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The Helix: A multi-modal tactile stimulator for human functional neuroimaging

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Abstract

In order to expand the repertoire of somatosensory functions that can be effectively studied through functional MRI, we have developed a tactile stimulator which can deliver rich and varied combinations of stimulation that simulate natural tactile exploration. The system is computer controlled and compatible with an MRI environment. Complex aspects of somesthesis can thus be studied independent of confounds introduced by motor activity or problems with precision, accuracy or reproducibility of stimulus delivery.
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1. Introduction

Rigorous neuroimaging investigations of touch have often been hampered by lack of control and reproducibility of stimulation. For example, manually delivered stimuli (Polonara et al., 1999; Sadato et al., 2004) do not afford precision in force, velocity, or other stimulus parameters that may affect brain activation patterns. Moreover, hand movement by the subject is often not prevented or controlled (Bodegard et al., 2001) which may confound somatosensory processing with activations related to motor planning and movement. These uncontrolled motor activities also result in uncontrolled somatic stimulation. Automated tactile delivery systems help in circumventing these problems but typically deliver simple stimuli such as air puffs (Nguyen et al., 2005), vibration (Briggs et al., 2004), or unnatural electric stimulation (Boakye et al., 2000; Nihashi et al., 2005). These stimuli are not well suited to provide insight into more complex perceptual aspects of touch (e.g. form recognition).

In order to expand the repertoire of somatosensory functions that can be studied through functional MRI, we have developed an MRI-compatible tactile stimulator, the Helix. The Helix is a computer-controlled system that provides controlled delivery of vibrations, spatial patterns, and textures to the fingers of a subject in a scanner. Precise, quantitative, and reproducible stimulus parameters including force, vibration frequency/amplitude, and position/velocity of the drum under the fingertip facilitate the comparison of neural events evoked by stimuli. Tactile stimulation can be delivered in a multi-modal fashion, and this enables the study of a specific stimulus feature of interest through selective attention task paradigms. Sensory stimulation is passive and yet can simulate exploratory scanning of active touch by adjusting stimulus force and velocity. Furthermore, longitudinal studies, such as those of tactile learning or sensory rehabilitation, are facilitated by the inter-session reproducibility of stimulation afforded by the system.

2. Materials and methods

2.1. Helix: overview of system

The Helix system, referring to the helical array of spatial patterns wrapping the surface on the drum, delivers

