論　文　内　容　要　旨

Involvement of the Rostromedial Prefrontal Cortex in Human-Robot Interaction: fNIRS Evidence From a Robot-Assisted Motor Task

（人とロボットの相互作用における吻内側前頭前野の関与: ロボットアシスト運動課題時の近赤外分光法による立証）

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【Introduction】

Stroke is a significant global health issue, contributing to high mortality rates and causing disabilities that profoundly impact daily activities. In recent years, robotic rehabilitation utilizing assistive exoskeleton robots has emerged as a promising approach to aid in the recovery process for individuals affected by stroke. By providing targeted and intensive training, these robotic devices offer the potential to improve functional limitations and facilitate the restoration of motor skills. During robot-assisted tasks, the exoskeleton robot analyzes user’s motion intention in real time (e.g., bioelectrical signals from muscles). This analysis enables the robot to translate the user's intentions into physical assistance, allowing for smoother and more precise task completion. Moreover, the user receives somatosensory feedback generated by their interactions with the robot. This feedback provides crucial sensory information, aiding in the adjustment and refinement of movements during subsequent interactions.

This intricate human-robot interaction places demands on the brain's executive resources, which govern the allocation of cognitive processing. In this context, the brain must effectively prioritize the processing of external information, such as feedback from human-robot interactions, over internal information derived from self-generated movements. This process of executive control at a higher level ensures that the brain's state optimally aligns with the goals of the ongoing behavior, thereby enhancing overall performance. The prefrontal cortex is a region known for its crucial involvement in executive control during task-oriented behavior. However, the precise neural mechanisms underlying executive control in the context of human-robot interaction during robot-assisted tasks remain largely unexplored. Understanding these mechanisms is crucial for enhancing the effectiveness of robotic rehabilitation and maximizing the potential for recovery in stroke survivors. Therefore, the aim of this study was to investigate the cortical activity associated with executive control during a motor task performed with an assistive exoskeleton robot.

【Methods】

To conduct the study, a wearable assistive exoskeleton robot called HAL-SJ and a self-built resistance exoskeleton device were used to manipulate elbow movements. Healthy participants performed cyclic right-elbow flexion-extension movements under three task conditions: self-controlled movements without external loading (NON), movements with a constant resistive force (RES), and movements with combined assistive and resistive forces from HAL-SJ and the resistance exoskeleton (ROB). Each condition included 4 trials consisting of a 40-s rest period, a 10-s preparation phase, and a 20-s execution phase. Task performance was evaluated by measuring the kinematic consistency of the range of motion. A functional near-infrared spectroscopy (fNIRS), a non-invasive neuroimaging technique, was employed to measure cortical hemodynamic activity as an index of brain activation during the tasks. We focused on cortical regions associated with executive control, including the rostromedial prefrontal cortex (rmPFC) and dorsolateral prefrontal cortex (dlPFC), using 42 measuring channels. One-way repeated measures analysis of variance and general linear model-based methods were employed to examine differences in behavioral and brain measures across task conditions.

【Results and Discussion】

The study revealed significant differences in kinematic variability among conditions, with participants exhibiting higher variability during ROB compared to RES. This suggests that the level of physical interaction with the robotic device influences motor performance and introduces variability in participants' movements. In terms of brain activity, the study revealed that the ventral rmPFC demonstrated stronger task-related responses during ROB compared to both RES and NON. The dorsal rmPFC showed increased task-related activity during ROB compared to NON, and the dlPFC exhibited higher preparation-related activity during ROB compared to NON. No significant correlation was found between behavioral and brain measures. These findings indicate that specific subregions of the rmPFC were activated during human-robot interactions, suggesting their involvement in top-down executive control processes that prioritize the processing of external information to support human-robot interactions.

【Conclusion】

Overall, the study found that robot-assisted tasks enhance executive control in specific subregions of the rmPFC, compared to manual motor tasks. These findings contribute to a deeper understanding of how top-down executive control operates within the context of human-robot interactions, expanding our existing knowledge in this field. As assistive exoskeleton robots become increasingly prevalent in various aspects of life and rehabilitation, this study serves as a useful baseline for future researchers to comprehensively explore human-robot interactions in both healthy individuals and clinical populations. By further exploring and optimizing the brain processes involved in human-robot interactions, we can unlock the full potential of assistive exoskeleton robots in stroke recovery, ultimately improving the quality of life for stroke survivors.