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A hypothetical explanatory sensorimotor model of bilateral limb interference

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ABSTRACT

Goal-directed movements of a limb are optimized by sensorimotor integration, a process that merges both sensory and motor representations. In a previous study, we revealed that abnormal sensory representation can impair reach-to-grasp movements in patients with spinothalamocortical pathway lesions. This abnormal motor control was significantly recovered when referencing correct somatosensory information with the intact hand. Furthermore, motor control of the intact hand was impaired when referencing abnormal somatosensory information with the affected hand. Such bilateral limb interference suggests that there is only one common integrated sensory representation and only one common motor representation for both hands. The single sensory representation would be integrated from the somatosensory information received from both hands. Subsequently, the integrated motor representation would be derived from the integrated sensory representation, and would then be split and sent out via motor commands to both hands. Considering that bimanual coordinated movements are reportedly smoother than unimanual movements, information transfer between the integrated sensory and the integrated motor representation would be suitable for such efficient bimanual movements. Therefore, we propose a novel hypothetical model to better explain the observation of bilateral limb interference. The proposed model might contribute to the development of novel sensory and motor rehabilitation strategies by promoting the use of the unaffected hand.

Introduction

Motor outputs of goal-directed movements are programmed based on multisensory inputs. The central nervous system (CNS) computes a suitable transformation of these sensory inputs into motor outputs, which allows for greater motor control. This sensorimotor transformation is known as "an internal model" (also known as "a sensorimotor loop") [1,2]. The internal model includes not only the sensory representations but also the motor representations on which the motor output is programmed [3,4]. The sensory and motor representations interact with each other, and this interaction makes it possible to optimize motor control based on body sensory states [4]. For example, a prior study demonstrated that the updating of sensory representations following repeated tool-use (e.g. sticks, pliers) influences the kinematic output of reach-grasp movements [4]. We showed a similar effect in patients who suffered from abnormal sensory representations following spinothalamocortical pathway lesions [5]. The maximum grip aperture (MGA) of the affected hand during grasp movements was shown to be significantly impaired compared with the MGA of the intact hand (Fig. 1). Assuming that such an abnormal MGA reflects an impairment of motor planning processes within the internal model [6,7], these results support the idea that the abnormal sensory representations directly affect the motor representations, which in turn lead to impaired motor outputs. We further analyzed grasping movements under other two different conditions:

(1) In one condition, patients were asked to reach for and grab a target bar with one hand, while simultaneously holding onto a similar sized bar with the contralateral thumb and index finger (i.e. the matched somatosensory reference (Matched-Ref) condition).
(2) In the other condition, patients were asked to hold on a different sized bar with the contralateral (intact) hand while performing a reach-to-grasp movement with the impaired hand (i.e. mismatched somatosensory reference (Mismatched Ref condition). We found that the MGA of the affected hand improves under the Matched-Ref condition (Fig. 1), indicating that referencing the 'correct' sensory representation with the intact hand improves the sensory and motor representations of the affected hand. Interestingly, in contrast, we found that the MGA of the intact hand is disrupted when referencing the 'abnormal' somatosensory information from the affected hand (Fig. 1). This conversely indicates that the abnormal sensory representation of the affected hand can also interfere with the sensory and motor representations of the intact hand. On the basis of these findings, we propose a novel hypothetic model below to better account for the observed effects of bilateral hand interference.

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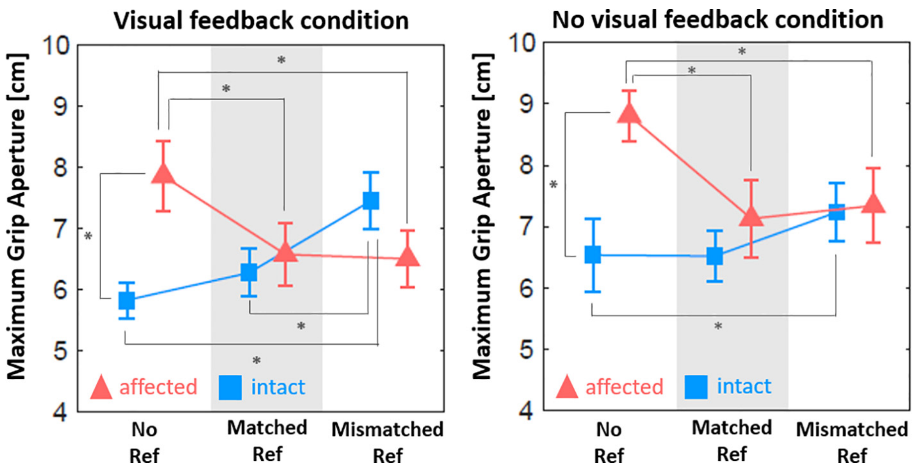

