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Development of a Polymer-Based MEG-Compatible Vibrotactile Stimulator for Studying Neuromagnetic Somatosensory Responses

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ABSTRACT Vibrotactile technology has been gaining increasing interest for effective human-computer communication in various applications. In addition to psychophysical approaches commonly used to study tactile vibrations, neurocognitive responses to vibrotactile stimuli can provide new insights into mechanisms underlying human vibrotactile perception. In this study, we developed a magnetoencephalography (MEG)-compatible vibrotactile stimulation device based on a polyvinyl chloride (PVC) gel actuator to study neuromagnetic somatosensory responses. A symmetric, double-layered PVC gel structure was applied to minimize the magnetic noise from the actuator. The device was used to generate sinusoidal stimuli at high frequencies to activate mechanoreceptors responsible for high-frequency vibrations greater than 50 Hz, and this device showed very little variability in stimulation onset time from the displacement measurements. We successfully observed vibrotactile-evoked magnetic fields by analyzing whole-head MEG data recorded during the high-frequency vibrotactile stimulation of the fingertips. Prominent peak responses were observed at approximately 56 ms (M50) in the contralateral hemisphere and at approximately 100 ms (M100) in both hemispheres. We identified the activation of contralateral primary somatosensory areas as a source of the vibrotactile M50 response. These results demonstrate the feasibility of using our new device to study vibrotactile perception with neuromagnetic imaging methods.

INDEX TERMS Mechanoreceptors, vibrotactile perception, PVC gel actuator, magnetoencephalography.

I. INTRODUCTION

The widespread use of touchscreen technology in the mobile industry was accelerated by the development of smartphones and tablet computers, replacing traditionally used mechanical keypads with capacitive touch sensors for an interactive display environment. Despite the benefits of touch input, such as the flexibility to use full screens of devices for visual display and intuitive user interfaces for simple operations, the flat physical surface of touchscreens lacks tactile feedback, thereby increasing the user's attentional demands to control touchscreen interaction [1]. Adding tactile feedback to touchscreen mobile devices has shown great potential for improving the user performance of touchscreen interactions; therefore, tactile interface systems have gained attention as effective channels for communication between users and interaction devices [1]–[3]. To make tactile interfaces lightweight, energy efficient, and easy to use, tactile feedback

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is frequently created using vibration actuators embedded in mobile devices [4]–[7]. The psychophysical and neurophysiological analyses of tactile vibrations have provided the fundamental framework for understanding human vibrotactile perception and the guidelines to design optimized vibrotactile devices for potential applications [8]–[12].

Cutaneous receptors in the skin, such as cutaneous mechanoreceptors, thermoreceptors and nociceptors, can receive sensory inputs including touch, temperature, and pain, respectively [13], [14]. Among different cutaneous mechanoreceptors, Pacinian corpuscles are most sensitive to high-frequency vibrations (50–400 Hz), whereas Meissner's corpuscles are sensitive to light touch and low-frequency vibrations (5–50 Hz) [15], [16]. Recent evidence shows that inputs from different mechanoreceptors are integrated in the cortex to process tactile information, suggesting overlapping functional roles of different mechanoreceptors [17]–[20]. Cortical responses to high-frequency vibrations differ from responses to low-frequency flutters [21]–[25]. The frequency range for maximal skin sensitivity is between 100 and 300 Hz, the range in which Pacinian corpuscles are primarily activated [4]. However, the neuronal basis of information processing for high-frequency vibration input is still relatively unknown.

Since cortical information processing occurs very fast, i.e., on a millisecond timescale, magnetoencephalography (MEG) or electroencephalography (EEG) can be used to study the temporal processing of tactile information [26]–[29]. Most prior studies, however, evaluated tactile responses to light touch or flutter stimuli, where air-puffs [30]–[32], pneumatic balloon diaphragms [33]–[35], and brushes [36], [37] were used for tactile stimulation. While loudspeakers [38] or piezoelectric devices [39]–[41] were used to generate high-frequency vibrations in MEG experiments, it is very challenging to produce precise and natural vibrotactile stimuli without noise due to electromagnetic interference [27].

MEG measures magnetic fields generated by neuronal currents inside the brain with excellent temporal resolution [42], [43] and can be used to estimate the spatiotemporal dynamics of cortical activities during sensory information processing. Unlike EEG signals, MEG signals are less distorted by the layered head structure with its inhomogeneous electric conductivity, and these signals produce more accurate estimates of brain activation [44]. The sensitivity of MEG to tangential cortical sources is another advantage of using MEG to study the human somatosensory system because the central and lateral fissures significantly contribute to somatosensory information processing [45]. In human somatosensory research, MEG has been successfully used to provide the preoperative localization of the somatosensory cortex for epilepsy or brain tumor surgeries [46], to evaluate reorganization in the primary somatosensory cortex during stroke recovery [47], [48], to investigate developmental changes in the human somatosensory system [49], [50], to characterize cortical oscillatory activity during somatosensory and thermal stimulation [51], [52], and to elucidate underlying physiological mechanisms by linking human data with computational neural models [53].

