood of non-convergence). The explicit formulation is inherently dynamic, accounting for inertia. As the problem posed by optical palpation is quasi-static, the ratio of the kinetic energy to total energy was monitored for all simulations. Kinetic energy was validated to be two, or more, orders of magnitude smaller than total energy, ensuring that inertial behaviour did not significantly modify estimated tactile stresses [8].

The FEA model was constructed entirely in Matlab R2013a (The MathWorks Inc., Natick, MA), and parsed into the Abaqus solver using their proprietary '.inp' format. Simulation results were extracted using Python 2.7, and parsed into Matlab. Paraview (Kitware

Inc., NY) [9] was used for visualisation. A description and link to code can be found in the Data Accessibility section.

Assembly

The FEA assembly is described in section 3 and presented in figure 1(c). Briefly, three parts are employed: the window contact body (WCB); the compliant layer; and the sample contact body (SCB), representing the position of the sample-layer interface. In the initial step, the compliant layer is positioned between the WCB and the SCB, with both interfaces in contact and coplanar with each other. In the initial step, the SCB represents the unloaded thickness of the compliant layer, $L_0(x, y)$.

The size of the compliant layer is noted for each result. The WCB and SCB geometries were extrapolated by an extra 1 mm in x and y to ensure that, as the compliant layer expanded beyond its initial size, its axial compression would still be constrained at the boundaries.

Meshing

Structured meshing was employed for all parts due to their regular geometry. Meshing was performed in Matlab, by regularly subdividing a rectangular volume, and then warping the body to a desired shape. The compliant layer was meshed using hexahedral 'C3H8' elements, with 8 integration points [10]. These are preferred to tetrahedral elements due to their reduced rigidity; however, tetrahedral meshing is available as an alternative in the attached code, Data Accessibility section. The window and sample contact bodies were meshed similarly; however, using hexahedral 'C3H8R' elements with reduced integration. Meshing density is noted individually for each result.

Contact

Contact between the WCB and the layer surface was defined as a pure master-slave contact pair with kinematic enforcement. Due to the simple geometry of contact, a hard pressure-overclosure relationship was defined to simplify computation. Contact between the layer and the SCB was defined as a balanced master-slave contact pair with kinematic enforcement. Due to the large deformation and, potentially, large spatial variations of stress across that boundary, an exponential contact pressure-overclosure relationship was defined. Contact pressure was set equal to a hundred times the layer stiffness at zero clearance, and clearance was set to 0.1 mm. For both boundaries, a Coulomb friction model was employed. It is parameterised by a single coefficient of friction, the value of which is noted for each result. These methods for modelling contact are described in detail in [10].

Boundary conditions

As a rigid body, the WCB is prescribed to have zero displacement in all axes. The SCB is prescribed zero displacement in the x and y directions. The z displacement, however, is given as $L_1(x, y) - L_0(x, y)$, *i.e.*, the change in compliant layer thickness. The layer thickness was smoothed using a Gaussian kernel, with a full width at half maximum smaller than the mesh size. The z displacement was applied with a smoothed step amplitude to minimise kinetic energy.

Simulation of the optical palpation experiment

The accuracy of computational optical palpation in mapping spatially resolved tactile stress is described in section 6. For this purpose, an FEA model of a realistic optical palpation experiment is employed, as described in section 6 and presented in figure 3. The model comprises a rigid glass window, a deformable compliant layer and sample, and a rigid compression plate. The mechanical model used for the compliant layer and the sample is similar to the one described in section 3. A notable difference from the FEA model used for computational optical palpation is that computation is performed using an implicit formulation (as opposed to the explicit [10, 11]). The implicit solver uses an inherently different numerical method, and in our case particularly, we employ a truly static model, reducing the equation of equilibrium, section 3, to $\nabla \cdot \boldsymbol{\sigma} = \mathbf{0}$. In the FEA model of the experiment, the geometry and deformation is controlled and simple; therefore, a static implicit formulation was preferred for its speed; with an added benefit that, due to the vastly different numerical methods employed in the implicit vs. explicit case, similar errors would be unlikely to arise, propagate, and then be discounted when comparing the output tactile stresses.

The compliant layer and sample are meshed using 'C3D8H' hexahedral elements, which are preferred for modelling incompressible materials, such as the silicone rubber [10]. Boundary contact is defined similarly to the computational optical palpation method, with an added boundary between the sample and the compression plate. This contact formulation is identical to the contact between the compliant layer and the WCB. To model the optical palpation experiment, the window is prescribed zero displacement in all axes. The compression plate is prescribed zero displacement in the x and y directions, and a constant displacement in z. Sample and compliant layer boundaries are unconstrained

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