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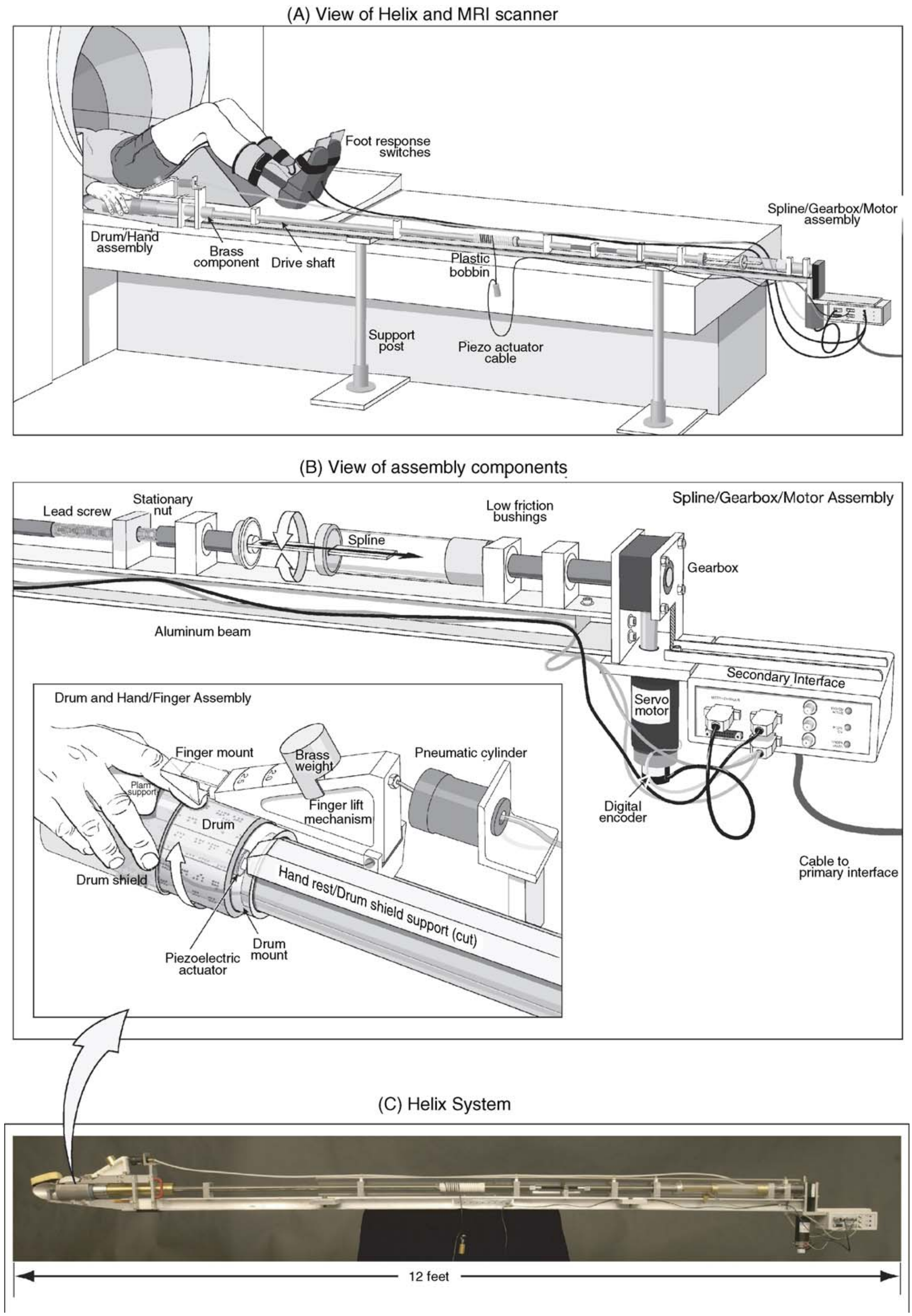

Fig. 1. Helix system. (A) Overview of Helix in relationship to subject position and MRI Scanner. (B) View of assembly components for finger positioning and movement of drum. (C) Photo (reduced scale) of Helix system.

complex sensory stimulation to a subject's fingertip in a passive and controlled fashion (Fig. 1). The system can raise or lower the fingertip into contact with a drum, embossed with a sequence of spatial patterns or textures. The drum can both vibrate axially and move helically (hence the name) under the fingertip, providing long sequences of tactile stimulation, despite the restricted space available.

The Helix system is comprised of mechanical, electrical, computer hardware, software and safety systems. The mechanical system includes the drum assembly, hand/finger positioning assembly, drive shaft, gearbox and motor. The electrical system is comprised of a primary interface unit, servo and piezo amplifiers, a secondary interface unit and actuators. The computer has three peripheral component interconnect (PCI) cards which interface with the Helix. The LabVIEW™ (National Instruments Corp., Austin TX) software development environment facilitates precise computer control of the Helix. The design of the Helix allows safe and effective operation in the magnetic environment, without corrupting MRI images or posing safety hazards to subjects.

2.1.1. Mechanical system

The mechanical system is supported by an aluminum beam and consists of an interchangeable drum with embossed stimuli affixed to its surface, a piezoelectric device embedded within the drum, a hand/finger positioning assembly and a drive assembly which turns the drum in a helical fashion through a motor assembly and spline (Fig. 1). The Helix is attached to the MRI scanner bed by two posts that are adjustable in height and axial position.

