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Characterization of Suction and CUSA Interaction with Brain Tissue

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Abstract. Basic and ultrasonic aspirators are the most commonly used surgical devices in neurosurgery. In this study, a tissue removal model was adjusted to experimental results of interaction between ultrasonic aspiration and brain tissue-mimicking material. Tissue grasping with a basic aspirator was also further investigated on fresh calf brain tissue obtained from several animals. Tests were conducted on both grey and white matter. The simulation screenshots, compared with the experimental photos, are presented to demonstrate the results.

1 Introduction

Surgical aspirators are one of the most widely used surgical devices in neurosurgery [1,2,3]. Reports on the interaction of aspirators with tissue are scarce and do not provide enough information to develop a suitable model for simulation purposes [4,5,6]. Surgical aspiration is achieved using suction through a tube. The tube includes a keyhole allowing for vacuum pressure to be controlled by the surgeon's thumb. This basic aspirator has three main functions: (1) it can remove liquids, such as blood or cerebrospinal fluid [7]; (2) at low vacuum pressure it can grasp soft tissue [1]; (3) at higher vacuum pressure it can remove some soft tissues [8].

Ultrasonic aspirators, such as the Cavitron Ultrasonic Surgical Aspirator (CUSA) which is commonly used in neurosurgery, are also used to remove tissue that is too stiff to remove with a basic aspirator mentioned above. A general overview of the ultrasound technology in surgery is given in [9]. Briefly, the ultrasonic aspirator differs from the basic aspirator in its ability to generate a high frequency vibration, which liquefies soft tissues in the vicinity of its tip. The liquefied tissue is then removed with vacuum pressure inside the tip. Irrigation is used for tool tip cooling and tissue select allows the surgeon to selectively fragment tissue based on its stiffness. A console is used to control CUSA parameters: vibration amplitude, vacuum pressure, irrigation and tissue select. Unlike the basic aspirator, the CUSA is not used for tissue grasping. It is solely used for the removal of liquids and soft tissues.

A mathematical model of interaction between soft tissue and a basic aspirator has been proposed [10]. This model, comprised of three equations, predicts the

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grasping and tissue removal behavior of the tool: First, the profile of the grasped tissue in the vicinity of the tool tip is given by

$$||\boldsymbol{u}(r)|| = \frac{h^2}{h + \alpha r^3} \tag{1}$$

where $h = ||\boldsymbol{u}(0)||$, r is the distance between a point on the plane $\mathcal{P}$ tangent to the undeformed tissue surface and the projection of the tool tip center $\boldsymbol{c}$ on that plane, and α is a material parameter (see figure 1).

Second, the reaction force applied by the grasped tissue to the tool tip is given by

$$f(h) = -\beta h^2 \boldsymbol{n} \tag{2}$$

where β is a material parameter and $\boldsymbol{n}$ is a unit vector normal to the plane tangent to the undeformed surface.

Third, the tissue removal behavior of the tool is given by

$$F_{new}(\boldsymbol{x}) = \min(F_{old}(\boldsymbol{x}), ||\boldsymbol{x} - \boldsymbol{t}|| - D/2) \tag{3}$$

where $F_{new}(\boldsymbol{x})$ and $F_{old}(\boldsymbol{x})$ are the current and previous values of the zero iso-surface of a distance field defining the tissue boundary, $\boldsymbol{x}$ is a point in space, $\boldsymbol{t}$ is the position of the tool tip and D is the diameter of a cutting sphere.

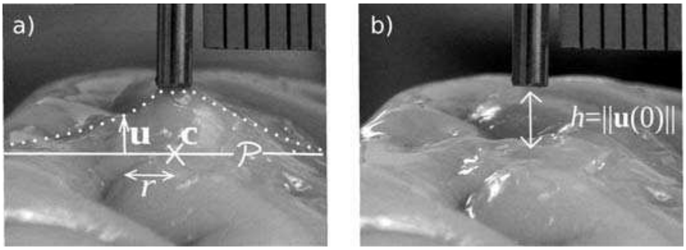

Fig. 1. Definition of h, $\boldsymbol{u}$, r and $\boldsymbol{c}$ in the model [10]