With advances in haptic technology, vibrotactile feedback has been widely used for applications in mobile communication, navigation, gaming, and virtual reality [6], [7]. We believe that real-life-like vibrotactile stimuli compatible with the MEG system could therefore be a tool to help us understand vibrotactile perception mechanisms in the human brain by activating cutaneous mechanoreceptors under well-controlled conditions.

To provide functional neuroimaging insights into vibrotactile perception studies, we developed an MEG-compatible vibrotactile stimulation device based on a polyvinyl chloride (PVC) gel actuator. The PVC gel can be easily deformed by applying an external electric field to create a vibrational force larger than the perception threshold for humans over a wide range of frequencies [54], [55]. We designed the structure of the PVC gel actuator to minimize magnetic field noise during neuromagnetic recordings. The frequency, amplitude, and duration of the vibrations are controlled by a variable, high-voltage simulator with external triggers. The vibration performance of the actuator was evaluated by displacement measurements using a laser interferometer system. Then, we investigated the ipsilateral and contralateral brain responses to tactile vibrations by recording whole-head MEG data during the high-frequency vibrotactile stimulation of the fingertips to demonstrate the feasibility of using the new stimulator to produce neuromagnetic activities.

II. MATERIALS AND METHODS

A. MEG-COMPATIBLE VIBROTACTILE STIMULATOR

Electroactive polymers (EAPs) can be deformed by applying external electric fields across EAPs. The simple structure of the EAP actuator can be considered a flat capacitor with a thin dielectric film sandwiched between two compliant electrodes (Fig. 1(a)). Since an actuator made from the EAPs is incompressible, an electrical voltage applied between the two electrodes generates actuation forces perpendicular to the plane of the electrode. As a result, mechanical vibrations can be created by applying sinusoidal external electric fields across the EAP. EAP actuators require high driving voltages (on the order of kV) and can operate at frequencies higher than a few kHz [56].

In addition, the alternating electric displacement field within the dielectric EAP layer induces magnetic fields in parallel with the EAP layer, according to Maxwell's equation [57]. Since the induced magnetic field strength is proportional to the applied voltage amplitude, we decided to prepare a vibrotactile actuator using plasticized polyvinyl chloride (PVC) gel, which operates at a relatively low actuation voltage (<1 kV) [58]. Next, we focused on the structure of the PVC gel actuator to minimize the induced magnetic field. As shown in Fig. 1(b), PVC gel layers were placed both above and below the input voltage electrode, as a symmetric

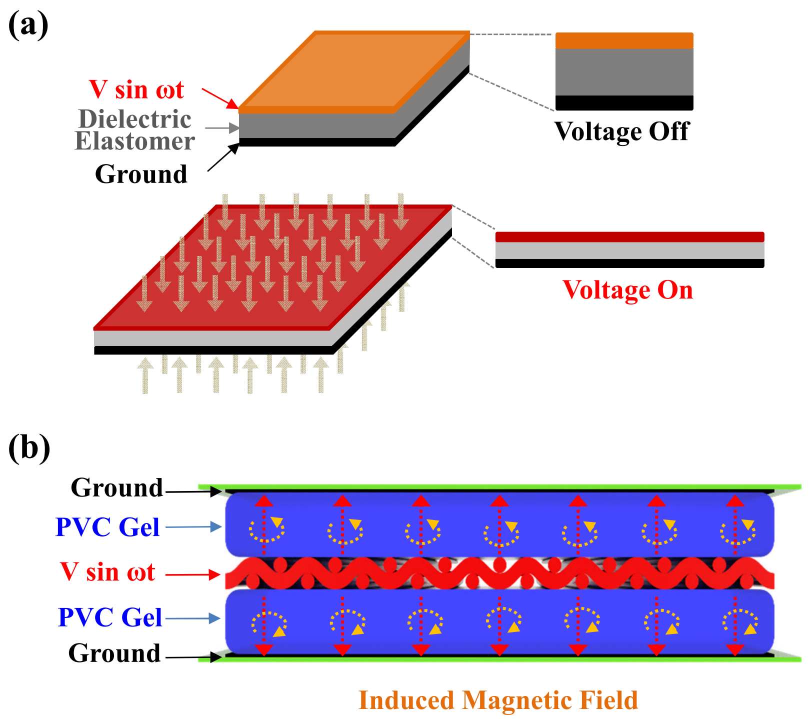

FIGURE 1. Illustration of (a) a conventional EAP actuator with the deformation mechanism and (b) the proposed low-magnetic field actuator with induced magnetic fields.

