

Preliminary study of a sensorized system for real-time feedback for arachnoid collapse during neurosurgical training

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Abstract— The transsphenoidal surgery approach is a new minimally invasive procedure used by neurosurgeons to treat pituitary adenomas. One of the most challenging aspects of the surgery is handling the arachnoid membrane when it starts collapsing, as it is a thin and fragile membrane that contains the cerebrospinal fluid (CSF). 3D-printed training models do not provide a system capable of mimicking the arachnoid collapse during surgery. This work reports the results of two tests on a specifically designed system capable of reproducing the arachnoid and the CSF within. The system consists of a jar filled with distilled water and sealed with a food film and a screw cap. In addition, a pressure sensor is inserted into the system to measure the change in pressure generated by an indenter connected to a load cell. The idea is to correlate the indentation force with the pressure variation. Data show a promising result in both tests, with a evident correlation between force and pressure. The first test shows a linear trend, with an $R^2 = 0.984$ for the loading phase and a $R^2 = 0.999$ for the unloading phase. The second test shows a linear trend with $R^2 = 0.954$ from the unloading phase, while as for the loading phase, it has a non-linear trend for values of applied force less than 1 N, which then tends to a linear trend above this value, with an $R^2 = 0.996$. However, there is a low repeatability when comparing one test with another due to the initial conditions of the food film, residual stresses and deformations once positioned on the top of the jar and closed by the cap, and probable pressure losses in the system.

Keywords—Surgical training model, transsphenoidal surgery training, pressure sensing, arachnoid.

I. INTRODUCTION

The endoscopic endonasal transsphenoidal approach (EETA) is a new minimally invasive procedure used by neurosurgeons to access the pituitary gland directly from the sella turcica, a saddle-shape protrusion on the back of the sphenoid bone [1]. The approach is used to remove pituitary adenoma (PA), a tumor that grows near the pituitary gland, within the sella turcica. One of the most challenging aspects of EETA is that PAs grow near to the arachnoid membrane; in fact, if the tumor is larger than 15 mm, it usually causes deformation of the arachnoid. The arachnoid

membrane is one of the three meninges and it consists of two parts: the external arachnoid barrier cell membrane and the arachnoid trabeculae, a spider web-like structure. The external barrier adheres to the dura mater, the outermost and thickest meninges attached to the skull, while the arachnoid trabeculae adheres to the pia mater, the innermost meninges attached to the brain [2]. The arachnoid and pia mater together form the pia-arachnoid complex (PAC). Within the arachnoid trabeculae, in what is called the subarachnoid space, flows the cerebrospinal fluid (CSF), a filtered plasma solution consisting of 99% water [3]. When the neurosurgeon starts removing a large pituitary adenoma, the arachnoid collapses within the sella turcica and it may cover the remaining of the mass. It is the pressure of the CSF, which commonly ranges from 10 to 15 mmHg for healthy adults [4] that causes the collapse of the arachnoid membrane inside the sella turcica. Therefore, the surgeon has to lift the arachnoid to proceed with the resection. Unexperienced neurosurgeons must learn how to interact with the arachnoid without breaking it to avoid a CSF leak that significantly increases the risk of meningitis for the patient. Nowadays, the best possible training in transsphenoidal surgery for residents consists of simulating an operation on human cadaveric heads. Even though this approach is the best suited to mimic real-life operating conditions, it involves great costs [5]. In this frame, 3D-printed training models are an alternative that has gained momentum in recent years [6]–[17]. Although they are not yet able to replace cadaveric heads, they have the advantages of being low cost and that they can be enriched with sensors that can monitor the forces and movements of the instruments, to enhance the simulation of the surgery providing direct feedback to the surgeon in training. However, the arachnoid collapse is something unfamiliar with both cadaveric and 3D-printed training models. In addition, in the literature, there are only studies regarding the mechanical properties of the PAC, since a separation protocol of the pia and arachnoid membranes has not been described yet, as pointed out in the systematic review of Walsh et al. [18]. In the work of Benko et al. it is described a procedure

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used to characterize the mechanical properties of the human PAC by inflating the membranes with saline solution to a pressure of 30 mmHg. The results obtained show some variability depending on the location where data were taken, the mean value of the inferior regions of the brain is 10.4 ± 4.2 kPa [19].