Fig. 1. Comparison of the maximum aperture length between the intact and affected side for three grasp movement phase conditions with eight patients suffering from abnormal sensory representations. Red triangles and blue quadrangles indicate the affected and intact side, respectively. Error bars indicate ± SD. * indicates a significant difference using Wilcoxon signed-rank test ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hypothesis

Executing goal-directed movements using a single hand generates a sequence of motor outflows (motor representation, intention, and commands) to the musculoskeletal system of the hand. In addition to these motor outflows, a copy of the intentional signal (i.e. the efferent copy) is stored within the sensory representation of the movement, which monitors the congruence between predicted and actual sensory feedback information (including tactile, visual, and proprioceptive information). The efferent copy then transfers the error signal, if available, toward the sensory representation for efficient motor execution. Assuming that the CNS computes the respective internal models for both the left and right hands independently, bilateral limb interference should not emerge. However, we have provided previous kinematic data showing that the sensory information from one hand could influence the motor outputs of the other hand. It is thus possible that the CNS might share an internal model with both hands and then integrates and computes outputs independently for both hands to optimize motor control. This implies that when either the motor output of the affected hand or the motor output of the intact hand diverges from an integrated motor representation, referencing the sensory representation of the intact hand might improve the motor control of the affected hand, and vice versa. In light of these findings, we propose here a novel representational model of bilateral limb interference (Fig. 2). This model posits that a single integrated sensory representation is formed based on somatosensory information from both hands, which then updates a single integrated motor representation. The motor commands from the integrated motor representation are then split and sent to both hands. The integrated motor representation theoretically sends efferent copies from both hands to the integrated sensory representation. More specifically, when executing goal-directed movements with a single hand while referencing the other (contralateral) hand, visual and somatosensory feedback information from both hands converge onto the integrated sensory representation. Such interactions between the motor representation and the sensory representation for each hand would occur continuously. Given that a previous report revealed that the somatosensory reference from one hand can interfere with the movement smoothness of the other hand [8], our model posits that the interaction between the sensory representation and the motor representation allows for a more efficient correction of movement error. Consequently, our model can then adequately explain the observation of bilateral hand interference.

Evaluation of the hypothesis

Previous studies have confirmed that somatosensory information from one hand can interfere with the information from the other hand; for example, tactile acuity in one hand improves after tactile perceptual