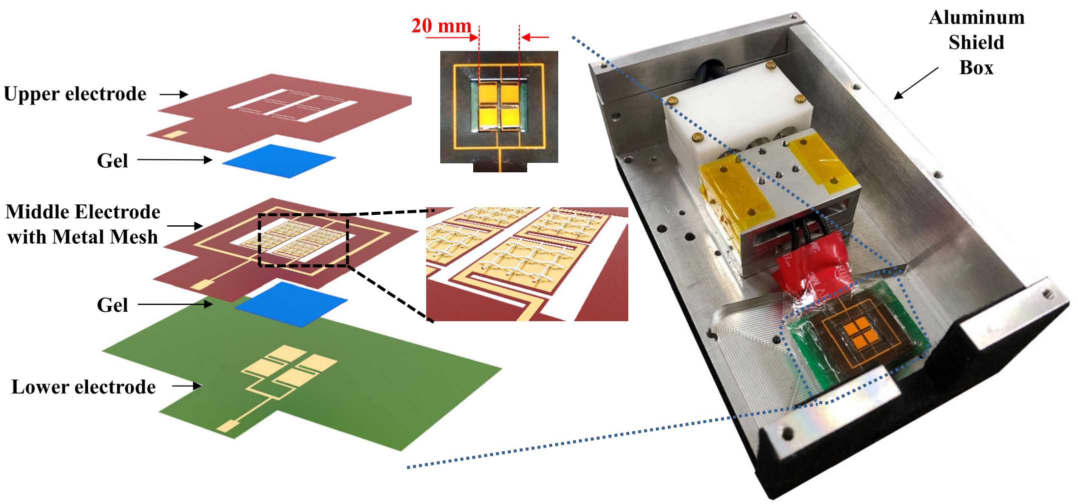

FIGURE 2. Structure of an MEG-compatible vibrotactile actuator based on the PVC gel with a picture of the actuator module placed inside an aluminum shield box.

double-layered structure, while the ground electrodes were placed at the top and the bottom of the stack. Since the direction of the displacement current in the upper PVC gel layer was opposite to that of the displacement current in the lower PVC gel layer, the induced magnetic fields from both dielectric layers were supposed to cancel out each other at far distances. Instead of using a plate, we used a mesh structure for the middle electrode, since the mesh electrode was known to increase the displacement of the PVC gel actuator [58]. In fact, similar structures were reported in a previous study [58], [59], in which a DC field was applied to induce a contraction-type deformation in the PVC gel actuator. In our study, however, we applied alternating electric fields to generate sinusoidal vibrations and cancelled magnetic induction using a symmetric, double-layered PVC gel structure; coincidentally, our study produced a similar structure as that described in the previous study.

As shown in Fig. 2, four separated thin copper electrodes shielded with polyimide film were used both for the upper and lower ground electrodes to increase the flexibility of the actuator [60]. The 2×2 array structure is more flexible than the single cell structure, thereby increasing the contact area between the actuator and the curved surface of a fingertip. The thickness of the single PVC gel layer was 800 μm, and a single gel was 20 mm $\times$ 20 mm in size. Finally, the vibrotactile actuator module was placed inside a shield box made of 10 mm thick aluminum plate to reduce any further magnetic field noise generated from the stimulation device. The aluminum shield box was covered with black felt fabric to avoid unwanted cold thermal contact to the skin.

To create high-voltage sine waves, we created a variable, high-voltage simulator consisting of a circuit that generated two high-voltage sine signals with different frequencies [61]. The input frequency was variable, ranging from 70 to 220 Hz, and the actuation voltage amplitude remained between 0 and 800 V. External triggers from the PC were used to control the vibrotactile stimulation sequences.

B. DISPLACEMENT MEASUREMENT

The performance of the MEG-compatible vibrotactile stimulator was tested by measuring the displacement of the vibrotactile actuator using a laser scanning vibrometer (PSV-500, Polytec GmbH, Waldbronn, Germany) at a 50 kHz sampling rate, while the actuator was stimulated 100 times for 200 ms at 150 Hz with 2 s interstimulus intervals (ISIs). The acceleration time series was obtained by calculating the second derivatives of the displacement data after low-pass filtering at 2 kHz. The event onset of a single vibrotactile pulse was defined at the closest local minimum of the acceleration time series after the onset of each stimulus TTL pulse (> 2.2 V threshold level). The delay from the stimulus TTL onset to the vibrotactile event onset was calculated to evaluate the temporal variability in the stimulus presentation.

