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Face and Upper-Limb Reorganization in the Human Somatosensory Cortex after Spinal Cord Injury

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Abstract

The somatosensory cortex has the essential role of discerning a number of sensory modalities. Representation of these sensory modalities in somatosensory cortex is highly organized, yet the cellular architecture demonstrates a flexible nature. This ability of the cortex to reorganize has a crucial role after spinal cord injury (SCI). Damage at the spinal cord, particularly the dorsal column, impairs ascending sensory axons involved in sensation. This has important implications on somatosensory cortex, with neurons of the deprived cortical region becoming unresponsive immediately after injury, which also results in behavioral consequences. This review will focus on how the human somatosensory cortex reorganizes to tactile stimulation of the face, hand and arm following SCI at the cervical level. Several different methodological techniques (such as electrophysiology and functional magnetic resonance imaging) will be discussed, with an emphasis on later large-scale reorganization. A greater understanding of how the somatosensory cortex reorganizes after SCI and the underlying mechanisms may help facilitate recovery of function after injury by targeting and promoting functionally relevant changes, but also minimizing maladaptive plasticity.

Keywords: Spinal cord injury; Somatosensory cortex; Plasticity; Reorganization

Introduction

The composition of the somatosensory cortex is located in the postcentral gyrus of the parietal lobe and, in humans and non-human primates, this includes the primary somatosensory cortex (Brodmann's area 3a, 3b, 1, and 2; S1) and secondary somatosensory cortex (Brodmann's area 40 and 43; S2) [1,2]. Important bodily sensory modalities experienced daily are processed in the somatosensory cortex. For example, sensory information for proprioception (muscle and joint receptors) is represented in cortical area 3a, whereas information for touch (cutaneous receptors) is represented in area 3b. In S1, cortical area 1, which shares many common features in topography with cortical area 3b, also processes cutaneous information, whereas cortical area 2 combines touch and proprioception information [3]. The somatotopic representation of these sensory modalities projecting to the somatosensory cortex is organized into general body parts, with a medial (lower limb) to lateral (upper limb, head and face) topography [4-6]. Tactile stimulation of the digits and face in humans and non-human primates activates large proportions of cortical area 3b (the primary innervation for touch in S1) compared with other body parts, such as the trunk, which demonstrates the importance of these body parts in providing cutaneous information to the cortex [3]. The cellular architecture of the cortex demonstrates a complex yet flexible nature where there is potential to functionally and structurally reorganize following physiological (learning) and pathological (injury or disease) events [7].

Following complete and incomplete cervical spinal cord injury (SCI) in non-human primates, face representation expands into the deafferented hand region of the S1 and S2 after a prolonged period of recovery (minimum of six weeks) with both cortical and subcortical changes likely to contribute to this large scale reorganization [6,8-14]. Non-human primate studies have also shown that reactivation of the hand representation following cervical dorsal column transection occurs only if the injury is incomplete [6,9,11,13-19]. Importantly, in contrast to the face, there is a functional role for reactivation of S1 hand representation following a prolonged period of recovery after SCI [16,17].

It is evident that non-human primate studies on somatosensory cortex following SCI provide a great deal of relevant information to humans because of their central nervous system (CNS) similarities [20]. However, this review we will specifically focus on the reorganization in the human somatosensory cortex of the face and upper limb following cervical SCI.

Reorganization in the Somatosensory Cortex after SCI in Humans

There are a number of studies that examine sensory function at acute and chronic stages after spinal cord injury in humans. For example, there is evidence to suggest that some sensations such as light touch and pressure recover quickly and completely, whereas vibration and proprioception are slower and never return to levels before the injury [21]. However, studies that examine the reorganization of the somatosensory cortex after SCI in humans are limited, especially when compared with animal models.

Reorganization of the Face Representation of Somatosensory Cortex after Cervical SCI

In humans, there is limited information on the reorganization of the face representation after cervical SCI. However, a fMRI case study in a tetraplegia patient (C2, >75% loss in spinal cord area) 8 years after injury demonstrated that the S1 hand area in this patient (which was inactive following sensory stimulation of the hand, vibration ~100 Hz) is activated by sensory stimulation of the tongue and lips resulting from tongue movements [22]. This supports a face expansion into the deafferented S1 hand region demonstrated in non-human primates [6,8-11].