This work presents an initial non-anatomically accurate design of a sensorized system designed to replicate the arachnoid membrane and the CSF. The device is designed to provide direct feedback to surgeons as they practice lifting the arachnoid with real surgical instruments in a safe environment.

In the future, a more anatomically accurate design will be implemented on a 3D-printed training model to enhance the training experience for surgeons. The system will be tested by a team of experienced neurosurgeons who will determine an applicable force threshold value. In this way, surgeons will learn how to handle the arachnoid membrane before entering the operating room, thereby reducing the risks of surgery.

II. MATERIALS AND METHODS

A. Experimental Setup Description

The system developed to mimic the arachnoid collapse, consists of a jar filled with distilled water, with a screw cap on, in which a 30 mm hole has been cut. An additional hole was made in the jar to connect a pressure sensor to the system with a silicone tube. A piece of Domopak food film (Cuki Cofresco S.r.l., Italy) was used to mimic the arachnoid external membrane and was placed between the jar and the cap so that when the jar is closed, the film comes out. The thickness and the transparency of the food film make it a reasonable substitute for the membrane as, suggested by Harada et al. [20], where a PVCD film together with a water-insoluble tissue paper were used to mimic respectively the membrane and the arachnoid trabeculae. For this preliminary study, the arachnoid trabeculae were not reproduced. As previously mentioned, CSF is made of 99% of water, and it has a viscosity that is slightly different from pure water [21] in fact, for training models it is mimicked with saline solution [22]–[26]. In this work, distilled water was used to mimic the CSF as more convenient. The pressure sensor used has an operating range from 0 to 15 PSI (103,421 kPa) and, according to its datasheet has a 0.2 mV (0.09 kPa) of repeatability and hysteresis. The aim of the sensor is to measure the variation of pressure of distilled water inside the jar when an indenter presses the film. The indenter used during the tests has a diameter of 7.5 mm. It is connected to a computer controlled micrometric slide. With the provided software it is possible to control how the slide moves, as well as its speed and acceleration. A load cell is also used to provide feedback on the applied force and to correlate this data to the fluid pressure. Before starting the experiments, a static characterization of the load cell was carried out to obtain its calibration curve. This resulted linear ($R^2 = 0.999$) with a sensitivity of 4.35 N/mV. Fig. 1 shows the hereby described experimental set-up. The previously described sensors, presented both a full Wheatstone bridge configuration. In sake of simplicity, they were both supplied using the same regulated 10 V voltage source and measured using an HP34401a multimeter (Hewlett–Packard, Palo Alto, CA, USA) each. The two multimeters were then connected to

a PC and interfaced with a LabVIEW virtual instrument that samples them at 1 Hz.

B. Experimental Protocol Description

Two tests were designed to explore the response of the polymeric film to an external load through an indentation cycle. After the first test the polymeric film was changed in order to exclude the influence of any residual deformation that could impact on the results of the following test. Prior to the start of both indentation cycles, an initial pause was made in an unloaded state, to measure the offset of the load cell and the pressure sensor. Then the slide was slowly moved with steps of 0.2 mm until the load cell detected a variation of force. In this way it was possible to determine when the indenter entered in contact with the film. Once finished the preparation, the designed loading cycles started. For the first test a continuous load cycle was performed. The slide was programmed to descend of 0.25 mm, from 0 up to 3 mm of depth into the polymeric film with a 5 s break after each step. Then, after a 30 s delay the process was inverted and the slide rises of 0.25 mm in 5 s intervals back to the starting position. As second test (stepping load test), the indenter was programmed to perform a series of fourteen alternating descents and ascents with, with the slide movement going from 0 to 7 mm in 0.5 mm. After any descents and ascents, a delay of 30 s was performed. Lastly, after the last unloading cycle, a continuous descent was imposed to the slide till the polymeric film broke in order to measure its resistance. The force measured during the tests is comparable to the results of the studies conducted by Bekeny et al. [27], where a load cell was mounted on a curette during a pituitary tumor resection through an EETA surgery. And although the lift of the arachnoid membrane is not mentioned, it is reasonable to assume that the force required is similar to the values registered for soft tissues, with a mean value that ranges from 0.1 to 0.5 N.