C. PARTICIPANTS AND STIMULI

In this study, 30 right-handed healthy subjects (15 females/15 males, aged 20–28 years, mean age = 22.9 ± 2.0 years) with normal or corrected-to-normal vision were recruited from the local community. The participants had no history of neurological or psychiatric disorders and gave written informed consent to a protocol approved by the Korea Research Institute of Standards and Science Institutional Review Boards (KRISS-IRB-2016-07). All procedures were conducted in accordance with the Declaration of Helsinki. The data from one participant were discarded because the exact head position within the MEG dewar helmet was not available due to the movement of the head position coils during the recordings. For each subject, three fiducials (nasion and right and left preauriculars) and four head position coils were digitized using a 3D digitizer (ISOTRACK II, Polhemus, Colchester, VT, USA) to coregister the head position relative to the MEG sensors. Approximately 65 additional points distributed over the skull were digitized to create the pseudoanatomy of each participant. Each subject sat in a comfortable chair under the MEG dewar, which was located inside a magnetically shielded room, and was asked not to move the head during the measurements. The subjects placed their right index finger gently on the vibrotactile pad, without pressing on it, and were instructed to fixate on a small cross presented in the center of the projection screen, positioned approximately 80 cm in front of them to reduce ocular activity.

The tactile stimuli, sinusoidal vibrations, were repeatedly applied to the tip of the right index finger at 150 Hz for 200 ms (Fig. 3). A total of 300 stimuli were delivered, and the interstimulus interval (ISI) was randomly varied from 1.6 to 2.4 s. The vibration amplitude was kept fixed at the maximum level of the stimulation controller, and we checked that tactile vibrations were clearly detected by all subjects prior to the actual recordings. No subject reported any perception of auditory sound during vibrotactile stimulations.

D. DATA ACQUISITION AND PREPROCESSING

MEG data were recorded using a 152-channel whole-head MEG system (KRISSMEG, Daejeon, South Korea [62], [63]) with first-order axial gradiometers. The data were sampled continuously at 1024 Hz with an analog low-pass filter at 234 Hz. The preprocessing and sensor space analysis of the data were performed using the FieldTrip toolbox [64], and source space analysis was performed using the Brainstorm [65] toolbox. Both FieldTrip and Brainstorm are open source toolboxes for MEG and EEG data analysis running in MATLAB (MathWorks, Natick, Massachusetts, USA). Raw MEG data were bandpass filtered between 0.1 and 511 Hz and were then decomposed with the second-order blind identification (SOBI) [66] method implemented in the FieldTrip toolbox. Independent components corresponding to eye blinks, eye movements, heartbeats, breathing movements, and power line noises, were identified by visual inspection and were removed to reconstruct clean MEG data. Trials with large variances, due to muscle activities or mental fatigue, were marked as bad trials and were rejected from further analysis.

E. EVENT RELATED FIELDS AND SOURCE ESTIMATION

Continuous MEG data, after artifact removal, were low-pass filtered at 50 Hz, segmented into epochs from -0.4 to 1.0 s with respect to stimulus onset and were baseline corrected by subtracting the mean values of individual channels during the baseline period (-0.4 to -0.2 s) from each sample point. For each subject, event-related fields (ERFs) evoked by vibrotactile stimulations were obtained by averaging good trials (mean 291 ± 5 trials) identified during the preprocessing step. For group analysis of the sensor space, we realigned individual ERFs to average sensor positions for all subjects using MNE-based interpolations implemented in the ''ft_megrealign'' function of the FieldTrip toolbox [64]. Grand average ERFs across 29 subjects (14 females/15 males) were computed and plotted to visually inspect brain responses to tactile vibrations in the sensor space.

Cortical source activities during the vibrotactile stimulations were calculated for each subject by applying the

