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Epidural motor skills measurements for haptic training

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Abstract. Epidural procedure can be a challenging skill to learn. Veterinarians must feel how many ligaments they get through before performing the injection in the exact location, relying solely on haptic perception, on a wide range of animal sizes. Force, torque, and position sensors were mounted on a needle to measure an epidural injection procedure. We provide here the data analysis that led to the needle insertion force profile extraction, to be used in procedural haptic simulators.

Keywords: epidural, force feedback, needle insertion, haptic training.

1 Introduction

There are many types of medical tools used in different procedures. Physicians conducting such procedures sense the interaction between the medical tool and the deformable specimen through haptic perception. One of the medical fields that requires high haptic sensitivity of the physicians is anaesthesiology. Epidural Analgesia is commonly performed in animals and taught in all veterinarian schools. This procedure is rarely image-guided and requires high haptic sensitivity to get through the tissue layers to perform the injection in the exact body space (the vertebral canal).

1.1 The Epidural technique data collection

Epidural needle insertion was performed on an anaesthetized dog in a veterinarian school on two occasions. The needle was modified to contain position and forces sensors in order to get two sets of corresponding data. Each experiment was documented with video, and complemented with CAT-Scans of the dog from the side as well as from top showing the steps of the procedure during the second experiment. The time scale of the data extends on around two minutes and a half. However, during the second experiments breaks were taken to take the pictures via CAT-scans and therefore the force data cannot be used to reproduce the interventional skill with a high fidelity as the needle was left dangling. The purpose of this data collection was to build training material for the students. Haptic and spatial measurements were meant to model the epidural skill. This paper focus on the first dataset that can be used to characterize motor skills to perform adequately the epidural needle insertion. The data analysis provided

here in terms of haptic measurements is meant to help building epidural skills training tools (virtual simulator, haptic device, or any other mean). This measurement consists of one directional force and position profile to characterize the sensitivity of layers perforations.

1.2 Anatomy

The epidural injection is a locoregional anesthetic technique that is commonly performed for pain management during veterinary surgical procedures on the hindlimbs as well as for humans mostly during labor. In small animal species like dogs and cats, animals are already under general anesthesia to ease the performance of this intrusive procedure on a still body. This operation consists in delivering a combination of local anesthetic and analgesic drugs in the epidural space in the low back at level of the intervertebral space between L7 and S1, which are respectively the last lumbar vertebra and the first sacral vertebra [1]. The very end of the spinal cord covered by the meninges sits at this level, making this procedure delicate and challenging. The needle has to cross 4 different tissues to get into the epidural space: the skin which provides for the first resistance; the supraspinous ligament and the interspinous ligament which offer the second resistance and then the ligamentum flavum that seems to provide the third and harder resistance. Three different Cat-Scans were taken during the second experiment (see figure 1) at each three key steps of the procedure: after the skin, before the ligamentum flavum; and after the ligamentum flavum in the epidural space. We can observe that the trajectory seems curved, due to the fact that the needle was left hanging before taking the pictures and the weight of the sensors made it tilt.

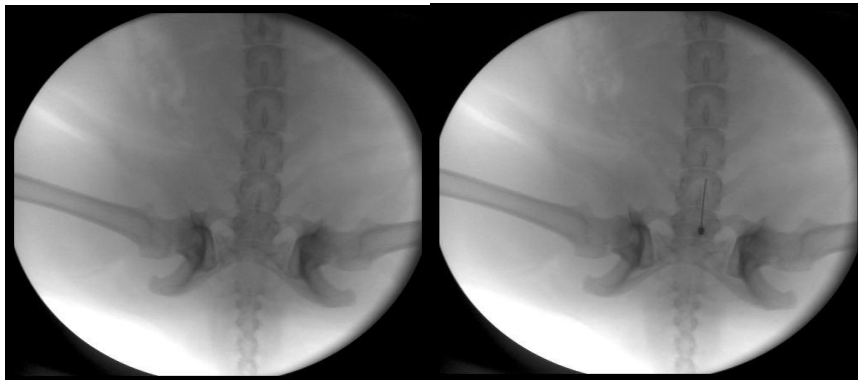


Figure 1: top view before and after needle insertion

2 Related Works

Epidural injection techniques are a widely studied interventional skill (over 16,000 references in PubMed). In his survey on epidural simulators [2], Neil Vaughan concludes “the ideal epidural simulator [...] would contain a force feedback haptic device, with force data originating from measured Tuohy needle insertions from patient”. Our study

is meant to extract an accurate enough epidural insertion force profile to be trusted by experts when using in a simulator.

Despite recent advances in virtual and real (3D printed) simulators [3,4], often for human size and anatomy, they do not focus on haptic accuracy: once the skin is passed with the needle, feeling the successive ligaments perforation is a real challenge for novices (or experts with infrequent practice). Notwithstanding ligament perforation can require little force [5], added frictions increase the epidural complexity: frictions between the needle and the animal tissue increase while being inserted forward. Our study focuses on procedural skills and training haptic sensitivity, as veterinarians only rely on haptic feeling to perform injection in the proper space, with the added constraints of being able to adapt to various animals size and anatomy.

