White paper for DoD Physics of Biology:

The Role of Fingerprints in Vibrotactile Discrimination

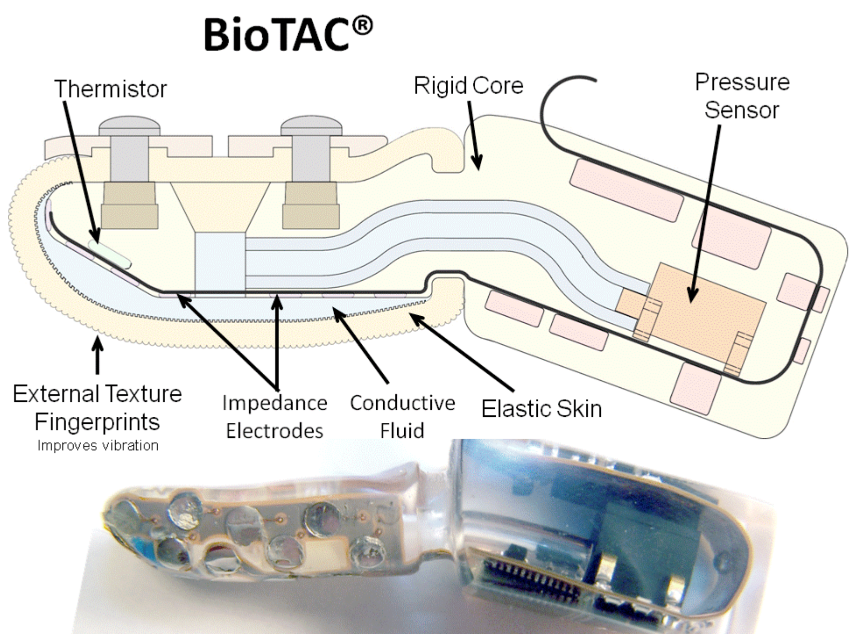
G.E. Loeb and J.A. Fishel

Department of Biomedical Engineering, University of Southern California, Los Angeles, CA USA
SynTouch LLC, Los Angeles, CA USA, www.SynTouchLLC.com
Contact: gloeb@usc.edu; mobile tel. 213-944-2283

Background

Despite our usual reliance on vision as our primary sense for identifying and interacting with objects, many important discriminations depend critically on tactile information. Sometimes the spatial resolution is beyond our visual capabilities, as in discriminating among fabric weaves. Sometimes the discrimination depends on mechanical properties such as stiffness and viscosity that require the application of a perturbing force. Sometimes the very act of grasping an object puts the critical interactions out of sight, as in detecting incipient slip under the fingertips. These tasks are difficult or impossible for robots equipped only with vision, but trivial for humans equipped with touch receptors. The most relevant tactile information comes from relatively high-frequency mechanical vibrations, essentially sound waves that are transmitted from the skin through the fluid-like soft tissues. These are transduced by extremely sensitive, specialized receptors such as Pacinian corpuscles that have low spatial resolution but high temporal bandwidth (~800Hz) (Mountcastle, 1972).

We have developed a finger-shaped sensor array (BioTAC®) that provides simultaneous information about the contact forces (Wettels, 2008), microvibrations (Fishel, 2008), and thermal fluxes (Wettels, 2009) induced by contact with external objects mimicking the full cutaneous sensory capabilities of the biological finger. The biomimetic array has an elastomeric skin inflated by fluid over a bone-like core, resulting in mechanical properties similar to a human fingertip. Contact force deforms the skin and underlying fluid, resulting in changes in the electrical impedance of an array of electrodes arranged on the surface of the core. Sliding the skin over a surface results in microvibrations that propagate as sound waves through the fluid to a MEMS AC-pressure transducer acting as a hydrophone. For tasks such as identifying objects or maintaining stable grasp, these sensory modalities tend to be synergistic (Johansson, 1987). For example, information about texture and slip can be derived from the vibrations, but only if the forces on the skin are known and well-controlled.



Motivating Results

When compared to a smooth skin, the addition of a fingerprint-like texture pattern to the external surface of the elastomeric skin (see photo to the right) resulted in a profound increase in the amplitude and complexity of the vibration spectra recorded while sliding the fingertip over various textures at a constant velocity and controlled force (see Figures and captions below).

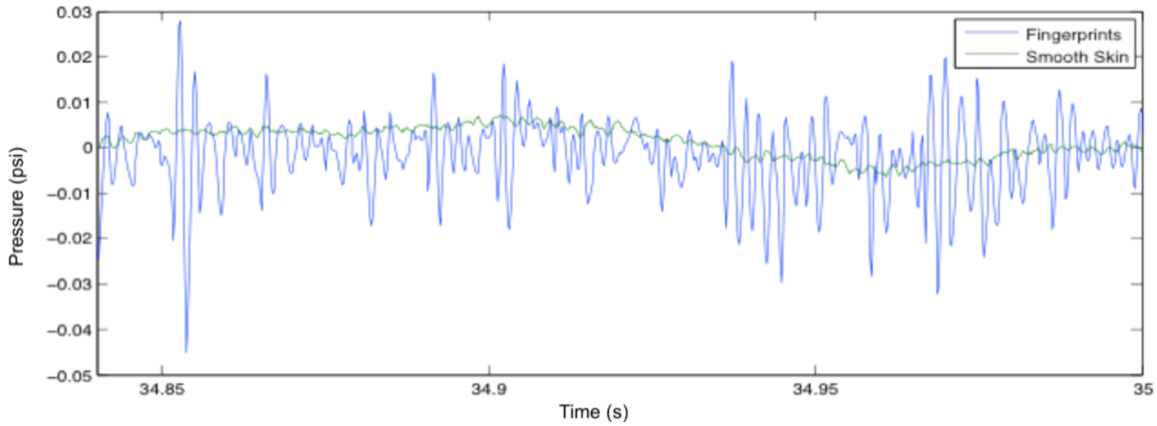


Figure: Acoustic spectra recorded from AC pressure signal contrasting smooth skin to skins with human-sized fingerprints when slid over a textured surface (sandpaper, 60 grit), at a light contact force (~0.5N) and moderate sliding speed (~1 cm/s). Results indicate substantial increase in signal amplitude and complexity with the addition of fingerprints.