The *Drum Assembly* consists of a drum with embossed patterns on its surface, a piezoelectric actuator embedded within the drum, and a drum mount (Fig. 1B, inset). The drum mount is attached to the drive shaft so that the long axis of the drum is aligned with the drive axis. The embossed patterns are molded into flexible acrylic sheets via flexography in a diagonal arrangement. These sheets are carefully wrapped and bonded to the outer surface of the stimulus drum, producing the desired helical sequence of tactile patterns on the drum's surface.

The piezoelectric actuator [PiezoMech Inc., Model # Pst150/7/40 VS12 VsB] output drives the axial vibratory movement of the drum. The actuator is coupled via a spring assembly to the drum mount and produces a vibration of 0–230 Hz with an amplitude range of 0–40 μm. This firm contact of the actuator to the drum assembly, eliminates harmonic resonances and transmits the vibratory stimulus to the drum's surface.

The *hand/finger positioning assembly* (Fig. 1B, inset) supports and isolates the hand from piezo vibration, and controls the position and force of contact between the finger and drum. The distance between the palm support and the stimulus drum is adjustable to accommodate a range of hand sizes. The entire assembly is mounted with a breakaway slide mechanism that allows rapid hand withdrawal and subject egression in emergencies. The finger is held via double-sided foam tape to a removable finger mount. This quick-release mount attaches to the finger-lift mechanism, which uses a pneumatic cylinder to lift the finger and a weight to bring the finger down onto the drum and provide a constant contact force. The nonmagnetic brass weight can be moved to provide a range of contact forces (0.8–2.5 N). For safety, the valve controlling the pneumatic cylinder is arranged so that the finger position defaults to the up position (e.g. absence of electrical power or computer operation stops) and is out of contact with the drum except when an experiment is running correctly.

The *drive assembly,* composed of a motor section which turns in a pure rotary fashion, is coupled to the drum section via a spline/lead screw assembly (Fig. 1B). The interaction of the spline's translational movement and the lead screw rotating in its stationary nut produces the desired helical motion of the lower shaft and drum. The high torque gearbox and the ceramic coated aluminum drive shaft supported by low friction Frelon™ bushings enables the system to override the effects of the magnetic field, resulting in smooth motion and accurate positioning at low speeds. A groove within the drive shaft supports the wires for the piezoelectric actuator. The wires for the actuator enter the moving shaft by winding onto a spiral groove in a plastic bobbin that fits around the drive shaft. The wires then run in a groove in the drive shaft, and then in the center of the final, hollow section terminating at the actuator in the center of the stimulus drum. The large mass of the brass component of the drive shaft attenuates transmission of drum vibration to the rest of the system, thus preventing inadvertent vibrations from reaching the rest of the hand. The brass component is slit along its length, which reduces the eddy-current drag effect from rotation in a high magnetic field, thus lowering the torque required during rapid positioning motions.

Motor and gearbox assembly. The helical motion of the drum is driven by a servo motor (Cleveland motion controls) and gear system (Fig. 1B). The motor, chosen for low radio frequency interference, drives the main shaft through a right-angle gear reduction unit. This gearbox increases the torque to override the eddy-current effects of the magnet and facilitates smooth motions at low speeds (0–25 rpm). A digital encoder is coupled to the gearbox to allow precise measurement of the position of the drum.

2.1.2. Electrical system

The Helix's electrical system interconnects a computer, primary and secondary interfaces with controls for the servo motor, pneumatic and piezo systems as well as a safety system (Fig. 2). The computer (Dell™ OptiPlex™ GX400) accommodates three internal PCI cards. The motion-control card controls the servo motor. The function-generator card produces the sinusoidal signal at the desired amplitude and frequency for the piezoelectric actuator. The multi-function card provides general-purpose input–output signals, which interface with the safety system, home-position sensor, pneumatic valve, foot switches, and audio tones.

