Robotic image-guided transcranial magnetic stimulation

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Abstract. This paper presents a new robotic system for automated image-guided Transcranial Magnetic Stimulation (TMS). TMS is a non-invasive technique that is currently being developed for the treatment of important pathologies such as depression. This stimulation technique requires an accurate positioning of a magnetic coil in order to induce a specific cortical excitation. The doctor currently positions the coil manually by means of a navigation system, which does not allow a precise clinical evaluation of the TMS procedure. In this paper, a novel robotic design is therefore proposed which aims at replacing the neurologist during a TMS session. The proposed robot architecture satisfies simultaneously the safety and accuracy requirements associated to the gesture, which allows the development of autonomous procedures.

Keywords: robot design, control, neuro-navigation, transcranial magnetic stimulation, treatment of neuro-pathologies.

1. Introduction

1.1 Motivation

Transcranial Magnetic Stimulation (TMS) is a new non-invasive method allowing to deliver an electric stimulation to the cortex. With this technique, a cortical excitation is created using a train of magnetic impulses emitted by an external stimulation coil. Its efficiency has been demonstrated in the case of depression (see [1] and [5]), and studies are currently conducted for other pathologies like post-traumatic anxiety, compulsive obsessive disorders, schizophrenia and even some kinds of epileptic disorders [3].

Even if the applicability of this technique seems very promising, it is not yet widely accepted because of the observed variability of efficiency between patients. This is partly due to the problem of defining right stimulation parameters (frequency [6], intensity of magnetic impulse trains). It is more essentially due to the difficulty of the gesture with stimulation systems that are available today which leads to a poor repeatability. Indeed, in the current procedures, once the target area of the cortex has been defined using functional MRI images, the magnetic stimulation coil has to be manually moved on the head of the patient by the neurologist to follow an accurate trajectory in space. Even if a visual feedback is provided to the neurologist by a navigation system to facilitate the positioning of the coil (see [2]), no precise motion can be practically achieved. Furthermore, a manual treatment of the patient cannot be considered in a clinical routine because of the duration of stimulation sessions, in the order of 30 minutes.

A robotic system is therefore needed to perform a reliable efficiency evaluation of the TMS procedure, as well as a workflow compatible with a medical gesture.

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1.2 Existing work

To our knowledge, little work exists on robotised transcranial magnetic stimulation. Peter Fox from the University of Texas Health Science Center at San Antonio has initiated a research project for which a Neuromate robot is used to hold and move the magnetic coil under the guidance of a neuro-navigation system [9]. However, the Neuromate robot was originally designed for minimally-invasive surgical procedures of the brain like, e.g., brain biopsies. In our opinion, such a robot is not adapted to move a probe around the head in contact with a patient who is not anaesthetised and could potentially move his or her head. Moreover, no control of the contact effort is provided. Similarly, the robotised system of [10] is based on a standard industrial robot, incompatible with the safety requirements of a medical gesture. A vision-based control has been implemented without any contact force evaluation.

Other medical robotic systems exist, which move probes in contact with the patient like, for example, robots developed for tele-echography applications [8]. However, these systems are used on soft tissues without the kind of precision required in TMS procedures and without automatic image-based guidance.

1.3 A new robotic design

In this paper, we propose a novel robotic system allowing a reliable clinical evaluation of the TMS procedure. The proposed robotic system also aims at replacing the neurologist during a TMS session. It therefore fulfils the constraints associated with an autonomous procedure.

The proposed robot architecture is a redundant seven-degrees-of-freedom serial structure that enables the treatment of the whole cortex. It satisfies simultaneously safety and accuracy requirements associated to the gesture.

2. The medical constraints

As introduced previously, the robotic device aims at replacing the arm and the hand of the neurologist during the complete stimulation session. Since the medical gesture is not invasive, the system does not need to satisfy sterility constraints. However, the system will have to work in a fully automatic mode, thus several safety and medical constraints have to be considered.

The medical gesture consists in positioning the magnetic stimulation coil on the head of the patient. A typical design of a coil is a figure-of-eight shape with a planar surface of contact with the patient head. Different models of the electrical field induced in the brain have been proposed (see [4], [7], [11]). They consistently demonstrate that the electrical excitation of the brain tissue is maximal along the line that is orthogonal to the contact plane and goes through the coil centre with a decrease function of the distance to the coil centre. Since a thin layer of air between the coil and head induces moreover a significant loss of effectiveness, the positioning is consequently considered to be composed of three tasks:

- The contact must be ensured between the stimulation coil and the head of the patient. The centre of the coil can be placed during a treatment in the area covered by the hair as well as the forehead and the temples.
- The coil plane needs to be tangent to the head.
- The orientation of the coil has to be precisely controlled since the cortical response to the stimulation is the highest when the induced electromagnetic field is oriented parallel to the cortical columns [7].

The stimulated zone must be controlled with an accuracy in the order of 1 millimetre. This implies a positioning accuracy of the centre of the coil being less than 1 millimetre and an orientation accuracy of the coil plane being less than 1 degree.