A recent fMRI study examined sensorimotor cortex reorganization after incomplete and complete (based on ASIA impairment scores) cervical SCI (C5-C8) [23]. Sensory stimulation administered through electrical stimulation (motor threshold intensity) of the median nerve at the level of the wrist demonstrated an increased S1 face area activation in SCI patients compared with healthy controls [23]. In addition, the amount of face area activation was dependent on spinal cord damage and tactile sensitivity. For example, increased spinal cord damage and a greater reduction in tactile sensitivity of the upper limb resulted in more face area activation of S1 [23]. While the cortical and subcortical mechanisms of this reorganization remain poorly understood, information from non-human primates suggest that this may arise from afferent volleys induced by the median nerve to the trigeminal nuclei [10].

The face expansion into the hand region observed after SCI is specific to injuries at the cervical level. Following cutaneous stimulation with a fine plastic brush at ~2 strokes/s on the right side of the lip in complete thoracic (T1-T11) SCI patients (neurological level of injury determined as ASIA A), fMRI demonstrated that there was no change in lip representation when compared to healthy controls [24]. However, following cutaneous stimulation of the little finger and thumb, S1 representation moved medially toward the lower body representation (area of sensory loss) by ~13mm and ~7mm respectively [24]. The authors also suggest that such large shifts in cortical reorganization indicate the growth of new lateral connections in humans, not simply the unmasking of existing lateral connections (which may have the capability for smaller shifts of 2-3 mm in cortical organization). While reorganization patterns after SCI in humans suggest a site specific and stronger reorganization in the region closer to the site of deafferentation, the tactile threshold required to elicit a neural response of the new face map or whether reorganization of face representation occurs in higher somatosensory areas remains unknown in humans after cervical SCI.

Reorganization of the Hand Representation of Somatosensory Cortex after Cervical SCI

In contrast to experimental injury in non-human primates, SCI in humans is less anatomically controlled and, as a result, human SCI patients have more diffuse tissue injury. There are also ethical considerations in the practicality of multiunit recordings in humans, which often limits the use of this technique to neurosurgical procedures. Together, these factors limit information and interpretation of somatosensory cortex reorganization after SCI in humans. However, somatosensory evoked potentials (SEPs) offer a non-invasive method of assessing dorsal column sensory pathways of the spinal cord. Following cervical SCI (C3-C6, classified by the ASIA score), cutaneous nerve stimulation of areas innervated at or below the injury level (thumb, index finger, and little finger) was performed within the first week after SCI to assess SEPs (Cheliout-Heraut et al., 1998). In patients with incomplete SCI, SEPs could be recorded in the territories that were clinically deficient. However, their amplitude was diminished compared with healthy controls [25]. In contrast, there were often no discernible SEPs in clinically complete SCI patients [25]. This finding is similar to that seen in non-human primates with multiunit recordings where following complete dorsal column transection the S1 is unresponsive to tactile stimulation of the hand, whereas after an incomplete transection the remaining dorsal column afferents of the hand continue to activate neurons within their normal cortical target regions [9]. Interestingly, there were two complete SCI patients where SEPs were present, although abnormal, which suggests that clinical examination soon after SCI is subjective and SEPs may alternatively be used to objectively differentiate between complete and incomplete SCI [25]. While the long-term effects in upper limb SEPs after cervical SCI are unknown, there is evidence that SEPs recorded in incomplete cervical SCI patients by electrical stimulation of the posterior tibial nerve (innervation below the injury level) increase in amplitude within the first year after injury [26]. Despite being in the leg, this finding is in agreement with the reactivation of the deprived S1 hand area by preserved inputs from the hand several weeks after incomplete dorsal column transection demonstrated in non-human primates [9].

Reorganization of the hand representation after cervical SCI in humans is not limited to the contralateral S1. Following vibratory stimulation of the hand, ipsilateral S1 was activated after vibratory stimulation of the hand in a chronic SCI patient (C2), but not in the control subject [22]. This increased activation of ipsilateral S1 has also been demonstrated in chronic incomplete cervical SCI patients (more than one year after injury) during movement (dorsiflexion of foot at a frequency of 1 Hz) when compared with healthy controls [27]. This finding suggests that increased ipsilateral cortical activity may help to compensate for the functional deficit after SCI.