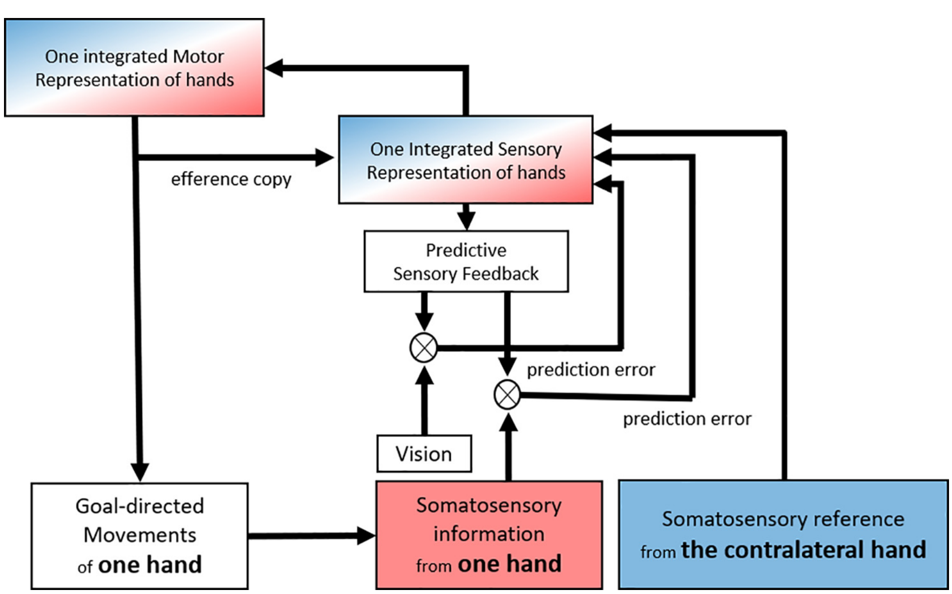

Fig. 2. Schematic diagram depicting the effect of somatosensory reference from the contralateral hand on grasp movement control.

learning with the other (contralateral) hand [9]. Similarly, grasping an object with one hand interferes with the grasping of a different sized object with the other (contralateral) hand [10,11]. Both such cases of bilateral limb interference can be explained by our proposed model. Somatosensory information from both hands is transmitted and integrated into a single sensory representation, which can be slightly different than the sensory representations of each hand, and consequently, the movement representation of each hand is altered. This hypothesis is supported by a pivotal physiological study that revealed that both somatosensory cortices contain neurons receiving somatosensory inputs from both hands, indicating that the inter-limb sensory transfer results from a singular convergent sensory representation of both hands [12]. In line with this finding, our previous clinical study showed that the abnormal sensory representation of the affected hand (in patients with unilateral hand deafferentation) disturbs the intact hand's sensory representation [13]. Similarly, because motor-related cortical potentials (MRCPs) are always synchronous and comparable between congruent and incongruent movements performed with two hands, bimanual movements appear to be programmed from a single bilateral motor representation [14]. These studies appear to support the existence of a single somatosensory bimanual representation and a single motor bimanual representation. Alternatively, if there were independent sensory and motor representations for each hand, bilateral limb interference would not be observed so frequently. Indeed, when somatosensory information from both hands is transferred to the motor system, a one-on-one interaction between the somatosensory and motor representations might be more efficient than two-by-two interactions.

To verify our hypothetical model, future investigations are required. One approach would be to use an experimental deafferentation method to modulate the sensory representation [15–17]. Therefore, we plan to conduct a kinematic analysis of bilateral limb interference during the transient deafferentation of either the tested hand or the referencing hand of healthy participants. Alternatively, the use of virtual reality (VR) is also a promising research avenue. Previous studies have shown that VR can be used as an effective method to experimentally modulate the sensory representation [18–20]. One approach would be to modulate the somatosensory representation following adaption to a different sized VR hand, which should, in turn, produce significant bilateral limb interference.

Consequences of the hypothesis

Our proposed model could have significant repercussions on rehabilitation methods for both motor and neuropathic somatosensory impairments. Considering that the motor control of both hands requires common internal motor and sensory models, referencing the intact hand should prove to be an efficient way of improving the motor control of the affected hand. For example, a somatosensory deficit in one hand could be improved by referencing normal sensory information from the intact hand. We have already shown, using VR, that tactile stimulation of the intact hand enhances the tactile perception of the deafferented hand in neuropathic pain patients [21]. In addition to somatosensory rehabilitation, using bimanual movements can also improve motor learning. Indeed, a previous study demonstrated that bimanual movement therapy produced greater improvement of motor paralysis compared with unimanual movement therapy [22,23]. Such bimanual movement therapy would not only be useful for upper limb rehabilitation, but also for lower limb rehabilitation. In fact, bilateral symmetry-based resistance training has been shown to improve the strength of lower limb extensions [24]. Furthermore, pending further study, bilateral movement therapy might also prove to be useful for treating unilateral movement disorders such as Parkinson's disease and for motor learning in athletes or musicians.

Conclusion

Based on kinematic data of reach-to-grasp movements from the impaired hand of stroke patients while referencing sensory information from the contralateral hand, we propose that both hands are controlled via a single integrated sensory representation and a single integrated motor representation. We believe that our proposed model has important implications for the development of new rehabilitation strategies.

Conflict of interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mehy.2018.10.025.

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