The first objective of this study is to adapt the proposed tissue removal model to the ultrasonic aspirator. Specifically, the parameter D of equation 3 was not characterized and it is likely to depend on tool settings for the ultrasonic aspirator. A second objective is to address some of the limitations discussed in the study [10] such as the fact that the grasping model was adjusted to experimental data obtained from a single specimen of a thawed calf brain and was limited to grey matter. In this study, the proposed grasping model will be characterized on fresh brain tissue obtained from several animals. Furthermore, the behavior of both grey and white matter will be investigated, as there is experimental evidence that the mechanical response differs between grey and white matter [11,12].

2 Methodology

2.1 Tissue Removal

Access to the ultrasonic aspirator was granted to the investigators in this study with the restriction that it be used only on non-biological materials. As such, tissue-mimicking phantoms as in [10] (12.5% mass concentration dessert gelatin) were used in the tissue removal tests with the ultrasonic aspirator. The CUSA EXcel^{TM} system (Radionics, Burlington, MA) with a 36 kHz handpiece was used. The measured tool tip inner diameter was 0.94 mm. The maximum amplitude according to the manufacturer's specifications was 210 μm, and the maximum vacuum pressure was -660 $mmHg$. The tests were carried out for each combination of three levels of vacuum pressure (10%, 30% and 60%) and three levels of vibration amplitude (10%, 30% and 60%), all expressed as a percentage of the maximum. Each test was done three times. The maximum setting was also tested once. The irrigation was held constant at a rate of 2 cc/minute. The tissue select was set for "standard". Each test was conducted using the following methodology:

1. The material sample was positioned on a movable platform underneath a CUSA (which was held at a fixed position and pointing down).
2. A combination of vacuum pressure and vibration amplitude was selected.
3. The platform was raised until the sample either completely obturated the tube tip or was sucked in by the vacuum pressure.
4. The platform was lowered to its original position once tissue was no longer removed.
5. The diameter of the resulting pit on the tissue surface was measured.

The pit diameter was modeled using the following non-linear model:

$$D(p, A) = c_1 + c_2 p + c_3 A + c_4 p A \qquad (4)$$

where p is the vacuum pressure (in percentage of maximum), A is the vibration amplitude (in percentage of maximum) and c_i are parameters that are dependent on material properties and tool tip geometry. They were adjusted to the experimental data using the multiple regression module of NCSS statistical software. The coefficient of determination (R^2) was used as a fitting criterion.

2.2 Tissue Grasping

Brains from three calves were obtained from a slaughterhouse, transported in phosphate buffered saline (PBS) and tested within three hours of harvesting for each experiment. Each brain was cut in two hemispheres and the brain stem was removed, while preserving pia mater. One hemisphere per animal was used in the grasping tests.

The grasping tests were carried out with the basic aspirator using a similar setup and methodology as described in [10], shown in figure 2. The tests

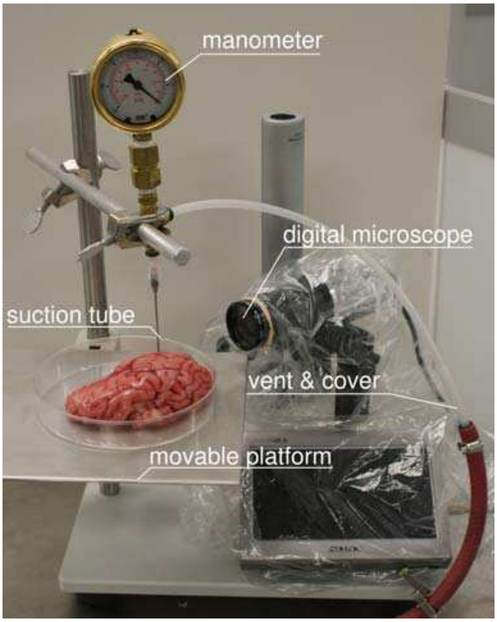

Fig. 2. Experimental setup

were conducted on the surface of the three brain hemisphere specimens at room temperature. Each specimen was kept moist with repeat PBS irrigation. The behavior of grey matter covered by pia mater was measured on 11-21 areas along the convexity of the brain.