There is evidence to suggest that reorganization of the hand representation following cervical SCI in humans occurs in higher somatosensory areas. Following vibratory stimulation of the hand (100 Hz) in a tetraplegia patient (C2), fMRI demonstrated that vibration failed to activate contralateral S1 as observed in the control subject [22]. However, contralateral activation corresponding to higher order somatosensory areas was observed. While vibratory stimulation of the hand activated S2 in the patient and control subject, additional higher order somatosensory areas (including the posterior postcentral gyrus and supramaximal gyrus) were only activated in the SCI patient [22]. This higher somatosensory cortex reorganization after cervical SCI in humans is supported by the reorganization of S2 face [13] and hand representation [19] in non-human primates, suggesting widespread reorganization of the somatosensory cortex after injury.

Functional Role of Hand Representation in Somatosensory Cortex after Sci

Positron emission topography (PET) can be used to examine cortical reorganization following SCI and typically combines activation from the precentral gyrus (motor) and postcental gyrus (somatosensory), referred to as sensorimotor cortex. This is most likely due to the reduced spatial and temporal resolution of PET when compared with fMRI [18]. While PET may not be the optimal neuroimaging technique to detect cortical reorganization, the findings from PET studies demonstrate a number of similar somatosensory cortex changes as fMRI following cervical SCI in humans. For example, during hand movement, PET demonstrates that cortical and subcortical reorganization is present in cervical SCI patients with impaired hand function [26,28]. Typically, there is an expansion of sensorimotor hand area toward leg area (increased contralateral sensorimotor cortex activation) following movement [28]. Importantly, this cortical reorganization was related to upper limb function in cervical SCI patients with impaired hand function [26].

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Reorganization of the Arm Representation of Somatosensory Cortex after Cervical SCI

The extent of arm representation reorganization in the somatosensory cortex following a cervical SCI in humans is currently not known. However, following thoracic SCI, there is the potential for the arm to reorganize. For example, a T6-level complete SCI patient experiencing referred phantom sensations demonstrated increased fMRI activity in the S1 forearm and chest regions following forearm contact [29]. These areas correspond to the body part being stimulated and also the area with phantom sensation. However, these areas in S1 that demonstrate cortical activity are non-adjacent, which is in contrast to cervical injuries observed in the non-human primates [6,8-13]. This finding may suggest that, in humans, reorganization may be more complex than non-human primates. Alternatively, reorganization may be more complex in thoracic compared with cervical SCI.

Conclusions

Reorganization of the somatosensory cortex often follows SCI where there is damage to the ascending afferents. Evidence in non-human primates, and to a limited extent in humans, indicate that the face representation expands into the deafferented hand region of S1 and S2 following cervical SCI. However, the new face map is evident only after a prolonged period of recovery (typically six months). This large scale somatosensory reorganization of the face representation after cervical SCI remains poorly understood, but is likely to involve changes in both cortical (growth of new lateral connections) and subcortical (growth of brainstem connection) structures.

In the upper limb, particularly for hand representation after cervical SCI, it is evident that somatosensory cortex can only be reactivated if there are spared afferents. While reactivation of the hand representation to tactile stimulation is most extensive in cortical area 3b, a global somatosensory reorganization is evident with other cortical areas of S1 (3a, 1, and 2) and higher somatosensory areas (S2) also demonstrating such reactivation patterns. Importantly, there is a functional role for reactivation of somatosensory cortex hand representation after cervical SCI, which is in contrast to the new face map evident after a prolonged period of recovery.

Despite the available information for face and upper limb somatosensory cortex reorganization after cervical SCI in humans and non-human primates, little is still known about the neuronal basis of recovery after injury. An increase in our understanding of the underlying mechanisms of somatosensory cortex reorganization after SCI will help to differentiate changes that are functionally relevant compared with those that are maladaptive. This critical information has the potential to facilitate functional recovery after SCI by targeting and promoting relevant changes, but also by minimizing maladaptive plasticity.

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