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Review

The motor organization of cerebral cortex and the role of the mirror neuron system. Clinical impact for rehabilitation☆

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ABSTRACT

The basic characteristics of Penfield homunculus (somatotopy and unique representation) have been questioned. The existence of a defined anatomo-functional organization within different segments of the same region is controversial. The presence of multiple motor representations in the primary motor area and in the parietal lobe interconnected by parieto-frontal circuits, which are widely overlapped, form a complex organization. Both features support the recovery of functions after brain injury. Regarding the movement organization, it is possible to yield a relevant impact through the understanding of actions and intentions of others, which is mediated by the activation of mirror-neuron systems. The implementation of cognitive functions (observation, image of the action and imitation) from the acute treatment phase allows the activation of motor representations without having to perform the action and it plays an important role in learning motor patterns.

Organización motora del córtex cerebral y el papel del sistema de las neuronas espejo. Repercusiones clínicas para la rehabilitación

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RESUMEN

Las características básicas del homúnculo de Penfield (somatotopía y representación única) han sido cuestionadas. La existencia de una organización anatomofuncional definida en la corteza cerebral entre segmentos de una misma región es controvertida. La presencia en el área motora primaria y en el lóbulo parietal de múltiples representaciones motoras interconectadas por circuitos parietofrontales y profusamente solapadas configuran una organización compleja. Todo ello sustenta la recuperación funcional después de un daño cerebral. En la organización del movimiento se puede incidir a través de la comprensión de las acciones y de las intenciones de los otros, lo que está mediado por la activación de los sistemas de neuronas espejo. El uso de funciones cognitivas (observación, imagen de la acción e imitación) desde la fase aguda del tratamiento permite la activación de las representaciones motoras sin necesidad de ejecutar la acción, y tiene un papel importante en el aprendizaje de patrones motores.

Introduction

The knowledge we have about the cortical representation of movement comes, essentially, from the works of Penfield et al., during the first half of 20th century .[1–3] Those works identified a somatotopic and unique representation of the different parts of the body, and postulated that movement organization followed a sequential order.[4,5]

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Throughout the years, critical ideas about this concept started to appear. The development of new investigative technologies has revealed the existence of multiple cortical representations overlapping onto each other.[5–7]

This evidence brings about the thought that the organization of movement requires the activation of several structures that work in parallel, integrating sensory and motor information, transforming all into motor actions.[3]

The anatomical and functional complexity of the motor system increased with the contribution of the mirror neuron systems (MNS), discovered by Rizzolatti and Sinigaglia at the beginning of 1990s. These systems are the neural substrate that allows us to understand the implication of cognitive functions such as observation, imitation and image of the action in the organization and the learning of the movements.[3,8]

The aim of this work is to review the different points of view regarding the cortical organization of movement. In addition, this work includes some considerations about the clinical impact derived from motor organization and its relationship with cognitive functions, regarded as potential therapeutic tools in the recovery of movement.

Development

In 1937, Penfield and Boldrey presented the cortical motor map (homunculus) that represented cortical regions corresponding to different parts of the body.[4]

In 1950, Penfield and Rasmussen, by means of direct stimulation of the cortex in conscious patients during surgical intervention, defined the organization of the first homunculus, obtaining the first map of the motor and sensory cortex separately.[3,4] These maps follow a somatotopic and unique organization (parts of the body represented in anatomic order and in a delimited way) where variations were not considered.[5]

The authors established that motor areas of the brain are exclusively dedicated to executive functions. According to this conception of movement, the brain follows a sequentially organized process following the scheme: perception → cognition → movement. These events are associated with different cortical areas, such as language in Broca's area or motor function in Brodmann's area 4.[3]