The pia mater was then grasped and lifted at a sulcus. In these areas the pia mater is less adhering to the brain tissue. An incision was made using microscissors. The pia mater was gently peeled away from the surface of the brain tissue. Only areas with no visible damage were used for testing. The tests were repeated on 4-7 areas of exposed grey matter. The hemisphere was then flipped over to repeat the test on 5-10 areas of the white matter.

Grasping tests were not performed with the ultrasonic aspirator. It was assumed that when vibration is off, the ultrasonic aspirator behaves like a basic aspirator.

3 Results

Pit diameters in the gelatin specimens are presented in table 1 with respect to vacuum pressure and vibration amplitude. After excluding one outlier (observation 15), a model (equation 4) yielding $R^2 = 0.784$ was obtained with $c_1 = 2.6$, $c_2 = 0.052$, $c_3 = -0.0024$ and $c_4 = -0.00030$.

Figure 3 shows the predicted pit diameter plotted against the observed pit diameter values.

Table 1. Experimental tissue removal results on gelatin with CUSA

Obs.	Vacuum pressure (%)	Vibration amplitude (%)	Pit diameter (mm)
1	10	10	2.8
2	10	10	3.1
3	10	10	3.2
4	10	30	2.8
5	10	30	2.9
6	10	30	3.0
7	10	60	3.0
8	10	60	3.1
9	10	60	2.9
10	30	10	4.3
11	30	10	4.2
12	30	10	3.6
13	30	30	3.5
14	30	30	3.5
15	30	30	2.3
16	30	60	3.4
17	30	60	3.7
18	30	60	3.7
19	60	30	6.0
20	60	30	5.6
21	60	30	5.0
22	60	60	3.6
23	60	60	3.7
24	60	60	3.9
25	100	100	5.0

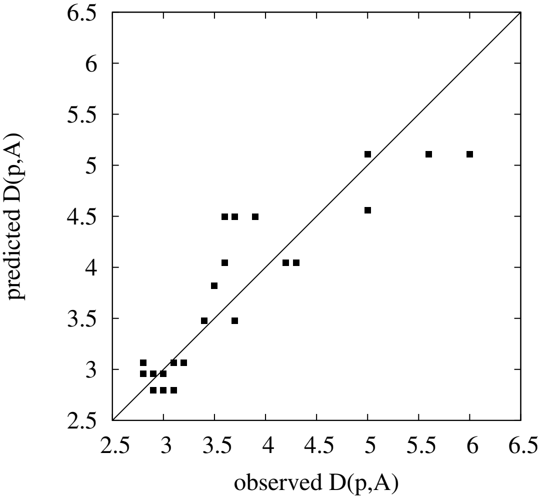

Fig. 3. Predicted vs observed pit diameter (see equation 4)

Deformation profiles $||\boldsymbol{u}||$ as a function of r are shown in figure 4 (a, c, e) for the three tissue types. The deformation profile material parameter (α) was determined for each type of tissue by fitting the experimental data with equation 1, where $\alpha_{\text{grey matter with pia}} = 0.234$ with $R^2 = 0.973$, $\alpha_{\text{grey matter}} = 0.922$ with $R^2 = 0.897$ and $\alpha_{\text{white matter}} = 1.361$ with $R^2 = 0.927$.

The tissue grasping force on the tool tip as a function of h is plotted in figure 4 (b,d,f) for the three tissue types. Experimental results from [10] are also plotted for grey matter with pia. The largest force on each graph is the force at which tissue rupture was observed, i.e. 70 kPa for grey matter with pia, 11 kPa for grey matter without pia and 20 kPa for white matter. The reaction force material parameter β was determined for grey matter with pia by fitting the experimental data to equation 2 where $\beta_{\text{grey matter with pia}} = 0.005$ with $R^2 = 0.793$. A linear fit, $f(h) = -\beta h\boldsymbol{n}$, was also investigated, which resulted in a lower value of $R^2 = 0.774$.