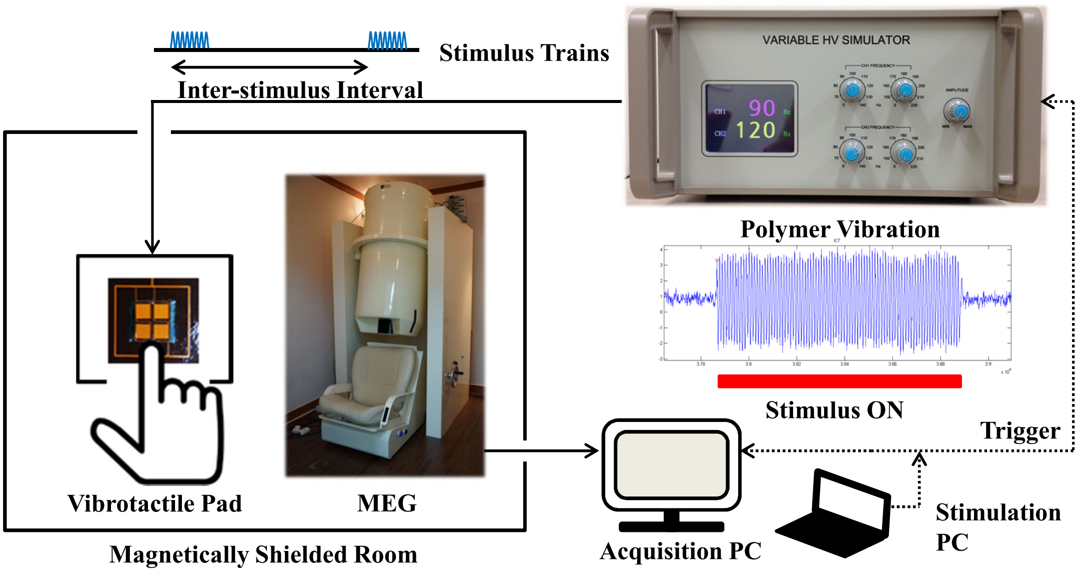

FIGURE 3. Schematic diagram of the experimental setup for recording vibrotactile-evoked magnetic fields using an MEG system located inside a magnetically shielded room.

weighted minimum norm estimate method (wMNE) [67], [68] implemented in the Brainstorm toolbox [65]. Since individual MRI scans were not acquired, pseudo-individual MRIs were obtained by deforming the ICBM152 template anatomy (the default template in Brainstorm) to the digitized head surface of each participant using the warping function in the Brainstorm software. The noise covariance for each participant was estimated from the baseline periods (-0.4 to -0.2 s) of all accepted trials. An overlapping-sphere head model was calculated [69] using the original sensor positions of each subject, and cortical sources were computed for unconstrained dipole orientations (three signals per grid point) with Tikhonov regularization [70].

F. STATISTICAL ANALYSIS

The topographical maps of grand average ERFs at each time point were statistically analyzed using the topographic consistency test (TCT) [71] to prove that consistent topography was present across all subjects based on randomization techniques. The global field power (GFP), which is equivalent to the standard deviation across all sensors, was used as a global index of scalp field strength for grand averaged waveforms at each time point. The number of randomization runs for TCT was 1000, and a p-value below 0.05 was considered statistically significant. The results were used to determine the time period in which the stimulus elicits consistent neural activation across all subjects.

The sensor-level topography of grand average ERFs at the maximum GFP peak was statistically examined by comparing the mean peak amplitudes (averaged between 50 and 70 ms after onset) and the mean baseline amplitudes (averaged between -400 and -380 ms before onset) using a paired t-test with Bonferroni correction ($\alpha = 0.05$). In contrast, cortical source activation at the maximum GFP peak was statistically evaluated in Brainstorm software [65] by applying a parametric, one-tailed power F-test against baseline values ($p < 0.01$ with Bonferroni correction). The source power was defined as the sum of squares of the current density values in three orientations at each source location, and the test statistic was the source power at each time point normalized to the mean baseline power averaged between -0.4 and -0.2 s before stimulation onset.

III. RESULTS

A. VIBROTACTILE STIMULATION

Fig. 4 shows the displacement time series of the vibrotactile actuator with stimulus TTL signals during the first few stimulations. We observed periodic oscillations at the frequency of the applied input voltages for the ON states of the TTL signals and observed slow mechanical actuation and relaxation responses for the ON and OFF states of the TTL signals. Mechanical actuations and relaxations occurred within a displacement range of less than 20 μm for every ON and OFF state of the TTL sequences. The onset of vibrotactile events was detected 1.98 ± 0.02 ms after stimulus TTL onset, and the amplitude of the acceleration at the event onset was 4.7 ± 0.2 m/s^2.

B. VIBROTACTILE EVOKED MAGNETIC FIELDS

Waveforms of the grand average ERFs obtained by vibrotactile stimulations of the right index finger are shown in Fig. 5. Prominent peak responses were observed at approximately 56 ms (M50) in fields measured from the left hemisphere and at approximately 100 ms (M100) in fields from both hemispheres. Dipolar field patterns were clear for both M50 and M100 components in the topographical maps shown in Fig. 5, and stronger responses were observed in the left hemisphere, which is contralateral to the stimulated side.