The patient security implies the definition of a maximum threshold for the force applied on the skull (~2.5N). In addition to that, since the patient is not anesthetised, he is susceptible to move his head during the TMS session. Consequently, the system has to be able to detect such movements and to act properly. Moreover, since a complete session of TMS can last more than half an hour, it is necessary to design an architecture which is comfortable for the patient. Therefore, the force applied to the skull by the coil has to be as small as possible.

Finally, concerning the kinematics and dynamics constraints, the operational speed during stimulation is about 0.05mm/s and the coil weighs approximately 1.5kg.

3. The robotic system and associated workflow

3.1 The robotic system

The proposed robotic system is based on the analysis of the previously described medical constraints. As a result, it is composed of three subsystems, according to the three tasks previously described for the coil positioning. This makes it possible to simplify the control of the system while increasing the safety of the patient.

Since the workspace is almost spherical, the first subsystem allows accurate positioning of the coil centre on a sphere centred on the head of the patient. It is performed by a serial spherical manipulator with 3 degrees of freedom (Fig. 1). This structure has been chosen redundant so that a highly acceptable manipulability can be obtained over the whole workspace. This latter is also obtained without any interference with the patient. Due to the weight of the stimulating coil, an original architecture based on circular guides has been designed to optimise the robot stiffness.

The second subsystem is dedicated to the control of the coil/head contact. The proposed architecture is a simple actuated prismatic joint combined with a force sensor directly placed inside the central part of the coil casing. The use of a sensor which is not sensitive to the magnetic field enables us to place it as close as possible to the contact area and therefore to directly measure the force exerted on the skull. No indirect compensation is therefore needed in the control algorithm. Using a vision-based head position measurement, a hybrid position/force control scheme will be implemented to guarantee the security of the patient.

The third subsystem aims at maintaining the coil tangent to the head surface during the stimulation and orientating it in order to follow the cortical columns. This is achieved by a serial spherical wrist. Two circular guides with orthogonal axes have been chosen in order to allow rotation around a fixed point without any rotary joint. This centre of rotation is the contact point between the coil casing and the head of the patient. These two degrees of freedom of the structure guarantee the tangency of the coil with the skull without changing its centre position. The last degree of freedom is directly controlled to follow the cortical columns direction.

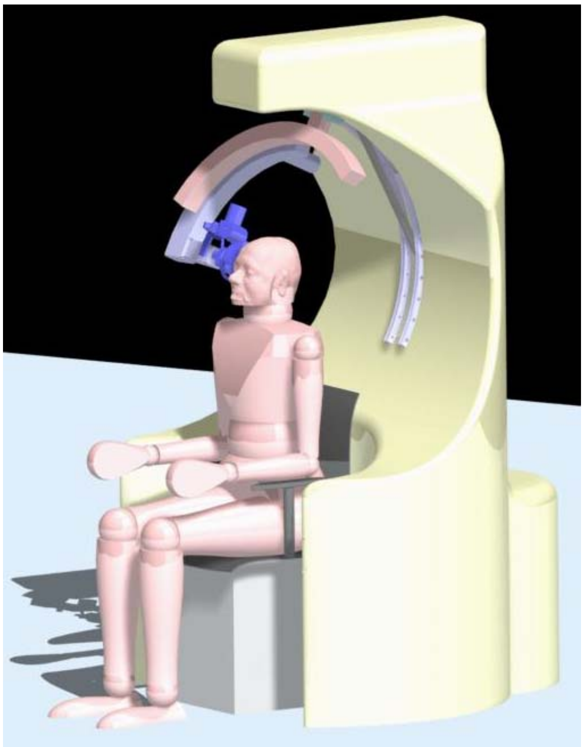

Fig. 1. The CAD model of the robot.

3.2 The associated workflow

The workflow of a robotized TMS procedure is conceptually the same as for manual procedures. However some additional tasks are necessary to allow an autonomous stimulation session. The first steps aim at preparing the stimulation session. Then the patient is placed before the autonomous execution of the process:

- Firstly, different MRI and fMRI images are recorded which are used to build a 3D model of the brain of the patient and its head.
- Secondly, the neurologist specifies the cortical regions to be stimulated and their orders. For each of them, he defines the frequency as well as the duration of the stimulation.
- Thirdly, the neuro-navigation system computes the trajectory of the coil centre on the head that best stimulates each region allowing for the required specifications.
- Fourthly, the patient is placed under the robotic system and a registration of his or her head with the robot and the 3D model is carried out.
- Finally, the stimulation procedure is executed autonomously enabling the head movements of the patient. In the mean time, the actual location and orientation of the coil are recorded for a post-procedure analysis.

The neurologist may repeat exactly the same automatic stimulation procedure as many times as prescribed by the treatment. Moreover, he does not need to be present during the stimulation session since an assistant can carry out the installation of the patient.

4. Conclusion

In this article, a novel robotic system is proposed for transcranial magnetic stimulation. It enables to move automatically a magnetic stimulation coil on the head of the patient in a safe manner. The robotic system and the proposed workflow enable to fulfil the medical constraints.

In the future, this robotic system will be completed by algorithms for 3D head reconstruction from pre-operative MRI images, planning and simulation of the magnetic stimulation procedure. We plan to use the robotic TMS system to clinically validate the therapeutic effects of TMS on different pathologies such as depression, schizophrenia or maniac disorders and so to precisely define the indications of TMS.

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