The *primary interface box* is the main connection point for most of the safety, sensor and control signals for the Helix. The primary interface also provides electronic signal conditioning for Helix's sensors and actuators. This signal conditioning minimizes the audible noise produced when activating the piezoelectric actuator.

The servo amplifier controls the motor voltage and provides feedback to ensure that the voltage is proportional to the command signal. The piezoelectric actuator is driven by a second amplifier [Piezomech LE-150/100] designed to drive capacitive loads. Both amplifiers' outputs are monitored by the Helix computer.

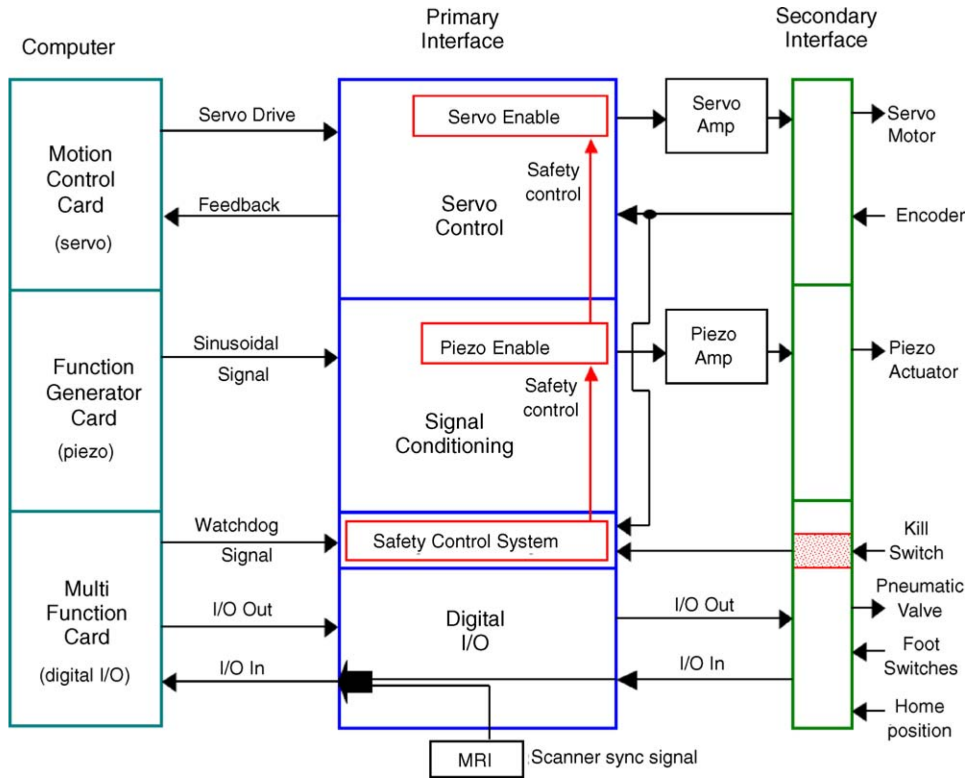

Fig. 2. Block diagram of electronic components. Computer and primary interface are located in scanner console room. Secondary interface is attached to motor assembly end of Helix (see Fig. 1B). Safety components highlighted in red.

The *secondary interface box* is attached to the motor end of the Helix (Fig. 1B). It contains a pneumatic valve that controls the up/down motion of the finger assembly, one of the emergency-stop switches, and all of the electrical and pneumatic connections between the Helix mechanism and the rest of the system.

All external connections are of a breakaway type, so that the patient bed can be quickly removed from the MRI room, should the need arise. Connectors on the secondary interface box go to the servo motor, piezoelectric actuator, the home sensor, and the foot-actuated switches. Continuity lights provide visual indicators for ensuring that the cables are connected.

