PROVIDING HIGH-RESOLUTION TACTILE AND PROPRIOCEPTIVE SOMATOSENSORY FEEDBACK IN HUMANS AFTER LONG-TERM AMPUTATION OF THE HAND

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ABSTRACT

The long-term goal of these studies is to provide rich, biofidelic tactile and proprioceptive feedback from an advanced prosthetic hand after prior amputation in humans. Six human subjects (S1-S6) received one or two 100-electrode Utah Slanted Electrode Arrays (USEAs; Blackrock Microsystems) implanted chronically (1-9 months) in residual median and/or ulnar nerves for stimulating sensory fibers (and recording from motor fibers) after long-term (2- to 25-y) transradial amputations. Sensory percepts were mapped by passing increasing current through individual USEA electrodes (biphasic, 200-μs pulses; 100-200 Hz, 200-500 ms trains) until the subject reported a percept (location, type, and intensity), or until stimulation maximum (< 100 μA). Experiments were conducted either in a MuJoCo (Roboti, LLC) virtual reality environment (VRE); or with a simple sensorized, motorized physical prosthetic hand (Open Bionics); or with a more advanced, motorized and sensorized prosthetic hand (DEKA) having 6 DOFs and 19 receptive fields. Subjects reported up to 131 different USEA-evoked cutaneous (e.g., pressure, vibration) or proprioceptive percepts (e.g., joint movement, muscle force). Typically, the evoked percepts covered most of the phantom hand, corresponded to normal afferent fiber distributions, and were enjoyed by subjects. Most percepts showed within-session stability, and in S6 more than half maintained location stability when retested at > 1 month. Subjects successfully discriminated among percepts having different phantom spatial locations or qualities, evoked by individual electrodes or combinations of electrodes. Recent subjects also used sensory feedback evoked by biofidelic afferent fiber stimulation to guide motor control in the VRE. Reciprocally, active engagement with the VRE influenced subjects' perceptions. S6 could discriminate between "soft" foam blocks and "hard" plastic blocks in a sensorimotor task using the DEKA hand (15 successes in 18 trials). S6 also showed objective evidence of embodiment of the simple sensorized, motorized prosthetic hand (as measured by proprioceptive shift from the amputated hand to the prosthetic hand and by responses to survey questions). Stimulation of sensory fibers also resulted in a 23.2% reduction in subjective phantom pain scores for S6 (from 3.75 ± .14 to 2.88 ± .18, $p < 0.005$). Such effects may enhance adoption of advanced hand prostheses by end-users. These results document an unprecedented level of high-resolution tactile and proprioceptive somatosensory percepts in humans with prior hand amputation. The emerging ability to provide a relatively complex repertoire of somatosensory inputs may enhance sensorimotor control, a sense of embodiment, and phantom pain reduction for users of advanced neuroprosthetic limbs.