4 Discussion

The goal of this study was to further characterize a neurosurgical aspirator model developed in a previous study [10]. Specifically, to define the tissue removal model according to ultrasonic aspirator tool settings and by characterizing the grasping behaviour of a basic aspirator with fresh tissue.

The previous tissue removal model was developed for a basic aspirator (equation 3) where the value of D (diameter of a cutting sphere) was defined as a material property. In this study, the model was adapted to the ultrasonic aspirator by characterizing the value of D based on two of the four tool settings: (1) vacuum pressure (2) vibration amplitude. Studies on ultrasonic aspirator interaction with tissue have shown conflicting results. It has been reported that only vibration amplitude has an effect on tissue removal [13]. Another study has determined that both vacuum pressure and vibration amplitude work in synergy to optimize tissue removal [14]. The results from the present study indicate that the value of D is dependent on the ultrasonic aspirator tool settings. It was found that both parameters, including their interaction, have a significant effect on the observed pit diameter, which is in agreement with [14]. Another report [15] stated that the CUSA fragments and aspirates tissue within 1-2 mm radius from the tip which is consistent with this study. This can be seen in table 1, where the average from all of the observations excluding the outlier (observation 15) corresponds to a radius of 1.9 mm.

The second objective for this study was to further characterize the behavior of fresh grey and white matter with basic aspiration. Investigations on the biomechanics of brain tissue have shown that the properties of grey and white matter differ, but consensus has not been achieved on which of the two tissues is stiffer [11,12]. Based on our results in figure 4 (b, d and f), denuded grey matter experiences a larger deformation and ruptures at lower vacuum pressures. This indicates that grey matter compared to white is less stiff and easier to remove with basic aspiration. Comparison between figure 4 (b and d) clearly demonstrates that the pia mater has a significant effect on the mechanical properties