All of this has an impact on understanding the way the primary motor area (M1) is organized: firstly, every cortical area is solely responsible for controlling a part of the body and its movement, which means that if there is a lesion in a certain cortical area, then the movement that depends on that area will not be recovered and, at the same time, the range of movements will be limited to a finite number of combinations. Secondly, the cortical region activated by the simultaneous movement of several fingers will be larger than that area activated by the movement of only one finger, as the first region would be the result of adding each finger's territory extension.[1,6,9]

Contributions to the knowledge of the anatomo-functional organization

In the second half of the 20th century, the work of Penfield was questioned and considered ambiguous. In fact, Penfield himself warned about the possible inaccuracy of his maps. The use of electrodes that were too large did not allow for more precise research. But even with these warnings, the idea of a somatotopic and unique organization was widespread and exerted a strong influence in the conception of the cortical organization.[1,9] Subsequent studies[3,4,6] using more sophisticated techniques have questioned the two essential characteristics of the Penfield homunculus: somatotopy and unique representation.

Studies confirmed a somatotopic organization in the representation of the big body areas (face, upper and lower extremities); although, there are controversies about the anatomo-functional organization of minor areas of the body (fingers, wrist, elbow and shoulder in upper extremity representation).[1,9,10] The existence of overlapping between cortical areas connected with each other by horizontal bidirectional connection was revealed.[1,10] The overlapping means different segments share the same neural network. Several authors[1,5] consider overlapping to be a differential characteristic of M1, transcending the somatotopic organization concept of Penfiel.[2,9] This allows the cooperation between proximal and distal muscles, for example, in upper extremities, enabling better coordination between shoulder, elbow and wrist in the task of reaching an object.[1,9] Other authors[11,12] advocate for the classical opinion, accepting the existence of a certain degree of overlapping and attribute the control of small movements to the somatotopy in M1.

Aflalo and Graziano[13,14] note the importance of motor and learning practices to go from one somatotopic map to another with overlapping representations between the different parts of the body. They suggest that the role of plasticity and the reorganization of the motor cortex are central to this process, and show that the lesser somatotopy, the greater complexity of the movements.

Several studies have shown the existence of multiple motor representations of different parts of the body, with a certain degree of overlapping. A movement may imply the activation of several cortical areas, sometimes distant from each other.[2,15] In the 1980s, Strick and Preston[16,17] discovered two representations of the hand in the monkey motor cortex, and observed that each of them were activated as a response to different somatosensory afferent activities: one reacted to tactile afferents and the other to the proprioceptive afferents. In 1986, Gould et al.[6,9] observed, in anaesthetized monkeys, that M1 presented a tendency to a somatotopy of the representations of the different segments, and the occurrence of the activation in several points of the brain, distributed like a mosaic, in the movement of any part of the body.

In addition, this multiple distribution (mosaic) is present in the posterior part of the parietal lobe, establishing horizontal interconnections with other areas of the brain, which allow for a somatosensory afferent flow to the motor area.[3,9,18] The different motor areas are connected to parietal areas via parieto-frontal circuits, forming a functional system.[3]

Neuroimaging techniques have shown that in the exploration of objects, when there is no visual control, the tactile and propioceptive somatosensory information was essential, as well as was the fronto-parietal circuit activation in shape and length discrimination by means of active finger movement.[19,20]

The same thing happens with actions that need vision, where visual information arrives at the parietal lobe, activating parallel and simultaneous parieto-frontal circuits that will produce a visuomotor transformation. This includes several processes, such as placing the object in space, orientation, shape and size, and controlling upper extremity trajectory displacement.[18]

Knowledge of the complexity of the parallel organization of the motor system allows us to see the possibilities of reorganization after damage. The affectation of any of the structures involved rarely leads to the complete loss of the only element capable of performing a task; a group of neurons can participate in more than one task.[21] The cortical area activated to move one finger is larger than the area involved in the simultaneous movement of several fingers, as the fragmented movement required to move only one finger implies greater control and organization.[6,9,15] Based on this evidence, the motor system cannot be reduced to a spatially organized map executor of orders originated in well differentiated areas