Haptic Simulation: Tactile Mechanisms, Restoration and Medical Applications

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Abstract: This paper mainly focuses on three sections: tactile capture, tactile restoration, and medical potential evaluation. It reviews the research progress of haptic simulation technology in the field of neuroscience, focusing on the mechanisms of tactile capture and restoration based on intracortical microelectrode arrays. Studies have shown that by integrating functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) technologies, the neural pathways and brain functional areas involved in tactile perception can be precisely captured. During tactile restoration, microelectrode arrays demonstrate higher accuracy compared to deep brain stimulation (DBS), especially in tasks requiring fine tactile perception, enabling subjects to experience natural tactile feedback. Furthermore, multimodal stimulation integration in the brain significantly enhances the effectiveness of tactile restoration. This technology has important applications in the rehabilitation of amputees and spinal cord injury patients, as well as in the treatment of neurodegenerative diseases. Future research should focus on improving the design of microelectrode arrays to enhance the precision and naturalness of haptic simulation and explore their integration with artificial intelligence technologies.

1 INTRODUCTION

Haptic simulation technology enhances users' perception of the external environment by integrating sensors and visual stimuli. Prosthetic limbs help amputees regain partial mobility but fall short of replicating the tactile feedback of natural limbs.

In psychophysical experiments, researchers found that by stimulating the skin while simultaneously providing visual stimuli, patients could almost completely restore their sense of touch (Schultz, Marasco, & Kuiken, 2009). The core of this discovery lies in "tricking" the brain into believing the missing limb still exists, enabling users to operate prosthetics with the brain's assistance.

Skin electrical stimulation therapy involves adjusting the frequency and amplitude of electrical stimulation at the afferent nerve interface and stimulating the residual nerves connected to the missing limb to restore prosthetic sensation. A widely used technique in this therapy is transcutaneous electrical nerve stimulation (TENS), which targets peripheral sensory nerves. Normally, the brain receives signals of touch through afferent nerves. However, when the residual skin of amputees is stimulated, these signals can "bypass" the traditional afferent nerve pathways, allowing amputees to regain non-corporeal perception (Christie et al., 2017).

Another approach is electrical stimulation of the brain and spinal cord. Through cortical stimulation, volunteers have been able to control robotic arms and achieve very simple pain reflexes (Muheim et al., 2024). This technique not only benefits prosthetic operation but also shows progress in treating neurological diseases such as epilepsy. Compared to the brain, the spinal cord's simpler distribution structure makes it easier to operate. Spinal cord stimulation is more suited for lower-limb amputees, but its sensitivity to somatosensory resolution remains a challenge (Kruger, Sininoff, & Witkovsky, 1961).

Currently, electrical stimulation technology offers promising solutions for both upper and lower limbs. While progress in temperature and pain perception is nearing maturity, tactile feedback has yet to reach natural levels. Scientists are currently employing hybrid strategies of bionic frequency modulation and amplitude modulation to enhance the natural perception of prosthetics (Valle, 2022). Bionic frequency modulation provides a more natural tactile experience, while amplitude modulation is more

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effective in tasks requiring fine recognition (Valle, 2022).

This paper focuses on the mechanisms of generating sensation through intracortical microelectrode arrays, with an emphasis on their impact on amputees. Microelectrode arrays regulate abnormal neural circuits in the brain, offering new therapeutic pathways for patients who have lost sensation and those with neurodegenerative diseases.

2 TACTILE CAPTURE

2.1 Methods for Tactile Capture

Before microelectrode array experiments, fixed-frequency oscillatory stimuli are typically applied to the subject's limbs while functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG) is used to capture the subject's tactile perception map. This ensures precise stimulation and avoids individual differences (Swan, Gasperson, Krucoff, Grill, & Turner, 2018; John, 2024; Rickard, 2000; Martijn, van den Heuvel, Hilleke, & Hulshoff Pol, 2010). This paper primarily outlines fMRI-based tactile capture processes in humans.

2.2 Data Collection

Some researchers set EPI scan parameters to multiple axial slices (approximately 20 slices), with a slice thickness of about 5 mm and a matrix resolution of 64 × 64 (Rickard, 2000; Cox, & Savoy, 2003). Anatomical images are obtained using T1-weighted 3D SPGR image acquisition (Rickard, 2000).

