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METHODOLOGY FOR THE SELECTION OF A SMART MATERIAL AS ACTUATOR IN NEUROSURGICAL ROBOTICS

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Summary. *In this article we define the criteria and present the methodology to choose a smart material in order to actuate a soft neurosurgery robot. These criteria are defined with the experience of a neurosurgeon.*
Key words: *smart materials, neurosurgical robotics, specifications.*

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Statement of the problem. So-called invasive neurosurgical robots, i.e. those that penetrate inside the patient's brain, are developed to help the surgeon reach the treated areas by progressing along paths that are not necessarily rectilinear. The specificity of interventions in the brain compared to more general medical robotics is that the systems designed must move within the heterogeneous organ's matter while minimizing the pressure and damage exerted to preserve the organic functions for the patient (1, 2). The use of smart materials, responding actively to external stimuli, is a promising way to actuate these systems. However, there is a wide variety of materials that can a priori be used (several dozen). Defining a methodology for evaluating these materials based on the clinical experience of the neurosurgeon is an essential step towards the design of invasive neurosurgical robots.

Analysis of the available investigations. A major obligation during a neurosurgical operation is to minimize the impact of the operation on the brain as much as possible, in order to improve the benefit-risk balance for the patient. It is therefore natural that robotics finds its place in this field. Robots external to the patient, such as Tool Holder type robots, e.g. the NeuroMate (3), make the neurosurgeon's work easier and safer by filtering out involuntary movements, such as tremors. But despite the development and marketing of this type of device for neurosurgery, some patients remain inoperable due to the difficult localization of the fault zone. Indeed, although robotics has contributed to the progress of neurosurgery, there is still no commercially available neurosurgical device that can follow paths other than straight lines, making certain areas inaccessible. Furthermore, new information on the architectural organisation of white matter, i.e. the connecting bundles, makes it sensible to respect these highly functional elements that connect the grey, cortical and deep matter regions. Hence the need to develop a neurosurgical robot, capable of progressing in the brain along non-straight paths, has arisen.

Various types of technologies have been recently investigated:

- The needles with bevel tip. The bevel allows the needle to follow a curved path thanks to the contact forces with the surrounding material (4).
- The pre-curved concentric tubes (5). They have the advantage of having small dimensions and being able to follow complex paths. They are pre-stressed tubes that are fitted together at the initial moment before deployment, and bend when they are slid together. The sensitive point for an application in neurosurgery is friction, which can create an unstable energy accumulation. In addition, the offset motorization of the tubes upstream of the system can take up a significant amount of space in the operating room, and the available internal space is restricted due to the initial interlocking of the tubes.
- Using a magnetic tip (6). This concerns a guide with a magnetic distal end for curved paths. It needs a magnetic generator to be actuated, taking a lot of space and still expensive.
- Active cannula. This a kind of needle incorporating a shape memory alloy for arc curved bend shapes (7).

To our knowledge, no studies have yet been carried out on the construction of different material selection criteria in order to design optimally functioning systems for neurosurgical tasks.

The objective of the work is to set a milestone by developing an experience-based methodology for the evaluation of smart materials in this context.

Statement of the task. In this article, we will formalize the requirements resulting from neurosurgical clinical experience. These requirements are then used to select smart materials with high potential.

Neurosurgical task. The term neurosurgery refers to operations on the central nervous system and peripheral. In our application we will focus mainly on the central nervous system, and more specifically on the brain. For a neurosurgery operation, the patient must first undergo an MRI, in order to visualize the area to be reached, but also to define the path to be taken to reach it. The main tool during a neurosurgery operation is the stereotactic frame, which is screwed directly onto the patient's skull and which will create a coordinate marker to be able to insert the neurosurgeon's tools precisely into the brain. These tools can be, for example, electrodes, which are inserted deep into the brain to stimulate part of the brain and stop tremors that some patients may suffer from. It is also possible to insert a clamp to perform a biopsy.

Based on this, and in discussion with the personnel of the Clermont-Ferrand University Hospital, we defined the systemic constraints (requirements) resulting from their experience and that an interventional robot will have to fulfil once in clinical situation. These are listed in the following table 1.

Table 1

Requirements for invasive neurosurgical robotics

Biocompatibility	
Possibilities for sterilization:	one of these: • 100°C temperature • steam under 6 bars pressure • UV • sterrad (low-temperature gas) • single use
No chemical exchange with brain tissue	
No lubrication	
No internal angles	
Technical specifications for the robot	
External diameter	6 to 12 mm (same order of a drill hole)
Inner diameter left empty for biopsy tube	2.6 to 3.6 mm
Aiming progression speed	0.5 cm/s
Reactivity	< 1 s
Operating temperature	< 40 °C
Accuracy	1 mm width envelope from the planned path
Manufacturing	
Possibility to manufacture in any desired shapes	
Price	
Easy mass production	

In addition to these constraints are those related to the internal functioning of the robot: the system must integrate its power and information transmission system. The problem of the local curvatures that the system can reach is directly linked to path tracking and therefore to the possibilities of trajectories offered to the surgeon. The maximum penetration force of 5 N (8) is provided by an external pushing actuator, smart material actuators then ensure the positioning of the distal part in the correct direction and also the overall deformation of the instrument to limit the contact forces with the tunnel wall created in the matter.

