Measurement of skin strain patterns caused by fingertip shearing

Humans have the ability to dexterously manipulate objects of different shape, weight, texture and softness with their hands. While such capabilities appear straightforward and easy, it actually reveals our ability to precisely adjust the grip force (GF) applied perpendicular to the object’s surface by the fingers, to counteract the load force (LF), acting tangentially to the surface and due to the object’s weight and inertia. Although excessive GF is not energy efficient and can result in damaging the object or the fingers, a minimal GF is required to prevent the object from slipping. Friction dictates this minimal GF and can vary by an order of magnitude depending on multiple factors such as object surface geometry, finger moisture and contact duration. Humans can quickly and accurately adapt their GF to changes in friction, but only with tactile feedback from the fingers. Indeed, friction information is only available from the contact point between the fingers and the object, but how it is estimated remains a puzzle. One possibility is that we take advantage of localized slips taking place in some parts of the contact between the object and the finger while the other parts remain in a stable contact. Those “partial” slips that have been observed between the finger and a transparent glass are the mechanical consequence of an increase in the tangential force. If the GF is insufficient, those partial slips propagate in the contact area and finally lead to a full slip (Fig 1C). Such relative movements between stable and slipping regions necessarily lead to surface skin strains.

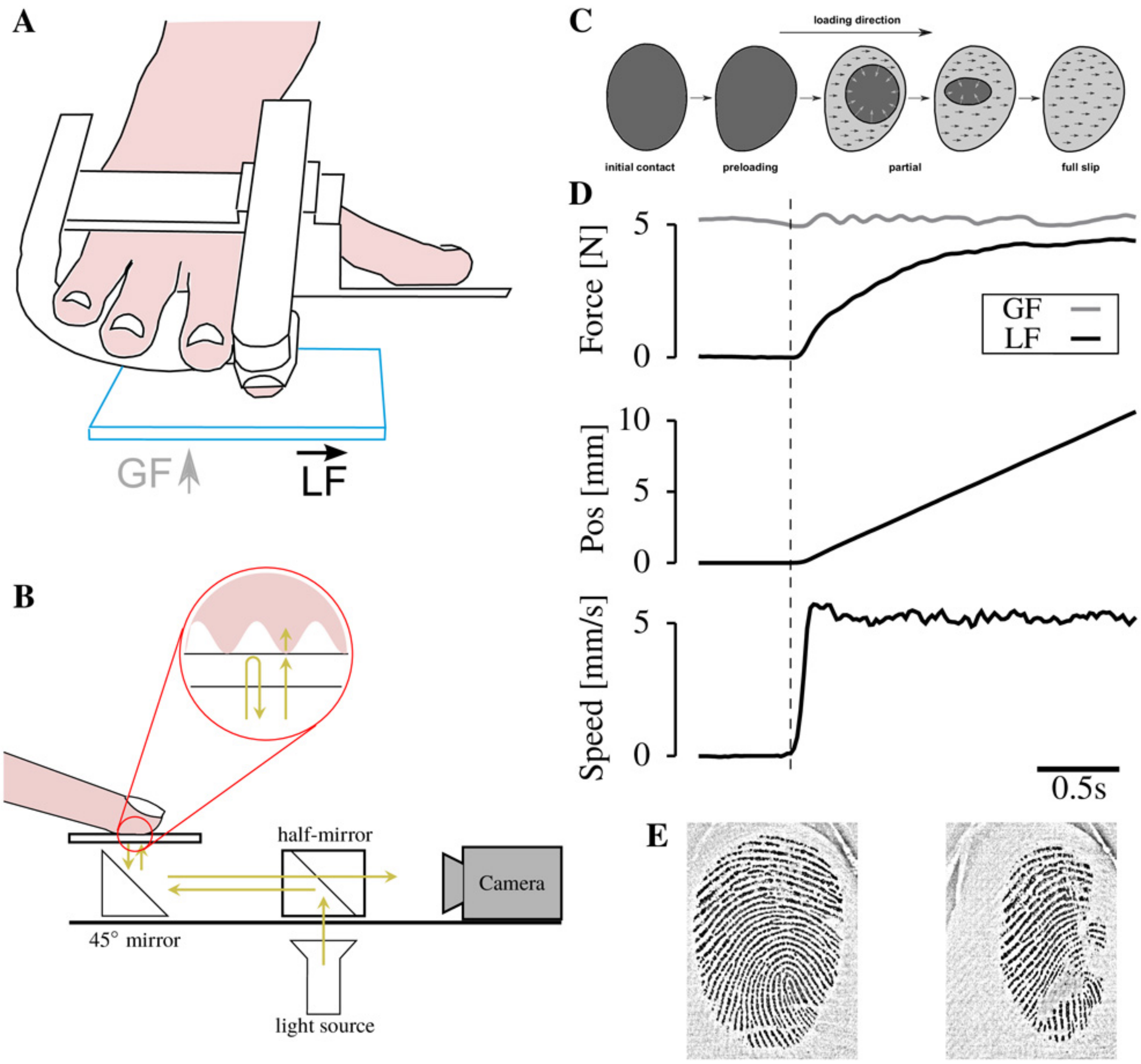

Fig. 1. Experimental setup and procedures. A) The subject’s hand rested in the hand support, with the right index finger fixed. The horizontal glass plate moved by means of a robot actuator. The plate loaded on the finger and moved sufficiently far such that the finger was completely sliding in one of four directions. B) Imaging system. High-contrast fingerprint images are obtained by a coaxial light source and camera. C) Course of evolution of the dynamics of finger contact from the initial contact to full slip. D) Forces, position and speed profiles during one example trial, traces are aligned to movement onset. E) Two typical images of the fingertip in contact with the glass surface. Left: fingerprint after initial contact; Right: fingerprint deformation observed during full slip.

