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Computer-aided training sensorimotor cortex functions in humans before the upper limb transplantation using virtual reality and sensory feedback

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ABSTRACT

One of the biggest problems of upper limb transplantation is lack of certainty as to whether a patient will be able to control voluntary movements of transplanted hands. Based on findings of the recent research on brain cortex plasticity, a premise can be drawn that mental training supported with visual and sensory feedback can cause structural and functional reorganization of the sensorimotor cortex, which leads to recovery of function associated with the control of movements performed by the upper limbs. In this study, authors – based on the above observations – propose the computer-aided training (CAT) system, which generating visual and sensory stimuli, should enhance the effectiveness of mental training applied to humans before upper limb transplantation. The basis for the concept of computer-aided training system is a virtual hand whose reaching and grasping movements the trained patient can observe on the VR headset screen (visual feedback) and whose contact with virtual objects the patient can feel as a touch (sensory feedback). The computer training system is composed of three main components: (1) the system generating 3D virtual world in which the patient sees the virtual limb from the perspective as if it were his/her own hand; (2) sensory feedback transforming information about the interaction of the virtual hand with the grasped object into mechanical vibration; (3) the therapist's panel for controlling the training course. Results of the case study demonstrate that mental training supported with visual and sensory stimuli generated by the computer system leads to a beneficial change of the brain activity related to motor control of the reaching in the patient with bilateral upper limb congenital transverse deficiency.

1. Introduction

The upper limbs are very special organs with unique level of functions and versatility. The high level of functions requires an integration of sensory input and excellent motor control not found anywhere else in the body. Hands are disproportionately represented in the motor cortex, indicating the degree of its importance.

There is no available exact data on the number of people with the congenital complete absence of upper limbs but the number of such cases can be roughly estimated. The incidence of Congenital Limb Deficiency has been reported as 18 per 10,000 live births [1–3]. According to the data of the Polish Register of Congenital Developmental Anomalies for the period 1998–2006 in Poland distribution of cases with complete amelia and birth prevalence were respectively from 1 up to 7 per 10,000 live births and 0.0 up to 0.3 (average 0.2) birth prevalence/10,000 total birth [4] being comparable to other countries [1–3]. Based on the demographic data on population growth in Poland in the last six decades (approx. 15,000,000) and assuming there are up to 7 cases of complete upper limb amelia/10,000 births (based on the only available report for the years 1998–2006), there can be about 1000 people living in Poland with congenital complete upper limb(s) absence (up to 2500–3000 including complete lower limb(s) absence as for the lower limbs the case distribution and birth prevalence are even higher), thus in entire Europe there can be up to 25,000–30,000 such people at different ages. After several years of living, some of them develop amazing motor skills using upper limb stumps or lower limbs, which gives them opportunity to function almost normally with comparably good quality of life. But there are also quite a large number of bilateral congenital upper limb amputees

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that would like to have new hands transplanted, which would improve their quality of life. We assessed that number to be 2500–3000 people. These people face significant limitation in motor function (such as for example washing the face or wiping the nose) in their daily lives that significantly impair quality of life. Some of these people develop remarkable ability to use their feet as a replacement for missing features such as handling and gripping, but the majority of these movements are not acceptable in social space. For instance, in order to grab something they would need to take the sitting position which is impossible in some situations, for example on a street.

One of the biggest problems of upper limb transplantation is lack of certainty as to whether the patient will be able to control voluntary movements of transplanted hands. Operational success of transplantation depends on the actions whose aim is prevent transplant rejection and on the total integration of transplanted limbs with the patient‘s central nervous system. However, complete control of motor function in the transplanted hand is possible only when hands obtain sensory and motor representation in the cortex of the brain as a result of plastic changes in the central nervous system (CNS). An additional problem is that currently available rehabilitation of people with congenital upper-limb deficiencies which stimulates the CNS plastic changes, cannot begin unless the patient is able to initiate movements, which occurs only after a period of convalescence. This situation considerably increases the amount of time needed to recover the ability of conscious control of motor function in the transplanted limbs.

Brain plasticity is any morphological and functional change in cortical properties [5] and it can be beneficial or maladaptive [6,7]. There have been several studies demonstrating the functional significance of cortical plasticity in motor and somatosensory cortex of upper extremity (limb) amputees and hand replantation [8–11]. Based on recent research findings in the field of the brain cortex plasticity, a premise can be drawn that training of the missing upper limb using a locomotor task supported by visual and sensory feedback can cause structural and functional reorganization of the sensorimotor cortex. This, in turn, can lead to recovery of function associated with the control of movements performed by the upper limbs.