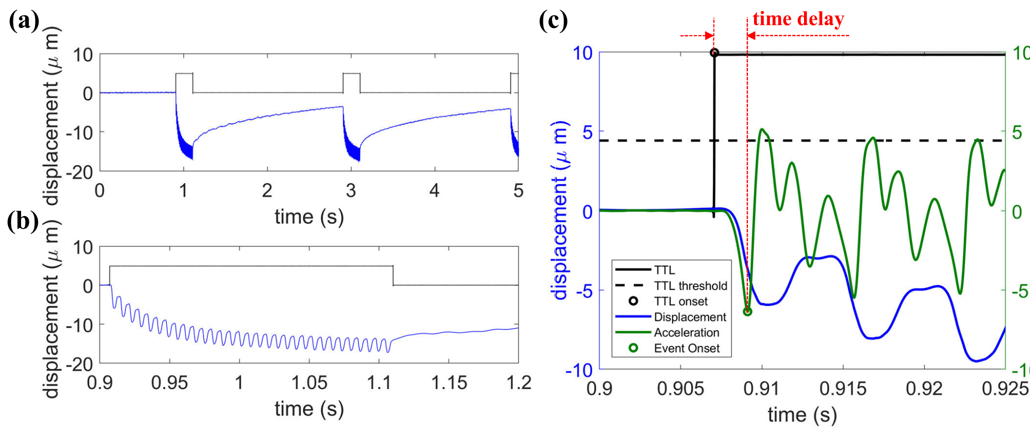

FIGURE 4. Examples of actuator displacement measured for a series of 200 ms vibration pulses at 150 Hz. Stimulus TTL signals (black lines) and displacement signals (blue lines) are plotted for different time scales from (a) to (c). Additionally, calculated acceleration signals (green lines) are plotted together with the TTL onset (black circle) and the vibrotactile event onset (green circle) in (c).

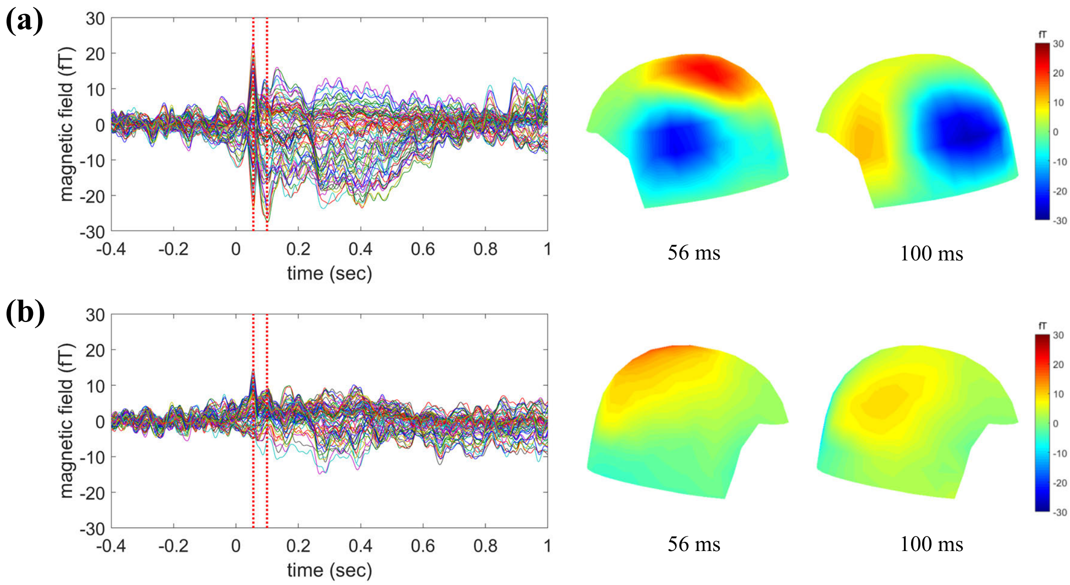

FIGURE 5. Grand averaged waveforms of vibrotactile-evoked magnetic fields (VEMF) obtained from (a) sensors above the left hemisphere and (b) sensors above the right hemisphere, with the topographical maps at 56 ms (M50) and at 100 ms (M100) after stimulus onset.

Fig. 6 shows vibrotactile-evoked magnetic fields (VEMFs) for all sensors and the results of applying the TCT to each time instance. We found the presence of a consistent topography across subjects beginning approximately 100 ms before the onset of the vibrotactile stimulation. At the largest VEMF peak (M50), the sensors over the left hemisphere showed significant responses to the vibrotactile stimulation of the right index finger (paired t-test, $p<0.05$, Bonferroni corrected). As shown in Fig. 7, cortical activations, corresponding to the M50 response, were observed in the contralateral primary somatosensory regions (F-test, $p<0.01$, Bonferroni corrected).

IV. DISCUSSION

In the present work, we developed an MEG-compatible vibrotactile stimulation device based on a PVC gel actuator to study vibrotactile perception using neuromagnetic imaging methods. The symmetric, double-layered structure of the PVC gel was applied to minimize the magnetic induction of the vibrotactile actuator. The device was used to deliver sinusoidal stimuli to a fingertip at a broad range of frequencies (70–220 Hz) to activate mechanoreceptors responsible for high frequency vibrations, and we were able to demonstrate the vibrotactile responses in the somatosensory cortical areas by analyzing whole-head MEG data recorded during the vibrotactile stimulations.