Smart material selection. The design of the robotic system can rely on a composite silicon matrix that conducts electromagnetic signals carrying information and power to precise positions (actuator, sensor, etc.). We reviewed and classified smart materials that could be used as actuators, and it helped us to exclude some of them based on the way of activation:

- Heat (shape memory alloys and polymers plus some liquid crystal elastomers), since temperature is too high for the brain.

- Chemical reaction (pH and ox-red reactive), because of risk of reaction with brain matter.
- Fluidic, pneumatic-type actuators, whose volume variations may cause brain damage, not to mention the risk of fluid exhaust or explosion.

A second selection based on mechanical properties was then done:

- Smart materials activated by light (polymers and gels, liquid crystals with azobenzene and chromophores) (9):
  - allow to save space because one could just use an optical fibre to lead the light,
  - shape memory polymer with photoreactive molecules has good bending ability,
  - but reactivity is too slow: 10 s to several min.
- Smart materials activated by magnetic field (polymers/gels with embedded magnetic particles, magnetorheological,…) (10):
  - good reactivity: 0,6s (11,12),
  - good size: µm-mm (13),
  - good bending ability (12),
  - no need of wire to lead the energy of actuation,
  - but need 0.5 to 1.5 T (14). This is high for a utilization by the neurosurgeon, and the magnetic generator takes a lot of space in the surgical room.
- Smart materials activated by power supply voltage:
  - piezoelectric: too small bending ability,
  - dielectric fluid: activation with a too high voltage of 1–10 kV,
  - Ionic Polymer Metal Composite:
    - low voltage 1–5 V (15, 16),
    - high bending ability (16),
    - size: µm-cm (15–17),
    - many possibilities to manufacture it, in any desired shape by 3D printing (18),
    - possibility to use simultaneously as sensor (15).

With all these considerations, we chose Ionic Polymer Metal Composite. It is a kind of electroactive polymer, made of an ionomer or an ion exchange polymer (as Nafion): a polymer reacting to electric potential difference, covered with noble metal (19).

Conclusions. We have established selection criteria to help us choose a smart material from which to design a robotic system in the future. The specifications eliminated many of the materials such as those that use heat, as most operate at 70°C or more. Light-activated materials were also excluded because of their reaction time of more than several seconds. Pneumatic-type actuators, whose volume variations and leakage may cause brain damage, are not suitable for our application. Those based on liquid materials or operating by means of acid-base or redox reactions cannot be used for our project because of the risk of leakage and interaction with brain matter. For magnetically actuated materials, the problem is the order of magnitude of the magnetic field required between 0.5 and 1.5 T. This leaves us with the materials using potential differences, among which ionic polymer metal composites are a promising candidate.

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МЕТОДОЛОГІЯ ВИБОРУ РОЗУМНОГО МАТЕРІАЛУ ЯК ПРИВОДА В НЕЙРОХІРУРГІЧНІЙ РОБОТОТЕХНІЦІ

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Резюме. *Так звані інвазивні нейрохірургічні роботи, тобто ті, що проникають всередину мозку пацієнта, розроблені, щоб допомогти хірургу дістатися до оброблених ділянок, просуваючись по шляхах, які не обов'язково прямолінійні. Специфіка втручань у мозок порівняно із більш загальною медичною робототехнікою полягає в тому, що розроблені системи повинні рухатись у речовині гетерогенного органу, мінімізуючи тиск та пошкодження, що здійснюються для збереження органічних функцій пацієнта. Використання розумних матеріалів, активно реагуючи на зовнішні подразники, є перспективним способом активізації цих систем. Однак існує велика різноманітність матеріалів, які апріорі можуть бути використані. Визначення методології оцінювання цих матеріалів на основі клінічного досвіду нейрохірурга є важливим кроком до проектування інвазивних нейрохірургічних роботів. Метою роботи є аналіз і обґрунтування на основі методології досвіду застосування розумних матеріалів. У цій статті формалізовано вимоги, що випливають з нейрохірургічного клінічного досвіду. Потім ці вимоги використовують для вибору розумних матеріалів з високим потенціалом. Встановлено критерії вибору розумного матеріалу, з якого в майбутньому можна буде розробляти роботизовану систему. За технічними характеристиками багато матеріалів відпали, зокрема такі, що використовують тепло, оскільки більшість з них працюють при температурі 70°C або більше. Матеріали, що активуються світлом, також були виключені через час реагування, що складав більше кількох секунд. Приводи пневматичного типу, коливання об'єму та витік яких можуть спричинити пошкодження мозку, теж не підходять для такого застосування. Ті, що базуються на рідких матеріалах або діють за допомогою кислотно-основних або окисно-відновних реакцій, не можуть бути використані для цієї мети через ризик витоку та взаємодії з речовиною мозку. Для матеріалів з магнітним приводом проблема полягає в необхідному високому значенні величини магнітного поля, від 0,5 до 1,5 Тл. Для привода запропоновано застосовувати матеріали, що використовують різницю потенціалів, серед яких перспективним кандидатом є іонні полімерно-металеві композити.*

Ключові слова: *розумні матеріали, нейрохірургічна робототехніка, технічні характеристики.*

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