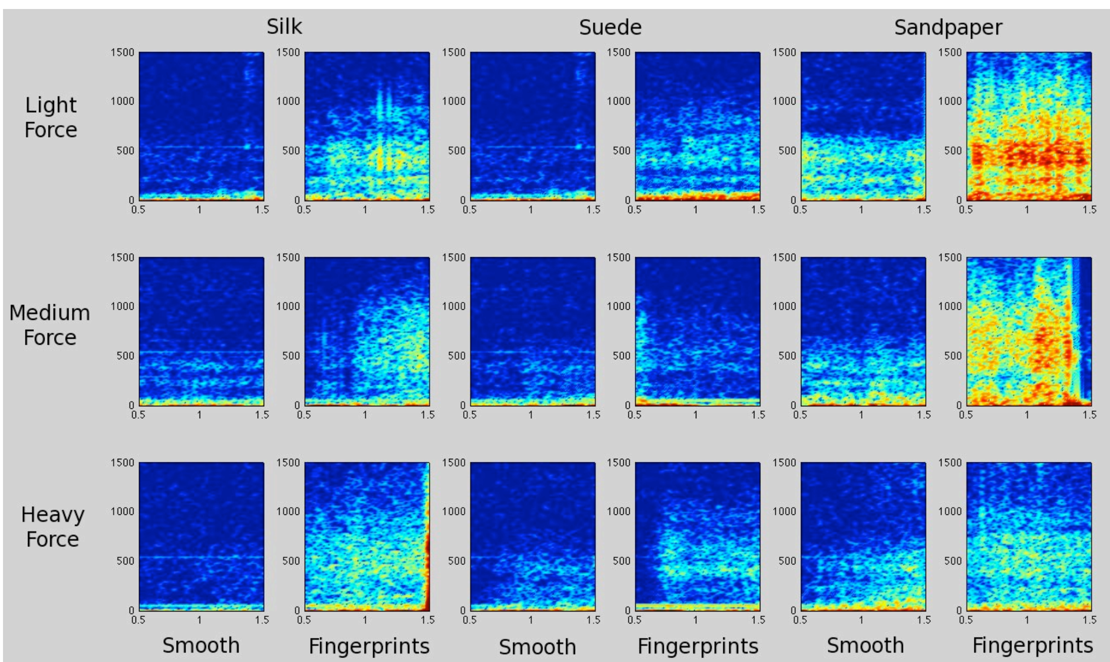


Figure: Log-Scaled Short-Time Fourier Transforms of frequency content recorded from AC pressure signal. X-axes: time (s), Y-axes: frequencies (Hz), power spectral density is indicated with color from blue to red on a logarithmic scale. Columns 1, 3 and 5 are spectrograms collected for smooth skins and columns 2, 4 and 6 are spectrograms collected from skins with human-sized fingerprints. Rows 1, 2 and 3 are used to encode light (~0.5N), medium (~5N) and heavy force (~20N) respectively. Columns 1 and 2 are experiments conducted with silk, 3 and 4: suede, and 5 and 6: sandpaper. In all cases trials with fingerprints produced amplified spectral responses.

Proposed Research

We hypothesize that fingerprints result in a coherent pattern of stick-slip behavior that amplifies their individual vibrations. Tangential force deforms the elastic skin ridges until they reach the limits of static friction, whereupon they release abruptly. Because the ridges are coupled together in the elastic substrate of the dermis, abrupt release of one ridge alters the stress on adjacent ridges, changing their probability of release in a spatially coherent way. We speculate that this gives rise to coherent summation of their released energy, similar to that seen in a phased-array radar. The timing and extent of these releases seems likely to depend on mechanical beating between the regular spacing of the fingerprint ridges and any repeating texture and friction of the surface being scanned. The effects of normal force, tangential force and scanning velocity are not intuitive and remain to be determined. Such effects would have to be controlled during a movement to explore a given surface.

Previous research into texture discrimination and the role of fingerprints has focused on rather coarse textures and slow scanning velocities well below biological scanning velocities, resulting in discrete sensory events as each new surface feature encounters the next ridge in the skin (Scheibert, 2009). While such signals are likely to arise and be used for such tasks, this mechanism would not account for the complex and distinctive spectra shown above for three different, finely textured materials. Fortunately, biomechanical models of human skin based on its complex histological structure and rheological properties are available (Maeno, 1998), however these do not take into account the complex properties of individual fingerprints in dynamic friction. We propose to model the elastic and dynamic properties of both human skin and the BioTAC elastomeric skin and to identify the dynamics of motion as these skins slide over surfaces with particular spatial patterns of mechanical features. We can systematically vary the fingerprint pattern, thickness and hardness of the elastomeric skins in both the computer models and the actual BioTAC to understand these effects and to validate the models. This will provide principles to optimize the design of sensors for specific tasks. Signal processing algorithms will be developed that maximize the discriminability of the texture-specific signals. These will be tested on a robotic haptics platform now under development at our laboratory at USC (NSF Major Research Instrumentation Development Grant) in which BioTAC sensors are being fitted on to the fingers of a Barrett hand+ arm system that is operated by compliant control algorithms that can emulate human performance.

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