2.3 Subjects with Perceptual Impairments

During the generation of tactile experiences, the brain integrates tactile stimuli with inputs from other senses, such as visual stimuli. When individuals observe their own body parts, tactile stimuli activate the premotor cortex and intraparietal sulcus, resulting in the tactile-visual enhancement effect (VET) (Swan, et al. 2018; Andrea, & Patrick, 2010). Based on VET, scientists collect data by guiding subjects who cannot directly perceive tactile sensations through touch to imagine touch while simultaneously providing visual stimuli (John, 2024).

2.4 Data Processing and Visualization

fMRI data processing methods include Independent Component Analysis (ICA), clustering analysis, large-scale network identification (LSNI), and seed-based analysis (Martijn et al., 2010; Cox, & Savoy, 2003). The LSNI method can identify functional networks in about 30% of the cortex (Cox, & Savoy, 2003). Researchers first use MCFLIRT for motion correction and BET to remove non-brain tissue (John, 2024). Subsequently, constrained volume-to-surface mapping methods project fMRI data onto the pial and white matter surfaces for reconstruction (John, 2024). By calculating z-scores of upper and lateral cortical areas and setting minimum z-thresholds, the distance to S1 can be further calculated for precise functional area localization (John, 2024).

2.5 Partial Results of Tactile Capture

Tactile sensations can be classified into three main categories: mechanical perception, thermal perception (cold and hot), and pain perception (Huang & Wu, 2021).

2.6 Mechanical Perception

In touch triggered by mechanoreceptors, the processing of tactile forms and positions exhibits hemispheric dominance (Van et al., 2005). In GO and GL tasks, the left intraparietal sulcus (IPS) processes tactile forms, while the right temporoparietal junction (TPJ) processes tactile spatial localization (Van Boven et al., 2005). The secondary somatosensory cortex (SII) is the neural basis for learning roughness and pressure information (Harris, Harris, & Diamond, 2001).

2.7 Thermal Perception

Pathways include the thalamus, primary somatosensory cortex, anterior cingulate cortex (ACC), orbitofrontal cortex (OFC), and precuneus (Xiu et al., 2014).

2.8 Pain Perception

Pain perception is regulated by the medial pain system, with the ACC being a key structure involved in generating pain experiences and processing pain-related emotions and motivation (Xiu et al., 2014).

2.9 Multisensory Integration

Under multisensory stimulation, enhanced BOLD signals are observed in multiple brain regions, including the left ventral and dorsal premotor cortices, left anterior intraparietal sulcus, left inferior parietal cortex, left postcentral sulcus, left insula, and bilateral parietal operculum (Swan et al., 2018). Subcortical structures involved in multisensory integration include the left putamen, left thalamus, and right cerebellum (Swan et al., 2018). These regions are highly interconnected anatomically, forming the basis for multisensory integration (Swan et al., 2018).

2.10 Tactile Classification and Decision-Making

Tactile classification and decision-making are regulated by different functional subdivisions of the supramarginal gyrus (SMG) in the parietal lobe (Lee, Chung, Kim, & Ryun, 2023). Tactile classification is influenced by PFt stimulation (rostral SMG), while decision-making is influenced by PF stimulation (caudal SMG) (Lee et al., 2023).

3 TACTILE RESTORATION

3.1 Successful Methods for Tactile Restoration

Due to the VET effect, limbs or prosthetics that cannot perceive touch are typically touched during brain stimulation to provide visual stimuli concurrently (Swan et al., 2018; Andrea, & Patrick, 2010). Tactile restoration can be achieved using microelectrode arrays and deep brain stimulation (DBS). Compared to DBS, which is suitable for broader brain region stimulation (eg.Parkinson's disease treatment) and uses monopolar configurations (Swan et al., 2018). Microelectrode arrays are better suited for fine tactile perception and neural repair tasks, employing bipolar configurations (Swan et al., 2018). This paper focuses on tactile restoration using bipolar-configured microelectrode arrays.