In an attempt to understand if and how those surface skin strains might be detected by our tactile receptors, we developed a device to precisely measure them. A robotic apparatus was used to apply servo-controlled forces through a transparent smooth surface to the tip of the index finger of volunteers (Fig 1A). Using a high speed-resolution camera, we filmed the contact area during the transition from a stable to a slipping contact (Fig 1B&E) when applying normal forces and tangential speeds spanning ranges relevant to object manipulation (Fig 1D). Then, we used image-processing techniques to track fingerprint features displacement relative to the contacting surface and derive the strain tensor at numerous points in the contact area.

As could be predicted from contact mechanics, the partial slips first occurred at the periphery and then propagated towards the center of contact (as shown in Fig 1C). As a consequence, a strain wave propagated from the periphery to the center (Fig 2A-B). The quadrant of contact area being located where the load force was directed was compressed (Fig 2A, first line), while the opposite quadrant was stretched (Fig 2A, first line) and the two other quadrants experienced shear strain (Fig 2A, third line). The strain component aligned to the tangential force direction was the highest (Fig 2A, first line). The spatial distribution of both the strains (Fig 2B) and the strain energy densities depended on the stimulus direction. Additionally, the strains varied with the normal force level and were substantial, e.g. peak strains of 50% with a normal force of 5 N, i.e. at force levels well within the range of common dexterous manipulation tasks. Finally, we observed that the fingerprint shaped the deformations. Specifically, the fingerprint tended rotate in such a way that they would end up perpendicular to the stimulus direction.

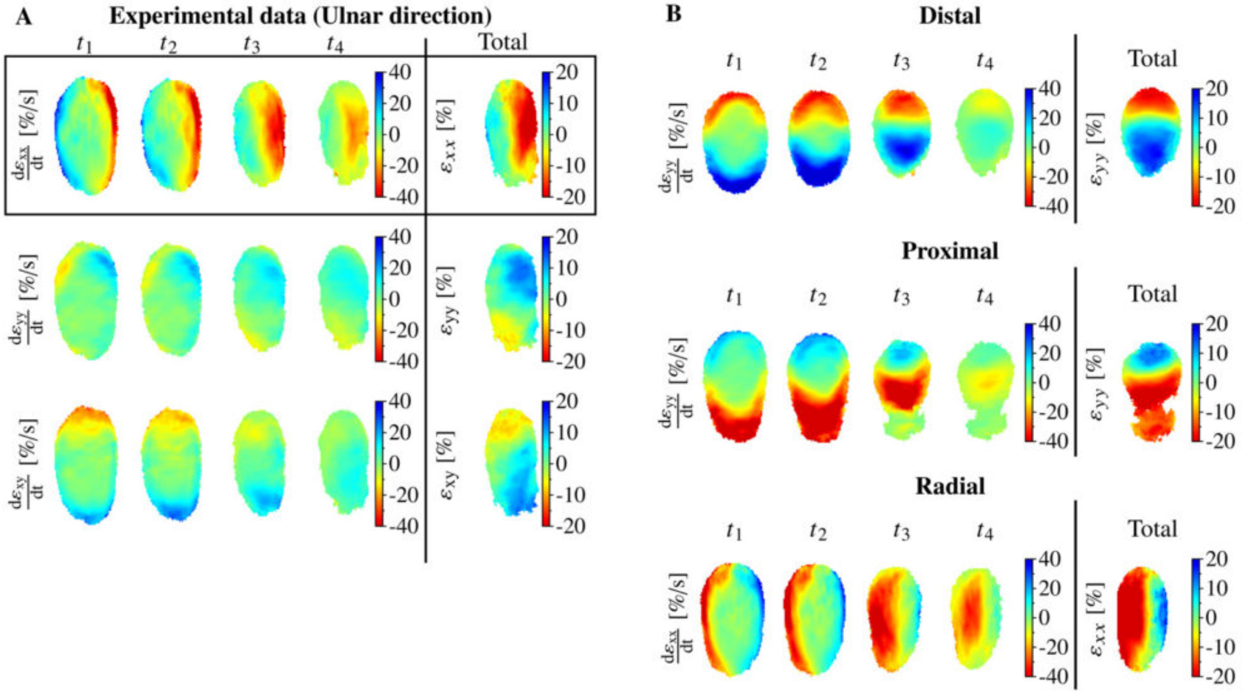

Fig. 2. Strain evolution during transition from stable to fully sliping contact. Population average strain fields are represented as heatmaps that show the evolution of strain fields in the contact area in the four directions: (a) each of the three rows represents a strain component. The component

aligned to the movement (e_{xx}) is emphasized by the black box. (b) Each row represents the relevant strains given the movement directions; right column shows the total strains. t_1 and t_2 correspond to different instants before full slip, t_3 corresponds to the instant of full slip and t_4 is after full slip.

We conclude that we captured events of direct relevance for the large majority of the low-threshold afferents in the human fingertip involved in encoding localized slip. Our results motivate further research on the neurophysiological encoding of mechanical events in the finger, and have important implications for the design of haptic interfaces and tactile displays.

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