3 Proposed Method

The measurements were setup in an operating room of the Nantes veterinarian school (see figure 2) with a C-arm, a motion tracking device, and a haptic sensor, described in the section below.



Figure 2: the operating room

3.1 OptiTrack

The position data sensor is an OptiTrack system, which gets the position data with infrared reflectors mounted on the needle, and a set of three FlexV100 cameras around

the operating table (Figure 3). The infrared reflectors were placed on top of the needle. The four dots on the sensor constitute a tetrahedron of which centre is the point that is used to determine coordinates in the frame of reference. The tetrahedron indicates the rotational coordinates around each axis consecutively x, y and z. The frame of reference was placed on the table with axes x and z being horizontal and y being the vertical axis.

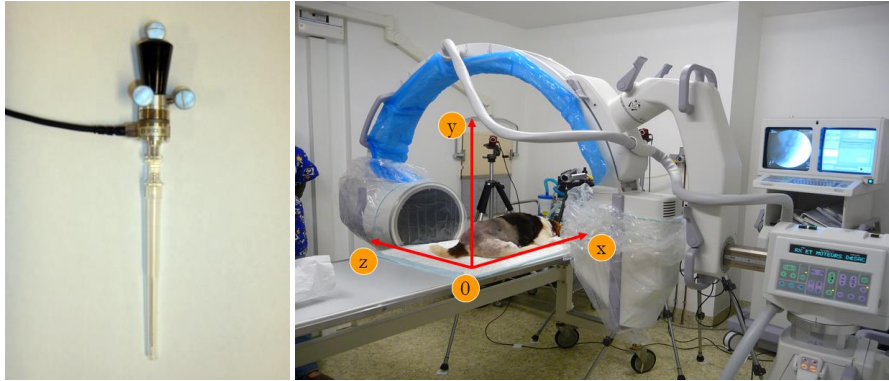


Figure 3: (left) the original epidural needle with mounted force sensor and infrared reflectors (right) motion tracking cameras frame of reference

Between the needle and the handle with the infrared reflectors, a force sensor is mounted to measure the forces applied to the needle. A Labjack U6 analog to digital acquisition board was used to record the ATI Nano17 transducer, the smallest commercially available 6-axis force sensor (see Table 1). The removable needle guide, situated into the lumen of the needle shaft, was modified and fixed inside the needle. The guide is usually here to help the needle pass through tissue without clogging and is removed to inject the drugs. For this sensor, the axis from the base to the tip of the needle is called the z axis.

Table 1. Force (F) and Torque (T) characteristics of the ATI Nano17

CALIBRATION REFERENCE	SENSING RANGES				RESOLUTION	
	Fx, Fy	Fz	Tx, Ty	Tz	Fx, Fy, Fz	Tx, Ty, Tz
SI-12-0.12	12 N	17 N	120 Nmm	120 Nmm	1/320 N	1/64 Nmm

4 Results

4.1 Retrieving and pre-treatment

The data is returned from the experiment in an xml file, using the open source HaCoE software [6] and the architecture seen in Figure 4.

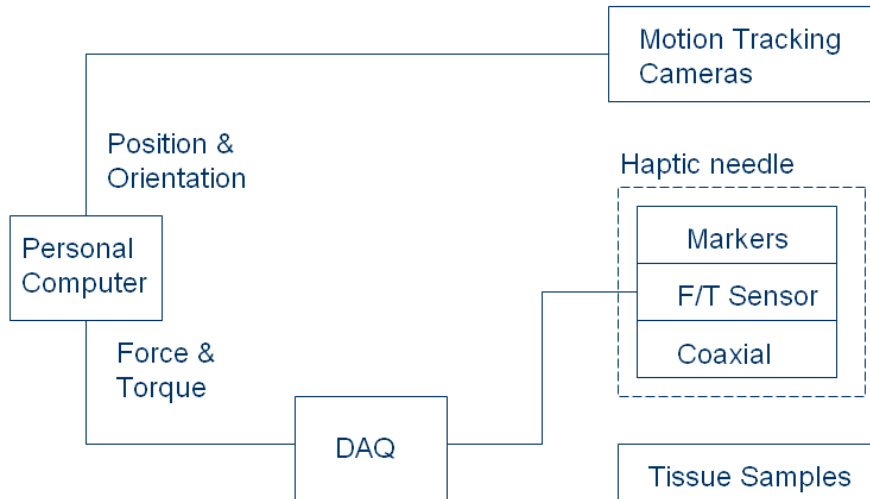


Figure 4: block diagram of the apparatus

With each timestamp in milliseconds, the position along each axis is stored in meters, then the orientation in degrees, then the forces in Newtons and the torques in Newton meters. A Python program was developed to retrieve the data from the xml file.