Passive finger movements can induce both kinesthetic and cutaneous sensations. Fingertip movements due to the actuation and relaxation processes of the actuator are shown in Fig. 4. However, these movements were much smaller than the absolute thresholds for kinesthetic perception, which is at least 0.5 mm [72]). The fingertip detection thresholds of

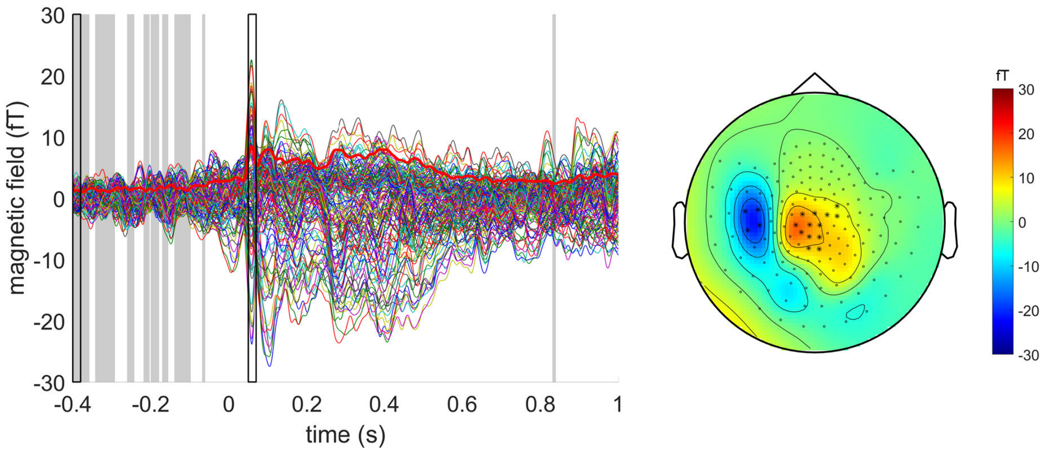

FIGURE 6. Statistical significance of vibrotactile-evoked magnetic fields (VEMF). Left: Grand averaged waveforms of VEMF from all sensors with TCT results ($p < 0.01$). The gray areas indicate nonsignificant time points, while white areas indicate time periods showing significant differences from the mean baseline activity. The thick red line is the global field power (GFP). Right: The topographical map of VEMF at the primary peak, with significant channels marked as asterisks (paired t-test, $p < 0.05$, Bonferroni corrected). The mean peak amplitudes, averaged between 50 and 70 ms after onset, were compared with the mean baseline amplitudes, averaged between −400 and −380 ms before onset.

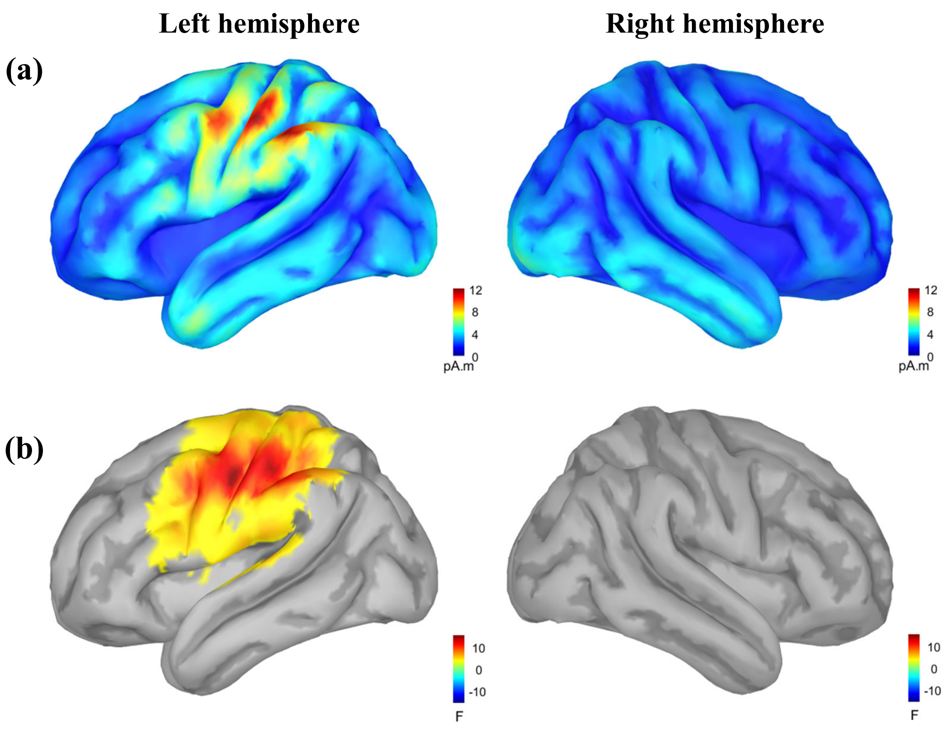

FIGURE 7. Estimated source activations in response to vibrotactile stimulations. (a) Current density maps and (b) statistically significant cortical activations at the primary peak of the VEMF (power F-test, $p < 0.01$, Bonferroni corrected).