3.2 Implantation Method

In related surgeries, the initial stimulation signal trajectory is typically mapped while the patient is awake (Swan et al., 2018). Commonly targeted locations are 2 – 3 mm posterior to the planned ventral intermediate nucleus (VIM) treatment trajectory, close to the visual cortex (VC) and sensory thalamus (Swan et al., 2018; Downey et al., 2024). Individual tactile capture results can influence these implantation locations. Additionally, tapered electrode arrays are recommended due to their significantly lower risk of cellular damage compared to blunt or angled arrays (McNamara et al., 2024).

3.3 Bipolar Configuration Stimulation Signal Mode

Most experiments use asymmetric bidirectional pulse sequences (BPS) (Swan et al., 2018; İsmail, Sevgi, & Burak, 2021). BPS consists of two currents or voltage pulses opposite in polarity, typically alternating between a positive and negative pulse. This design effectively reduces DC bias, minimizing the risks of tissue damage.

3.4 Bipolar Configuration Stimulation Signal Duration

The stimulation signal duration is typically greater than 500 milliseconds, as the minimum time required to activate specific neurons is generally around this threshold (Libet et al., 1991). Longer stimulation ensures the successful activation of neurons and provides more precise sensory feedback for subjects (Libet et al., 1991).

3.5 Bipolar Configuration Stimulation Signal Frequency

Frequency modulation is primarily associated with the roughness of perceived textures and the number of neurons activated within the cortical volume (Greenspon et al., 2024). In human studies, stimulation at a constant frequency of 100 Hz to 300 Hz typically results in sensations of light touch, pressure, or mild pricking without triggering vibratory sensations (Swan et al., 2018). For vibration perception, frequencies below 100 Hz are usually selected. For example, studies on rats have shown 40 Hz stimulation induces vibratory effects (İsmail et al., 2021; Öztürk, Devecioğlu, & Güçlü, 2023).

3.6 Bipolar Configuration Stimulation Signal Amplitude

Amplitude modulation correlates with the perceived pressure intensity and the cortical volume activated (Greenspon et al., 2024). In human experiments, when the current amplitude is set between 25 – 75 μA, participants generally report sensations of light touch, pressure, or mild pricking (Swan et al., 2018). Increasing the current incrementally can enhance the sensation's intensity and potentially induce pain when thresholds are exceeded.

3.7 Location and Size of the Perceived Sensation

The sensation area triggered by different electrodes and participants varies significantly (Greenspon et al., 2024). Existing data show that the average sensory area induced by a single wire for participants is approximately 14 cm^2, ranging from 1 cm^2 to 120 cm^2 (Swan et al., 2018).

3.8 Processing of Tactile Restoration Results

3.8.1 Statistical analysis

Data variability is represented by standard error (SE), and differences in task accuracy, task types, and test modes are analyzed using two-tailed t-tests (Van Boven et al., 2005). Researchers adjust significance levels based on the number of comparisons (eg.some set α to 0.05) and use Bonferroni correction methods to control experimental error rates while reporting differences at $p < 0.005$ (Van Boven et al., 2005; Harris et al., 2001).

3.8.2 Quantitative and qualitative analysis

Behavioral data collected during experiments are analyzed using mixed-effects models, considering the task as a fixed factor and participants as random factors (Swan et al., 2018). Quantitative analyses record the size of the sensory area and classify the distribution of sensation. Qualitative analyses categorize sensory qualities based on patient descriptions into natural pressure, touch, pricking, and vibration (Swan et al., 2018). Additionally, the effects of various stimulation modes (eg. constant frequency, increasing frequency ramp, decreasing frequency ramp, vibration modes) on the perceived naturalness of the sensations are compared (Swan et al., 2018; Öztürk et al., 2023).

4 EVALUATION OF MEDICAL AND REHABILITATION APPLICATIONS

4.1 Associated Technologies

4.1.1 Tactile Bionics Technology

To simulate natural tactile feedback, scientists have proposed bionic designs, including bionic frequency modulation and amplitude modulation (Valle, 2022). Specific signal details have been discussed previously. Experiments demonstrate that tactile bionic feedback induced by intracortical microstimulation aligns with the sensorimotor loop, improving the grasping ability of patients with severe sensory loss (Swan et al., 2018; Flesher et al., 2021).