2.1.3. Software

We developed the Helix software to achieve: (1) flexibility in task specifications and selection, (2) accurate recording of stimulus position, (3) precise control of stimulus delivery, (4) reliable recording and display of subject response, (5) on-line monitoring of system operations and integrity. The software, written with National Instruments' LabVIEW^{TM}, emphasizes flexibility and ease of use through displayed user instructions while maintaining control and accuracy of experimental parameters. These characteristics are accomplished by a graphical user interface (GUI).

Flexibility in task specifications and selection. The task specifications include the selection of a subset of stimuli for each experimental block by setting the drum position and by the control of: (a) velocity of stimulus presentation, (b) frequency and amplitude of stimulus vibration, and (c) auditory cues for subject responses. Experiments are run as an ON–OFF paradigm; during the ON period the finger is in contact with the drum. During the OFF (rest) period the finger is mechanically lifted away from the drum surface and the drum is positioned to the beginning of the next stimulus set.

Accurate recording of stimulus position. Stimuli consist of embossed patterns on the surface of a drum which vary in their dimensions and position (Fig. 1B, inset). These stimulus features are measured with the help of a laser aided calibration system that records the start and end positions of each pattern to the drum description file. A drum file is subsequently selected from a menu prior to beginning a run.

Precise control of stimulus delivery. Precise positioning of the drum in relationship to the finger is critical to the operation of the Helix. After attaching the subject's inked finger to the removable finger mount, the drum is moved to its calibration position and the finger is lowered and then raised from the drum. An inked impression of the finger remains and the laser based calibration system records the edges of this fingerprint. This enables accurate location of each edge of the finger with respect to the edges of the stimuli on the drum.

A vibrational component can be delivered at specified drum positions during drum rotation. The vibration is turned on and off based on predefined task parameters and on signals from the digital encoder attached to the drive motor. This feedback loop enables the combination of drum stimulus position and vibration to be precisely delivered at the fingertip.

Selection of task. The program guides the operator through the graphical interface by highlighting available features and displaying instructions in the text information window. The file of task parameters is selected from a pull-down list. Synchronization pulses arriving from the MRI scanner are monitored and can be used to initiate the drum sequence. Positioning information from the encoder triggers the presentation of the vibrational component of the stimulus. Although the onset and offset of this component is predefined, the operator can further adjust the delivery through the GUI.

Recording and display of subject response. Subject responses are transmitted electronically, displayed on the GUI and are recorded for post-processing along with reaction times. We employ a foot response device to circumvent the confound of bilateral cortical activation which may be elicited by hand responses.

Monitoring of system operations and integrity. The execution parameters (such as the run, block and time remaining), the subject responses and the performance of the drum are displayed and updated continuously. The position of the finger, the state of the piezo mechanism and verification of drum movement are also monitored. The "following error" indicates the extent of the position error of the drum, which occurs if the rotation of the drum is lagging due to friction or binding. Display fields allow the operator to monitor task progress, subject responses, finger position and vibrational state.

2.1.4. MRI safety and compatibility

A device operating in an MRI environment is required to be free of ferromagnetic elements that impose risk to patients and researchers and of components creating radio frequency interference potentially degrading the MRI image. The Helix is composed of nonferrous metals and plastics except for the drive motor, which is securely bolted to the far end of the bed. This distant positioning reduces interaction between motor operation and the magnet in accordance with the inverse square law. Insulation of electrical components is also an important factor in device design. The Helix has all control and signal cables contained within the aluminum frame and the drive shaft, eliminating possible contact with the subject.

The device also must not preclude the safe exit of the subject in an emergency. The Helix has a breakaway slide mechanism (Fig. 1C, red handle) that facilitates the unimpeded and quick exit from the scanner if necessary. Furthermore, a fail-safe design ensures that subjects can exit the scanner safely if the Helix system loses power. All of the electronic and computer signals that drive the actuators (servo, piezoelectric, and pneumatic valve) run through a safety relay in such a way that the Helix will stop all drum motions and vibrations and will lift the subject's finger clear of the drum unless all of the safety conditions are satisfied. Safety conditions monitored include correct operation of the Helix software, continuity in all critical cable connections, emergency-stop buttons status, and active enabling of Helix's hardware and software by the operator. The primary interface box connects the servo motor and the home sensor to the servo amplifier and to the motion-control card in the computer. It also provides a connection for the software to monitor the amplifier's output and the home sensor. If the safety system determines from the digital encoder attached to the drum that the servo motor is not moving when it should be, this will disable the system.