sinusoidal vibrations at 150 Hz are approximately 0.5 m/s^2 [12], [73], and therefore, the acceleration of 4.7 ± 0.2 m/s^2 measured at the stimulus onset in our study is strong enough to evoke vibrotactile sensations at fingertips.

On the other hand, event-related potentials (ERPs) and ERFs are generated by synchronous neuronal activities in response to external stimuli and are obtained by averaging stimulus-locked EEG and MEG data, respectively, over repeated trials [70], [74]. To increase the temporal resolution of measured ERP/ERF signals, it is important to provide the precise timing of the stimuli across trials [75]. Variability in stimulation onset times can blur temporal resolution, leading to peak broadening and amplitude reduction due to cancellation during the averaging process [75]. Since the delay time between stimulus TTL onset and the onset of the vibrotactile event is less than 2 ms, with variability equivalent to the sampling time interval (0.02 ms), the vibrotactile stimulation device developed in the present study is suitable for eliciting VEMF.

Using the MEG-compatible vibrotactile stimulation device, we observed clear VEMF waveforms, as shown in Fig. 5. The magnetic artifact signals due to the stimulation device were not discernible in the VEMF waveforms. Vibrotactile responses were stronger in the left hemisphere, which was contralateral to the stimulated side, and showed prominent peaks at approximately 56 ms (M50) and 100 ms (M100). Dipolar field patterns were clearly observed in the left hemisphere for the M50 peak and in both hemispheres for the M100 peak. The contralateral M50 and the bilateral M100 components are well-known somatosensory responses elicited by mechanical pulses or vibrations [21], [39], [40]. Moreover, we identified the activation of the contralateral primary somatosensory areas as a source of the vibrotactile M50 response (Fig. 6).

Expectations about sensory inputs can result in the prestimulus modulation of ongoing oscillatory activity [76]–[79]. The results of the TCT in Fig. 6 show the presence of vibrotactile event-related neuronal activity during the pre-stimulus time period. Therefore, the baseline time window must be carefully defined in VEMF analysis. Further investigation is needed to understand the mechanisms underlying the prestimulus activity prior to the onset of vibrotactile events.

In our study, we focused on the early vibrotactile responses observed within approximately 100 ms from the stimulation onset and successfully demonstrated the validity of the new vibrotactile device to evoke transient neuromagnetic responses to high frequency vibrations using MEG. Human vibrotactile perception, however, is a complicated process and is affected by many factors, including contact area, contact location, stimulation length, stimulation strength, stimulation frequency, and temporal relationships between stimuli [8], [12], [73], [80]–[82]. Our new device can be applied to explore brain mechanisms to detect changes in the vibrotactile input, but the effect of stimulation parameters has to be systematically investigated for an optimized experimental design. In addition, it will be of substantial interest to study the performance of the PVC gel actuator using numerical models, since various conditions of an actuator design can be tested before fabrication to balance the vibration strength and the magnetic field noise strength.

Our device can deliver vibrotactile stimuli in a frequency range between 70 and 220 Hz, which is widely used in vibrotactile feedback in touchscreen mobile devices. Since the stimulation parameters, such as frequency, duration, and strength, can be easily controlled, the device can be used in multimodal functional neuroimaging studies with fMRI and EEG/MEG to provide different perspectives of the vibrotactile perception process. In particular, the temporal changes of local cortical activations can be combined with dynamic functional connectivity networks, and we believe this approach can improve our understanding of human vibrotactile perception.

V. CONCLUSION

In recent years, vibrotactile feedback technology has gained attention as a tool to improve the user performance of touchscreen devices [1], [3], [6]. To understand the vibrotactile feedback system, the fundamentals of vibrotactile perception have been actively investigated using both psychophysical and physiological methods, with most studies focusing on threshold detection [8], [10], [12], [16]. However, the perception threshold is a subjective measure that relies on a participant's condition and the experimental circumstances. Thus, there is a need to study vibrotactile perception using objective measurements. We believe that the MEG-compatible vibrotactile stimuli presented in this study could contribute to our understanding of neural mechanisms during vibrotactile perception and that our study may be of interest for the potential application of vibrotactile feedback technology in basic research and industry.

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