Additionally, cortical electrical stimulation enables volunteers to control robotic arms, achieving basic pain reflexes (Muheim et al., 2024). Compared to traditional tactile creation methods (eg. rubber hand illusion via touch), computer-stimulated "rubber hand" illusions occur in shorter durations, presenting additional challenges for tactile restoration (Collins et al., 2017).

4.1.2 Tactile-Assisted Recognition Technology

Dynamic tactile feedback systems rely on computer vision to identify the characteristics of the touched object. Bionic tactile sensors trained with absolute fluid pressure, dynamic fluid pressure, temperature, and thermal flux can differentiate various materials, including frequencies ranging from 0 – 140 Hz (Huang, & Wu, 2021). Hershey lens, an AI camera module, has been used to learn and identify colors, facial features, and objects (Wang, Patnik, Wong, Wong, & Wong, 2018). Future applications anticipate observing tactile patterns and offering more intelligent tactile recognition systems.

4.2 Treatment of Related Diseases

4.2.1 Patients with Sensory Loss

Amputees lose limbs and often experience phantom limb pain. Through the VET effect, the brain can be tricked into perceiving the presence of limbs, creating an illusion of still having the missing body part (Swan et al., 2018; Andrea, & Patrick, 2010). While TENS is widely used to enhance tactile perception in amputees, intracortical microelectrode stimulation offers more precise and robust features. For spinal cord injury and paralysis patients, electrical stimulation of tactile-related regions in the brain using microelectrode arrays can activate residual neural pathways, restoring partial sensory functions (Kruger et al., 1961). Pain resulting from phantom limb sensations or spinal cord injuries can also be alleviated using brain-computer interface (BCI) technologies, which have demonstrated successful pain mitigation effects (Yanagisawa et al., 2020; Yoshida, Hashimoto, Shikota, & Ota, 2016).

4.2.2 Patients with Neurodegenerative Diseases

Neurodegenerative diseases such as Alzheimer's Disease (AD) are often accompanied by progressive loss of cognitive and sensory functions (Toh, Yolland, Gurvich, Barnes, & Rossell, 2023). Researchers have successfully mitigated disease severity in AD mouse models through gentle massage of the fingers or brushing with soft brushes, using protocols such as three times daily for 15 minutes over 15 days (Hossain, Karem, Jafari, Kolb, & Mohajerani, 2023; Hossain, Karem, Jafari, Kolb, & Mohajerani, 2023). Notably, tactile stimulation for newborns carrying relevant genes yielded better results (Hossain et al. 2023).

For Parkinson's Disease (PD), perceptual disturbances often impair recognition ability. Tactile illusions may further reduce patients' differentiation ability (Toh et al., 2023). Scientists have addressed freezing of gait (FOG) in PD patients by deploying vibrating socks to provide tactile hints, alleviating symptoms (Brodie et al., 2023). While DBS remains widely used for neurodegenerative disease treatment, brain microelectrode stimulation offers stronger and more precise effects. Tactile stimulation introduced by microelectrode arrays holds promise as an auxiliary therapy for neurodegenerative diseases in the future.

5 CONCLUSION

Haptic simulation, by combining sensors, visual stimuli, and electrical stimulation technologies, offers possibilities for restoring tactile sensations in patients who have lost sensation. In tactile capture, researchers integrate fMRI and MEG technologies for localization and employ methods like Independent Component Analysis and seed-based analysis for further study. Tactile restoration relies primarily on microelectrode arrays for fine tactile perception and incorporates multimodal input through the VET effect.

The advantage of microelectrode arrays lies in their higher suitability compared to DBS for achieving fine tactile perception tasks, and their bipolar stimulation configuration effectively reduces risks of tissue damage. By frequency and amplitude modulation, experimental participants perceive natural touch, pressure, and mild pricking sensations. The integration of haptic simulation with brain microelectrode arrays has demonstrated broad application prospects in the treatment of amputees, spinal cord injury patients, paralysis patients, and neurodegenerative disease patients.

In terms of implementation difficulty, the technology requires invasive surgical implantation of microelectrode arrays in patients while awake. The large variability among individuals also presents challenges to standardization. Future research should focus on further optimizing microelectrode array designs to improve precision and naturalness of tactile restoration. The integration of AI and neuroscience holds immense potential for the future of tactile simulation technology.

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