III. RESULTS AND DISCUSSION

Three different graphs are presented for both tests. The first shows a plot of the Load Cell (N) and the Pressure Sensor (kPa) as a function of Time (s), to show the loading-unloading cycle. The second is a diagram of the Pressure Sensor (kPa) vs. the Load Cell (N) where data are divided from “Load” to

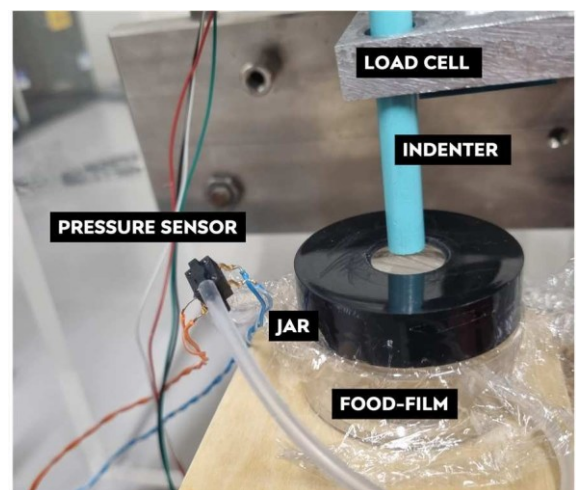


Fig. 1. The experimental set up ready. The pressure sensor is connected to the jar via a silicone tube. The indenter is connected to a micrometer slide on which a load cell is mounted.

“Unload”. Lastly, the third graph shows the Load Cell (N) and the Pressure Sensor (kPa) as a function of the Displacement (mm), i.e. the distance set to the slide. The values of the corresponding force and pressure in this graph are chosen at the peak of each descent. During both tests, no water losses were detected.

A. Continuous Loading Tests

Fig. 2 shows data measured by the load cell and the pressure sensor as a function of time. From the graph, emerge a clear correlation between the Load Cell and the Pressure Sensors, especially from $t=50$ s. Before that time the pressure sensors values registered are below its repeatability of 0.09 kPa. Moreover, both sensors present a progressive decrease of their output that is observed during the delay between loading and unloading phase. This effect is related to the viscoelastic nature of the polymer. In fact, when the slide is stationary, the indenter applies a constant strain on the polymer film that generates a stress relaxation phenomenon. The correlation between this two physical entities is showed in Fig. 3. From the plot emerges that there is an hysteresis phenomenon, underlining a difference of the output measured during the loading and the unloading phase. The hysteresis phenomenon is related to the limit of the pressure sensors. Beside the point at 1.6 N during the loading phase, both cycles show a linear trend. In fact, the coefficient of determination during the loading phase resulted $R^2 = 0.984$, while during the unloading is resulted $R^2 = 0.999$, thus suggesting a linear correlation. The displacement graph in Fig. 4 shows an initial non-linear correlation that converges towards a better linear correlation at higher pressures, where in the first part of the curve it is below its repeatability limit of 0.1 kPa.

B. Stepping Load Test

Fig. 5 reports the loading cycle and the obtained pressures on the fluid. As shown in the previous test, the correspondence between the two values is clear after the sixth loading/unloading cycle since before it the pressure measured is below the repeatability of the sensor. The effect of stress relaxation is evident immediately after each loading phase, as seen in the previous test. In Fig. 6 is reported the Pressure Sensor (kPa) vs. the Load Cell (N) of only the thirteenth cycle, to better understand the different behaviour of the polymeric film between the loading phase and the unloading phase. In Fig. 7 are reported the even-numbered test cycles from the sixth through the fourteenth plus the one to failure. The graph shows that the shape of each repetition is similar, even though it presents hysteresis, as already noted in the previous test. In addition, for force values greater than 1 N, the slope of the load cycle, including the failure, tends to be linear, with an $R^2 = 0.969$. In fact, below 1 N of the load cell, the corresponding pressure sensor data are close to 0.1 kPa, the repeatability of the sensor, which affects the measures. The unloading cycle has a linear slope with an $R^2 = 0.954$. Fig. 8 shows the displacement plot which shows a linear trend for the load cell while the pressure sensor has a non-linear trend below 0.1 kPa.