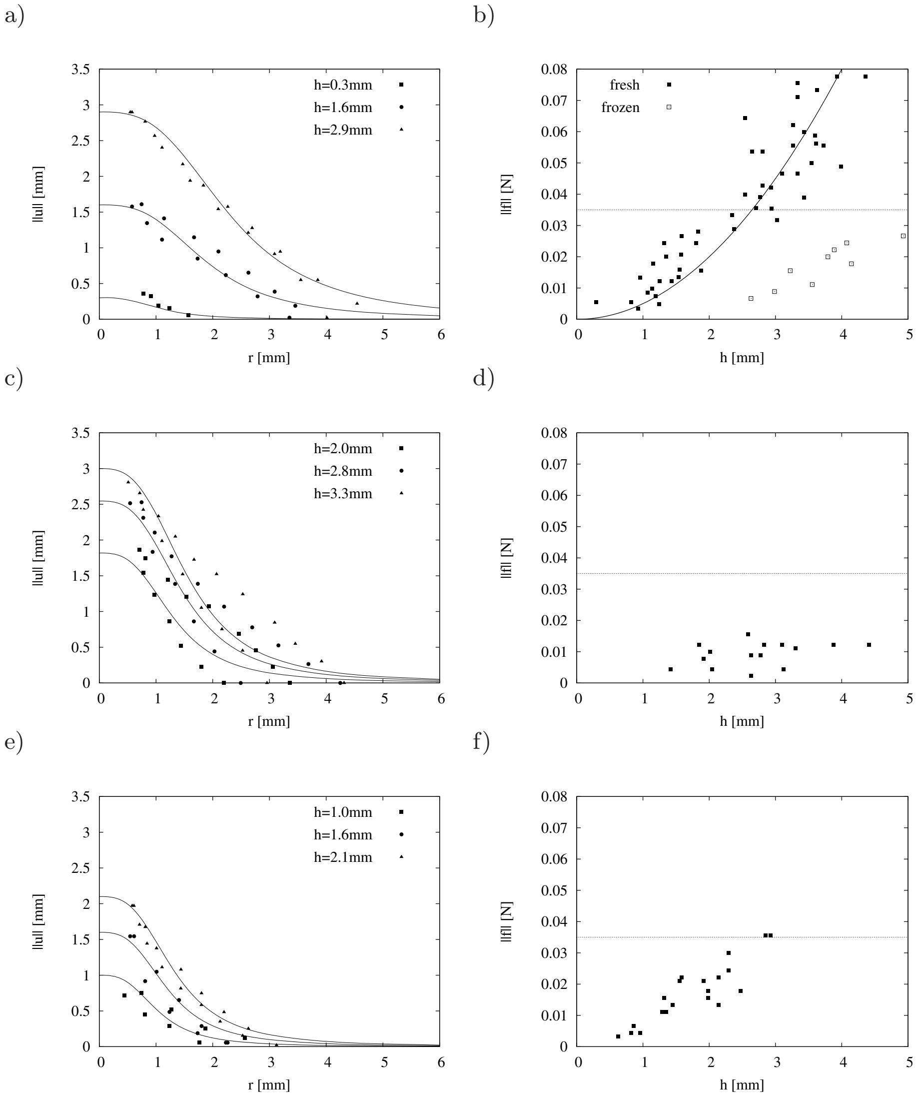

Fig. 4. Deformation profiles for different values of h for grey matter with pia (a), grey matter without pia (c) and white matter (e); Force as a function of h for grey matter with pia (b), grey matter without pia (d) and white matter (f). Solid lines represent the fitted models, and horizontal dashed lines represent the human touch perception limit.

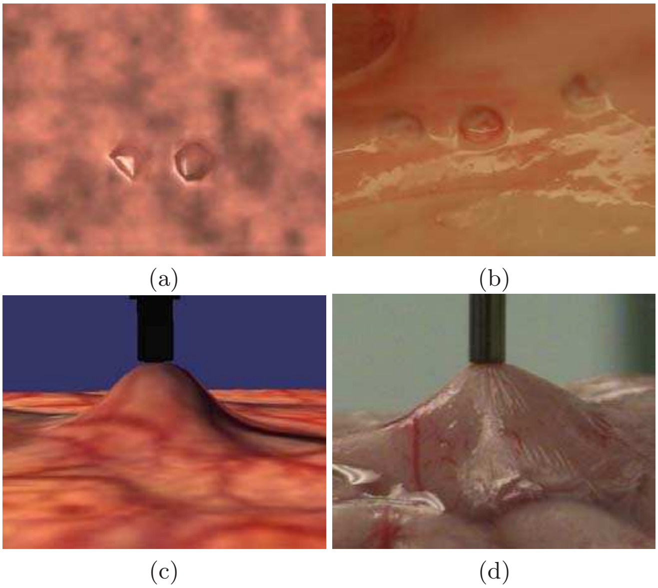
(a) (b) (c) (d)

Fig. 5. Simulation results on tissue removal and grasping compared to the corresponding experiment photos

of grey matter. The forces required to rupture grey matter with pia are approximately 4x greater than that required for grey matter alone. Human force perception limit is 10% of the weight of the object [16]. For a CUSA handpiece that weighs about 70 g, this limit is 70 mN. We assumed that a neurosurgeon with exquisite touch perception would not be able to detect a change of 35 mN in force applied on the CUSA. Given that the response of grey and white matter falls below this limit, it was not pertinent to model the forces felt at the tool tip with these tissues. It can be seen that forces can be felt for grey matter with pia at deformation heights approximately greater that 2 mm.

The information obtained from this study was used for simulating surgical aspiration interaction with brain tissue. The deformation profile models were implemented to simulate how brain deforms under the influence of basic aspiration, as can be seen in figure 5 (c and d). The simulated profile is different for each type of tissue. It varies according to the different α found for each type of tissue. Figure 5 (a and b) also demonstrates the simulation results for tissue removal. It can be seen that different tissue removal pit diameters can be achieved in simulation by varying the tool settings.

Based on the results it appears that the aspiration test is not sensitive enough to capture the small forces associated with deformation of white and grey matter. Further exploration using tensile tests will be done with the goal to improve precision of the reaction force equation. This study was limited in that tissue-mimicking phantoms were used to investigate the effect of ultrasonic aspirator parameters on tissue removal. As well, the diameter of the cutting sphere was not characterized for basic aspiration. Future experimentation for both will be conducted on fresh brain tissue.

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