In recent years we have seen a considerable increase in the technology of the so-called virtual reality (VR) [12,13]. It is based on creating an artificial environment, mapping the real or imagined places with the user placed in there and on simulating physical characteristics of both environment and user to enable mutual interactions. An important goal of this technology is to maximize the user‘s immersion in the virtual world, thus (besides image) it is necessary to provide appropriate sensory stimuli, such as touch, smell, taste, and the like. The possibilities of this technology are huge – from the most obvious, as entertainment in the form of games, movies and other forms of interactive media, through military applications and applications for the design and spatial modeling, to systems assisting in therapies and supporting the learning process [14,15].

In this study, authors propose the computer system using virtual reality to stimulate appropriate sensorimotor cortex centers via visual and sensory stimuli during the mental training in order to develop the patient‘s ability to control motor function in the transplanted limbs. The basis for a concept of computer-aided training is a virtual hand, whose reaching and grasping movements the training patient can observe on the screen of VR headset (visual feedback) and whose contact with virtual objects the patient can feel as a touch (sensory feedback). Such additional computer-generated stimuli in the course of mental training – as demonstrated by the preliminary experimental research – have a positive effect on cortical plasticity and increase the representation and motor functions of the upper limb muscles.

This paper is divided into 5 sections and is organized as follows. Section 2 provides the medical basis which justifies the concept of training patients before upper limb transplantation using the computer system with virtual reality and sensory feedback. Section 3 presents the computer training system and its three major components: the system generating 3D virtual world, sensory feedback and the therapist panel for controlling the training course. Results of the case study whose aim was to demonstrate that training conducted with the use of the computer system leads to a beneficial change of the cortical activity are presented in Section 4. Section 5 contains conclusions. In particular, Section 5 presents ideas for further development of the system using the experience of the authors in the biosignals (EMG and MMG) classification and analysis.

2. Medical fundamentals and motivation

Numerous studies that leveraged from neurophysiological techniques including transcranial magnetic stimulation, positron emission tomography, magnetoencephalography and electroencephalography, evidenced plasticity in the human motor cortex ([16,17]). These studies provided evidence that the cortical representation of the body parts can be modified as a result of central or peripheral nervous system injury or amputation [16]. In human amputees, the representation of unaffected muscles expands so that the stump region representation can also engage parts of sensorimotor cortex previously dedicated to the amputated segment [18]. There is some strong evidence that cortical reorganization results from traumatic amputation and that peripheral inputs are able to reverse the reorganization that occurred after amputation [19].

Understanding the mechanism of neuroplasticity and its functional role is important and can lead to development neurorehabilitation solutions in instances where there is no alternative treatment of the motor functions. The functional role of the neuroplasticity following peripheral nervous system injury can lead to beneficial and/or harmful changes [16]. It is important to identify exact neural mechanisms underlying beneficial brain plasticity which can provide more prompt CNS reorganization in patients following peripheral injury or central lesions. Most studies demonstrated positive plasticity induced by motor learning and motor practice, which provide to novel or reeducated movement strategy. It appears that increase of topographical cortical representation of the muscle above the amputation area may alter motor control strategy of the muscle to compensate limited number of motor units as well as muscles that can provide movement of the joint [16]. However, it has also been reported that the extent of sensory reorganization in amputees is correlated with the degree of phantom pain [7]. Siemionow and Mendiola [17] suggested that with consistent stimulus, motor training, accompanied by visual feedback, the myoelectric prosthesis has favorable effect on cortical plasticity. This study investigates potentially powerful training that may be administered before double-upper extremity transplantation to induce beneficial plasticity of sensorimotor cortex in bilateral handless humans.

Could it be possible that a person born without upper limb (or hands) is able to control a limb transplanted in his/her adult age? Is our brain able to update body sensory and motor representation and to form sensory as well as motor representations of the newly replanted limb or a part of it and how will they be incorporated into existing body representations? Unfortunately there is no strong evidence in literature that human cortex, especially the motor cortex, is so plastic that it would be able to control functionally relevant movement of the transplanted upper extremity in humans with congenital upper extremity transverse deficiency, which is the most important lawful and medical requirement for such kind of transplantation. However, recent research indicated amazing human sensory cortex plasticity and capability. Findings of Guterstam et al. ([20]) indicate that human body does not seem to be the fundamental constraint on which we can experience as our physical self. The authors showed that the body sensory representation can be updated to incorporate even an additional limb, and the illusion of owning a third hand induces the cortical reorganization. In our opinion results of presented studies [21,22] indicate that brain always adapts to new inputs from the environment and provide some premises to expect that the sensorimotor cortex is plastic to the extend that would give hope to bilateral handless people to train their brain before transplantation to