C. Test Comparison

By comparing the tests emerges a limited repeatability between similar applied loads that can be observed in Fig. 9.

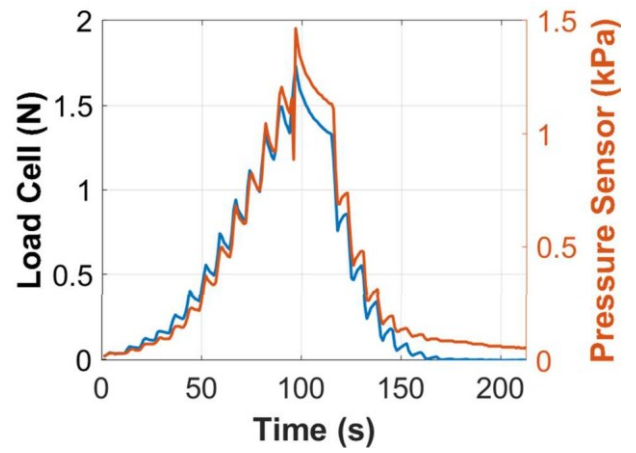


Fig. 2. Load Cell (N) and Pressure Sensor (kPa) reported as a function of Time (s) for the first test: load-unload cycle of 12 progressive movement of the slide, from 0 to 3 mm depth.

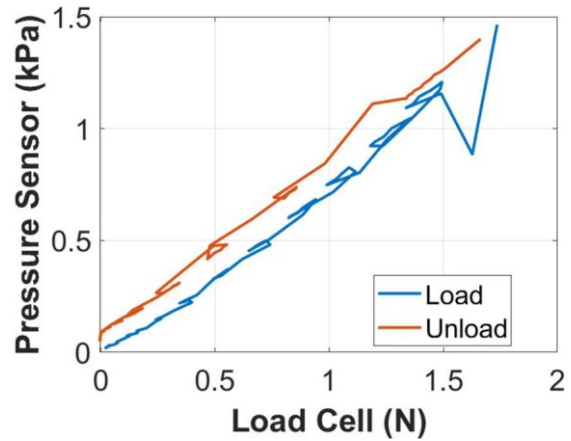


Fig. 3. Pressure Sensor (kPa) vs. Load Cell (N), the blue curve represent the loading phase, while the orange the unloading phase. The presence of an hysteresis loop is clear.

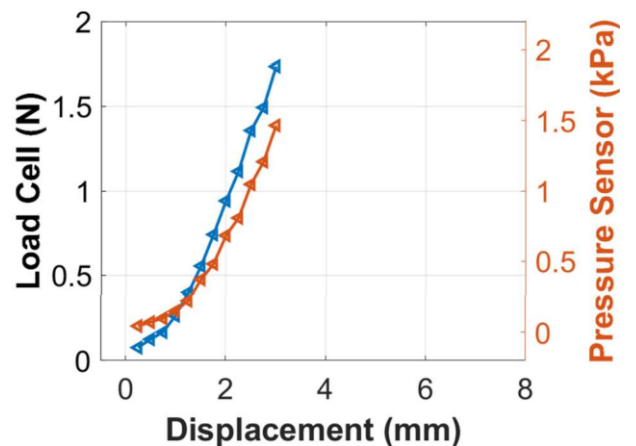


Fig. 4. Load Cell (N) and Pressure Sensor (kPa) as a function of the displacement (mm) during the loading phase. The first part of the pressure sensor curve is non-linear below 0.1 kPa.

