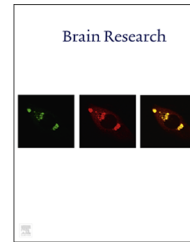
Available online at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/brainres



Research Report

Somatotopic reorganization of hand representation in bilateral arm amputees with or without special foot movement skill

Xiao Jing Yu[a,*,1], Hong Jian He[b,1], Qiao Wei Zhang[a], Feng Zhao[a,c], Chi Shing Zee[d], Shi Zheng Zhang[a], Xiang Yang Gong[a]

[a]Department of Radiology, Sir Run Run Shaw Hospital Affiliated to Medical College of Zhejiang University, Hangzhou 310016, Zhejiang Province, China
[b]Center for Brain Imaging Science and Technology, Department of BME, Zhejiang University, Hangzhou 310027, Zhejiang Province, China
[c]Department of Imaging and Interventional Radiology, Prince of Wales Hospital, The Chinese University of Hong Kong, Shatin, Hong Kong SAR, China
[d]Department of Radiology, USC University Hospital, Los Angeles, CA 90033, USA

A R T I C L E I N F O

Article history:
Accepted 19 December 2013
Available online 27 December 2013

Keywords:
Primary motor cortex (M1)
Reorganization
Nonsomatotopic
Amputation
Functional magnetic resonance imaging (fMRI)

A B S T R A C T

Bilateral arm amputees usually are excellent foot users. To explore the plasticity of the primary motor cortex in upper-extremities amputees and to determine if the acquisition of special foot movement skill is related with the bilateral hand amputation, we studied the primary motor cortex by using combined task and resting state functional magnetic resonance imaging (fMRI). We investigated 6 bilateral arm amputees with or without special foot movement skill. In the task fMRI study, we found that toe tapping of all the amputees activated the bilateral hand area, including cases without special foot skill. In addition, cases without special foot skill mainly activated the precentral gyrus, which differed from those with more adept foot motor skill who activated both the precentral and postcentral gyri. To further understand the plasticity of the hand area, the resting state functional connectivity was investigated between the foot and hand regions. One-tailed two-sample *t*-test suggested that the connections between two areas became significantly stronger in the amputee group. Our study demonstrates that hand region of the cortex does not remain 'silent' after bilateral arm amputation, but rather is recruited by other modalities such as adjacent or nonadjacent cortexes to process motor information in a functionally relevant manner. From the data presented, it seems that the bilateral arm amputees have a strong potential to develop new skills in their remaining extremities and practice may further enhance this potential.

*Corresponding author. Fax: +86 571 8603 2876.
E-mail address: yuxiaojing7@yeah.net (X.J. Yu).
[1]These authors contribute equally to this work.

0006-8993/$ - see front matter
http://dx.doi.org/10.1016/j.brainres.2013.12.025

1. Introduction

In the Penfield and Boldrey, (1937) homunculus, the body motor representations arrange in a grossly somatotopic manner and the representation of foot is located in the most medial aspect of primary motor cortex (M1) followed in medial to lateral direction by representations of the trunk, arm, hand, and face. The human cortex has the ability to reorganize and adapt in order to compensate for environmental changes, training or anatomical changes (Gizewski et al., 2003; Tuntiyatorn and Wuttiplakorn, 2011). Short-term and long-term M1 reorganization after unilateral arm amputation is marked by dynamically shifting borders between neighboring representations without the involvement of nonadjacent M1 regions (Irlbacher et al., 2002; Karl et al., 2001; Hamzei et al., 2001). This leads to enlargement and contraction of partly overlapping motor representations. Most prior animal and human studies support this view. Several experiments in non-human primates revealed that stimulation in the cortex representing the missing body part evoked muscle movements controlled by the cortex adjacent to the abnormal efferent cortex (Wu and Kaas, 1999). In humans, several studies have shown an expansion of the adjacent cortical representations into the cortical area representing the missing body part (Irlbacher et al., 2002; Karl et al., 2001; Hamzei et al., 2001).

However, if bilateral hand function is lost in childhood with subsequent functional compensation, a different pattern might emerge. In our initial study (Yu et al., 2006), we studied two bilateral upper-extremities amputees who were professional sculptors and painters with their feet. Functional magnetic resonance imaging (fMRI) data indicated that toe tapping of the amputees activated not only the classical foot M1 area, but also the 'hand' area of lateral M1. However, the functional relevance of this activation remained unclear: we did not know if the extra activation in the lateral M1 area was due only to bilateral hand function loss or due to bilateral hand function loss paired with exceptional foot dexterity. Why did it appear normal that the amputees had excellent foot movement skill (Fig. 1)? Was the acquisition of special foot movement skill related to the bilateral hand function loss?

Functional connectivity is a measurement of the spatiotemporal synchrony or correlations of the blood oxygen level-dependent (BOLD) fMRI signal between anatomically distinct brain regions of the cerebral cortex (Friston et al., 1993). In the resting state, low-frequency fluctuations (LFF) of the BOLD signal, considered to be related to neuronal spontaneous activity, have been used to identify the functional connectivity among different brain regions including those areas remotely located (Biswal et al.,1995; Xiong et al., 1999; Hampson et al., 2002; Greicius et al., 2003; Salvador et al., 2005). It has been hypothesized that the task-activated network is a subset of the resting-state network (Fox and Raichle, 2007; Greicius et al., 2003; Raichle and Snyder, 2007; Xiong et al., 1999). Comparison of BOLD task-activation maps and resting-state functional imaging results is a natural pairing. Pawela et al. (2010) studied interhemispheric neuroplasticity following unilateral limb amputation detected by fcMRI (functional connectivity MRI) and fMRI in rats and showed that severe injury in the peripheral nervous system causes disruption in the correlations of BOLD LFFs between regions of the sensorimotor system, but fcMRI conducted on human subjects after bilateral upper-extremities amputation is seldom done.

Fig. 1 – Our bilateral arm amputee volunteer was painting and writing with foot.

We combined task and resting-state fMRI to study M1 plasticity in this current study. In our previous study, we found that bilateral hand function loss paired with exceptional foot dexterity led to the hand area involvement with foot movement. Likewise, Stoeckel et al. (2009) showed similar activation in three volunteers with bilateral congenital hand function loss who also had exceptional foot dexterity. But in their study, the hand area was not activated during foot movement of a volunteer with *part* loss of hand function. Intuitively, this indicated that the existence of hand function may be the key for hand area participating in foot movement. So we hypothesized that bilateral arm amputation would produce a nonsomatotopic M1 organization consisting of an additional foot representation in the hand area, regardless of whether or not the amputee had sophisticated foot movement skill. To test this hypothesis, we studied six bilateral arm amputees with or without sophisticated foot movement skill. Their information was listed on Table 1. The amputation of cases 1–3 and case 6 was at shoulder level (only left upper arm of case 1 was partly preserved), so they had to learn to conduct daily tasks with their foot. In particular, case 1 and case 2 were excellent sculptors and painters with their feet and had acquired unusual foot dexterity after amputation of their arms through practice. The amputation of case 4 and case 5 was at elbow level, so they could use their stumps in their daily life. Their feet were only responsible for locomotion and gesture, and, in addition, case 4 used feet to handle socks. We think that combined task and resting-state fMRI will be