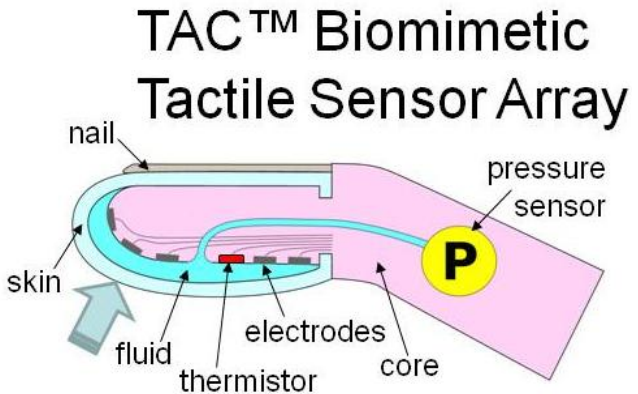


## Robust Biomimetic Tactile Sensing and Grip Control

Gerald E. Loeb, M.D., Professor of Biomedical Engineering, University of Southern California, Los Angeles, CA 90089, [gloeb@usc.edu](mailto:gloeb@usc.edu), in collaboration with Nicholas Wettels, Jeremy Fishel, Gary Lin, and Nora Nelson at USC and Roland Johansson, Umea University, Sweden

Rehabilitation therapists refer to the hand as “the third eye” because its function is highly dependent on the ability of touch to create a mind’s eye image of the objects that it encounters even without direct vision. That internal representation includes not just the object’s shape but those mechanical properties that are needed to develop useful strategies for its manipulation: mass, rotational inertia, texture, hardness, friction, etc. Much of the data to develop that image comes from the tactile sensors of the glabrous skin of the fingers. The actual signals result from the deformation of the skin and pulp of the finger tips as they interact with objects according to forces applied via the tendons of the muscles that actuate the fingers. The shape and viscoelastic properties of the fingertips are a critical determinant of the transduction process as well as the mechanical interactions that occur during manipulation.

We have developed a novel biomimetic technology for tactile sensing from anthropomorphic finger tips. The TAC™ array illustrated at right detects deformation of a viscoelastic skin and pulp over a rigid core in which all sensors, connections and circuitry are protected from the hostile environment in which hands are often used (Wettels et al., 2008). The core is covered by a silicone elastomer skin that is inflated with a weakly conductive fluid. Internal circuits measure the AC impedance of an array of electrodes mounted on the surfaces of the core. Deformations of the skin from contact with objects or sliding over the core as a result of tangential forces produces a distributed pattern of impedance changes similar to the distributed patterns of neural activity associated with biological skin receptors. Controlled texturing of the inner surface of the skin confers a wide dynamic range of force sensing and impedance changes (typically 0.1-30N, 10-1000kΩ). By adding a pressure sensor to the fill tube, we can sense the acoustic spectra of fluidic microvibrations associated with incipient slip and sliding over textured surfaces. A thermistor on the surface of the core provides temperature compensation and heat flow measurements to distinguish the thermal properties of contacted objects. The electrodes and signal processing, digitizing and multiplexing circuitry are mounted on a flex circuit that is molded into the rigid core. The only component subject to wear and damage is the inexpensive, molded skin, which can be easily replaced and reinflated with fluid.



We have incorporated a primitive version of an impedance sensing TAC with 6 electrodes onto the thumb of the Proto1 hand made by Otto Bock HealthCare (Vienna, Austria) for the DARPA Revolutionizing Prosthetics 2009 program. Normal and tangential forces were extracted by a Kalman filter and used to drive a simple algorithm for adjusting grip force in a manner similar to that employed by humans (Johansson and Flanagan, 2007). The hand was able to grip a fragile Styrofoam coffee cup and to adjust grip force incrementally as water was poured rapidly into it, thereby avoiding crush or slip failures.

The multimodal sensing provided by the TAC produces synergistic benefits. For example, the thermal and vibration signals obtained during exploration of an object depend on the location, magnitude and direction of the applied force from the fingertip, which can be determined from the impedance sensors. Some exploratory movements (such as texture discrimination) actually seem to be driven by their ability to excite selectively a particular class of afferents. Rather than imitating the exact procedures and classifications described for humans, it may be more productive to imitate the *process* whereby any intelligent organism comes to know and categorize its environment through its senses. We hypothesize that machines with a sufficiently rich set of receptors and coordinated movements can use artificial intelligence methods to develop their own exploratory procedures and object classification schemes.

Robots were originally conceived as machines that would work side-by-side with humans in our environments, rather than the glorified NC-milling machines now used on industrial assembly lines or the engaging but clumsy anthropomorphic robots demonstrated at trade-shows. Despite these obvious limitations, however, manufacturing companies have made and profited from huge investments in industrial robots, starting with the Unimate of the 1950s and progressing to the almost completely automated assembly lines for automobile chassis (Kamm, 2005). Yet industrial robots are almost completely absent from the rest of the labor intensive steps of manufacturing automobiles such as installation of wiring harnesses, upholstery, carpets, etc. Industrial robots are almost invariably segregated from human workers lest they unwittingly cause injuries. They generally cannot identify or handle common human tools. They function best in highly structured environments. The opportunities for robots in military and police missions are obvious but their inability to deal with even the simplest common objects such as doors and latches is legendary. While lots of tactile sensing technologies have been developed, none has provided the combination of robustness, dynamic range and multimodality that is required to support humanlike dexterity in realistic environments. We believe that the TAC technology meets those requirements but will now require substantial development of biomimetic artificial intelligence to make use of the distributed set of nonlinear sensors that it provides.

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## ACKNOWLEDGEMENT

Initial development of TAC technology was supported by a grant from the National Academy Keck Futures Initiative. Authors Loeb, Wettels, Fishel and Lin are principals in SynTouch LLC, a start-up company developing TAC technology with SBIR grant support from the US NIH and Department of Agriculture. Various aspects of this technology are covered by pending patent applications.