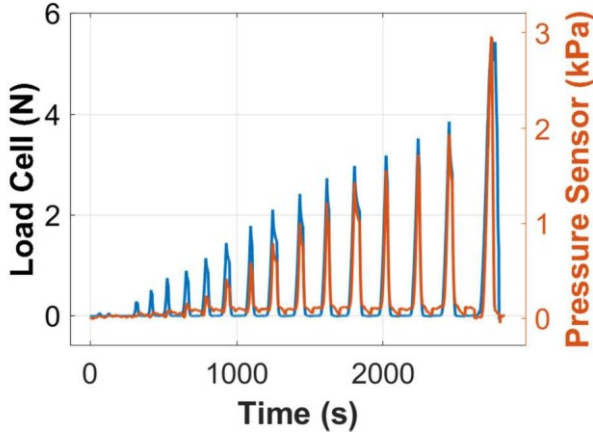


Fig. 5. Load Cell (N) and Pressure Sensor (kPa) reported as a function of Time (s) for the second test. A stepping load test from 0 to 7 mm depth plus the final rupture of the polymeric film.

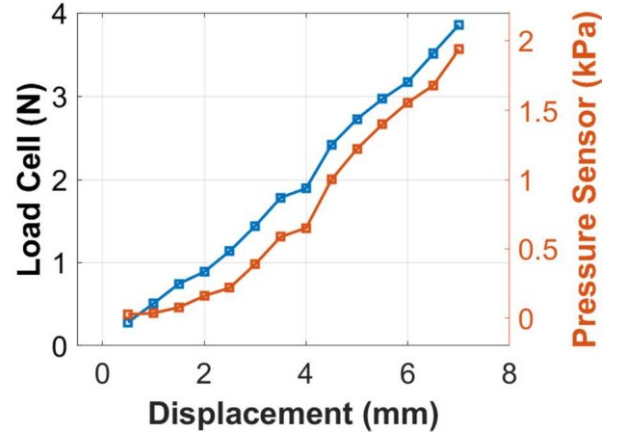


Fig. 8. Load Cell (N) and Pressure Sensor (kPa) as a function of the displacement during the loading phase. Data from the Load Cell are more linear.

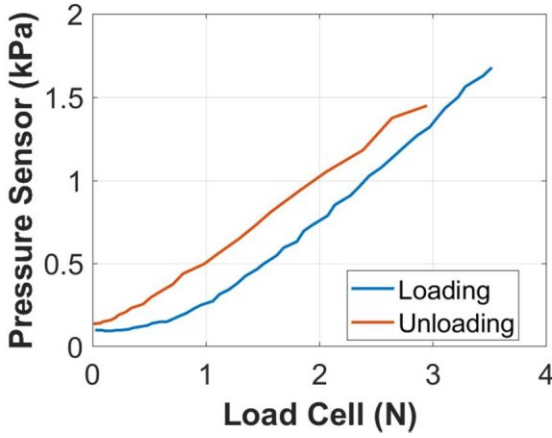


Fig. 6. Pressure Sensors (kPa) vs Load Cell (N) example of the second test. The lower part is the loading phase while the upper and more linear one is the unloading phase.

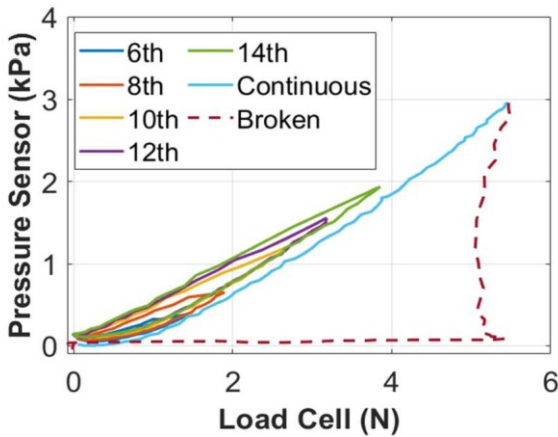


Fig. 7. Pressure Sensors (kPa) vs Load Cell (N) for the second test. Data show a clear hysteresis phenomenon. The “Continuous” and “Broken” curves show the last cycle where the film was broken by the indenter.