Absence of radiofrequency interference to the MRI image by either the drum movement or piezoelectric was verified using a phantom and recording background noise with the piezoelectric actuator engaged and the drum rotating.

2.2. fMRI tactile paradigms

Fig. 3 illustrates fMRI data acquired during a subject performing a one-back tactile form discrimination task. Informed consent was obtained according to a protocol approved by the institutional review board of the National Institute of Mental Health/NIH.

A block design with 10 alternating "task" and "rest" periods per run was employed. Seven runs in total were obtained. During the "task" period, the subject's finger was lowered in contact with the surface of the drum. The subject engaged in a one-back task discriminating a series of embossed braille-like patterns. Five patterns were presented over each 16 s "task" period. Four trials occurred during each "task" period. For each trial, the subject judged whether the stimulus pattern was the same or different from the immediately preceding pattern by plantar flexion of the right foot or left foot, respectively. At each "rest" interval, the finger was lifted off the drum by the pneumatic device. The drum was then positioned for the next "task" period, and the finger was lowered in contact with drum surface with a specified force delivered by a brass weight at the start of the next "task" period (Fig. 1B, inset).

The Helix also allows the selective study of a rich variety of tactile stimulus attributes including vibratory amplitude and frequency, surface form or roughness, or velocity of movement. Subjects can selectively attend to a stimulus feature of interest under conditions of identical, yet multimodal, stimulation. Selective attention tasks have been very useful in elucidating the neural basis of other perceptual functions including tactile form and location (Van Boven et al., 2005).

2.3. Image acquisition

fMRI data were acquired with a 3.0 Tesla GE Signa whole-body MRI system (GE Medical Systems, Inc., Milwaukee, WI) equipped with a head volume coil. T1-weighted spoiled GRASS anatomical brain volumes (1.2 mm thickness) and standard BOLD fMRI $T2^*$-weighted echo-planar (EPI) volumes were obtained. Rather than whole brain EPI data, the EPI volumes were restricted and extended anteriorly ($y = 14$) and posteriorly ($y = -64$) to facilitate higher spatial resolution of activity at brain regions known to be critical to somatosensory process-