The initial condition of the film changes between tests, and this can cause the indenter's descent resistance to vary, which explains the low repeatability of the displacement curves, especially for the pressure sensor in Fig. 10. To improve the signal, it is planned to change the pressure sensor to one with a lower full scale. In addition, the low values measured by the pressure sensor could be due to pressure losses in the experimental setup. The force measured are higher than those found in literature for soft tissue during an EETA surgery, because it is strictly linked to the non-anatomical design of the system where the food film is stretched. However, the repeatability evaluated during a load-unload cycle is high, meaning that this is a promising system capable of providing real-time feedback on the levels of force applied to the polymeric film.

IV. CONCLUSIONS

In this work it is described a preliminary sensorized system able to mimic the arachnoid membrane and the CSF within, when an external force is applied to it. The choice of the food film to mimic was made based on former works and surgeons experience, however in the future tests will be conducted on the food film to evaluate if the mechanical response is similar to the values of the traction modulus of the PAC available in the literature. Although the hereby presented setup shows low repeatability from one test to another, data show interesting inter-test repeatability. Both tests showed a difference between the loading and unloading cycles, resulting in hysteresis, which is related to the limit of the pressure sensors and also to the stress relaxation phenomenon typical of polymers that occurs when a constant strain is applied for a certain period of time. The constant strain was applied when the slide was stationary immediately after the loading phase. The first test showed a clear linear trend, with an $R^2 = 0.984$ for the loading phase and a $R^2 = 0.999$ for the unloading phase. On the other hand, the second test showed a linear trend with $R^2 = 0.954$ from the unloading phase, while as for the loading phase, it has a non-linear trend for values of applied force less than one, which then tends to a linear trend above this value, with $R^2 = 0.996$. The non-linearity of the first part of the curve is caused by the fact that the pressure change measured by the sensor is below the repeatability of the sensor. In the future new improvements

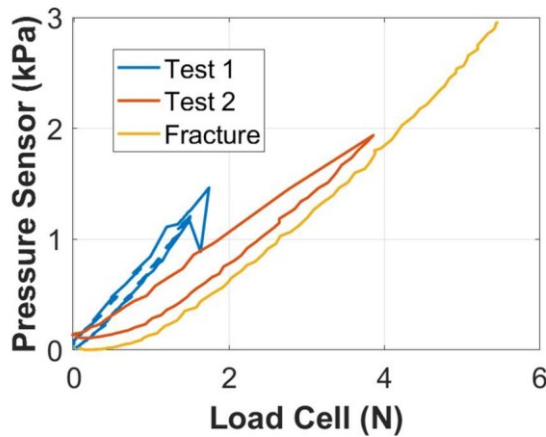


Fig. 9. Pressure Sensor (kPa) vs. Load Cell (N) of both tests. For the same applied force, the pressure increases faster in the first test.

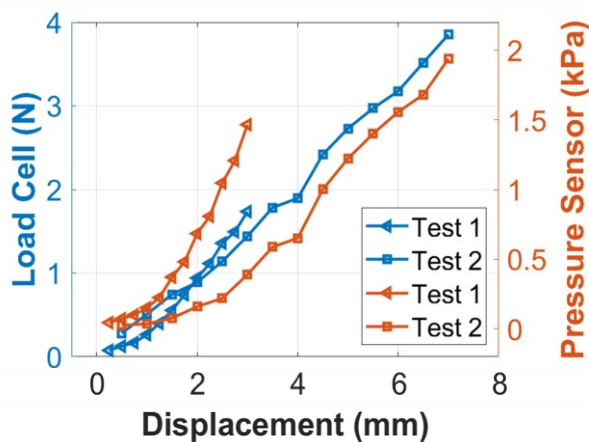


Fig. 10. Load Cell (N) and Pressure Sensor (kPa) as a function of the Displacement (mm) during the loading phase, a comparison between the two tests. The repeatability of the Load Cell data is better than the repeatability of the Pressure Sensors data.

are already in development to enhance the anatomical accuracy of the model, with a new pressure sensor with a lower full scale to explore better the values of pressure measured during these two tests. Additionally, a more anatomical design of the model is in study, the idea is to develop a system that permits repeatability in consecutive training sessions. The system in development tends to guarantee a repeatability in the assembly phase so to have the same starting condition. Moreover, future works will involve a study with a team of well-trained neurosurgeons to develop a set of threshold values to help training residents.

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