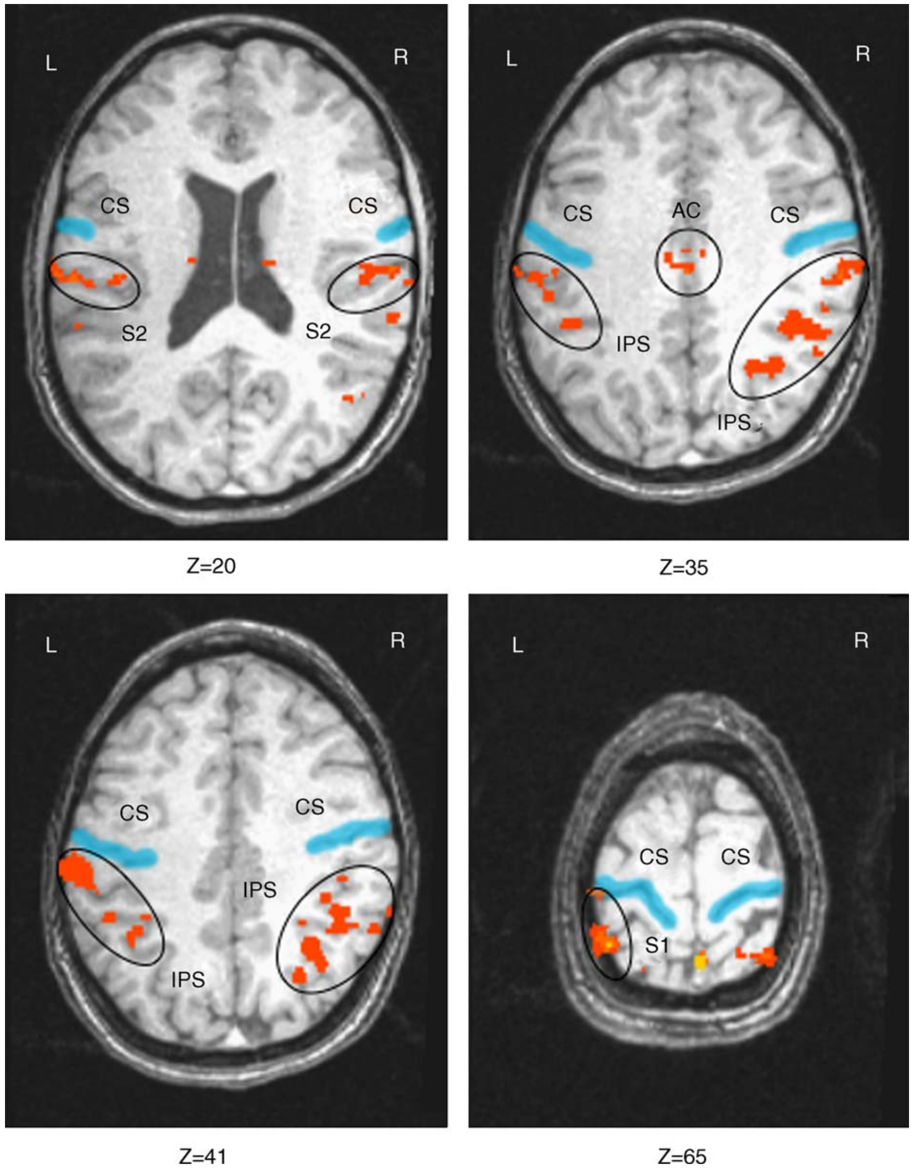

Fig. 3. Cortical activations during a one-back tactile form discrimination task with Helix stimulation at the right index finger (task vs. rest using a block design fMRI at 3 T ($p < 10^{-15}$)). Activations include the contralateral primary somatosensory cortex (S1), bilateral secondary somatosensory cortices (S2), anterior cingulate (AC), and bilateral intraparietal sulci (IPS). These activations evoked during the performance of tactile form recognition corroborates with previously published data (Van Boven et al., 2005). The thick, light blue lines show the location of the central sulcus (CS).

ing (e.g., S1, S2 and IPS, see (Van Boven et al., 2005)). For the EPI volumes, the flip angle was 90°, echo time (TE) was 30 ms, repetition time (TR) was 3.0 s, in-plane resolution was 1.9 mm × 1.9 mm, and 25 2.0-mm coronal slices were obtained. Blood oxygen level dependent (BOLD) fMRI data for the subject were collected in seven scan runs, each run lasting 6 min. Each run contained 120 volumes with the first two volumes (collected before equilibrium magnetization was reached) discarded, producing 840 brain volumes.

Data were analyzed using AFNI (Cox, 1996; Cox and Hyde, 1997). All EPI volumes were registered to the volume collected closest in time to the T1 volume (Cox and Jesmanowicz, 1999) and spatially smoothed with a 2-mm Gaussian filter. The task-related responses were analyzed using multiple linear regression (Friston et al., 1995). A single regressor representing the task was convolved with a canonical hemodynamic response function (Cohen, 1997).

3. Discussion

The Helix features enable controlled, reproducible and automated delivery of a variety of tactile stimuli that can be safely and compatibly delivered in the MRI environment. We anticipate that the system will facilitate new insights into the cortical mechanisms of more complex aspects of somesthesia.

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