After doing so, a quick plot of the data along the time shows that the position and orientation data. Position data are noised with a lot of its value being 9999.0 (no measurement) due to the occlusion of the needle from the cameras, that can happen during the procedure when the anaesthesiologist is moving the needle around. The force sensor has no such error with continuous measurements. A simple filter of the position data removing records with coordinate x above 100 was sufficient to remove the OptiTrack errors.

Synchronisation between videos, images and records was performed to identify which time window corresponds to the needle insertion. The recorded data file provides a hundred and fifty seconds long sequence, where the video of the procedure only lasts for thirty-eight seconds. To identify which part of the data coincides with the needle insertion, we looked at the force along the needle's axis and its fluctuations. By looking at this graph (figure 5) we can safely assume that the operation happens in the seventy-eight to one hundred seconds time frame.

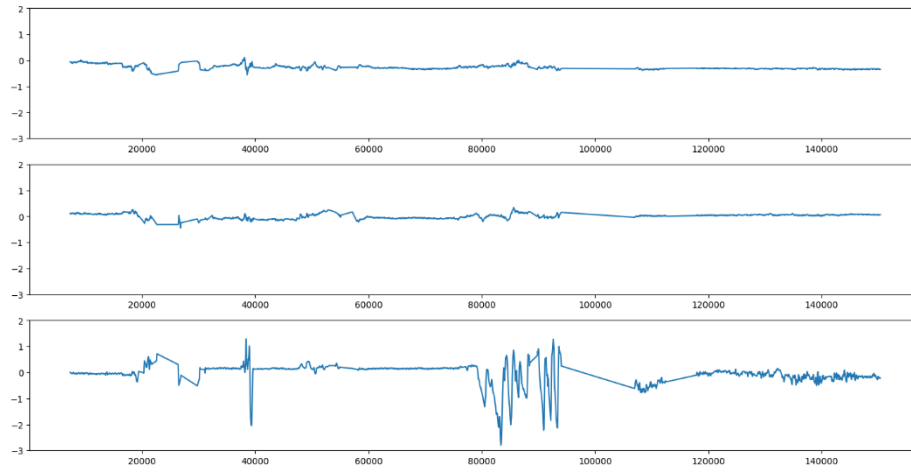


Figure 5: graphs of the force insertion profile (Fx, Fy, Fz)

Once this time frame is identified, we just proceed to filter the torques and forces with a simple low-pass filter using the left rectangle numerical method:

$$s_i = s_{i-1} + \frac{T_e}{\tau} \times (st_{i-1} - s_{i-1})$$

$$\tau = \frac{1}{2} \times \frac{1}{\pi \times f_c}$$

Where s is the filtered signal, st is the original signal, f_c is the filtering frequency and T_e is the sampling period. By trial and error, and looking at the graph, we use this filter to suppress high frequency noise without losing too much of the original information.

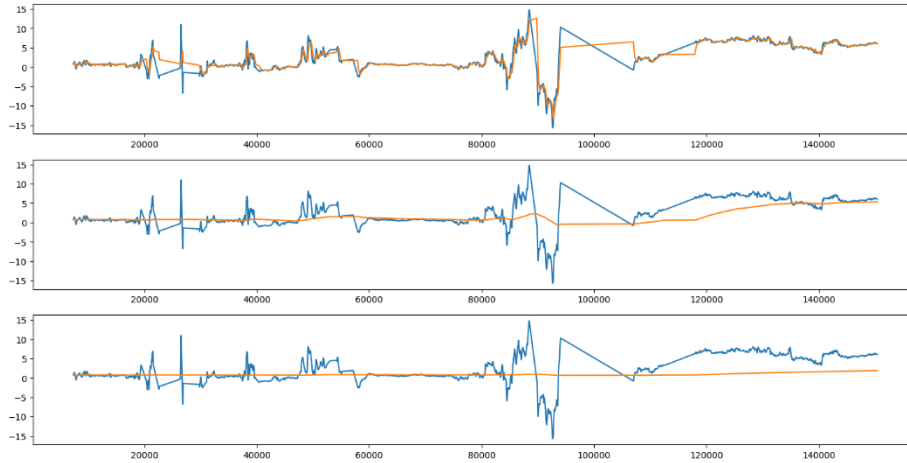


Figure 6: Graphs of torque along the x axis (blue) and the filtered torque (orange) at 0.5 Hz, 0.01 Hz and 0.001 Hz filtering frequencies

We chose 0.75 Hz filtering frequency. Better filters and better frequency determination methods could be used to lose even less of the data and to provide a better filtering method.

4.2 Geometrical transformation

We observed on the videos of the operation the needle is rotated often, so the tip of the needle and the handle have very different trajectories. We assumed that the needle is rigid, and we extrapolate the tip of the needle position from the measured handle position (where the IR reflectors are mounted).

In order to do so, we used the data provided by the OptiTrack. Using homogenous coordinates [7] and the OptiTrack documentation [8], we create a transformation matrix. Knowing the tetrahedron and the needle geometries, the OptiTrack sensor rotation and translation, we computed the needle tip position. From this we created a 3D plot of to check if the needles movement corresponds to the expectations (Figure 8).

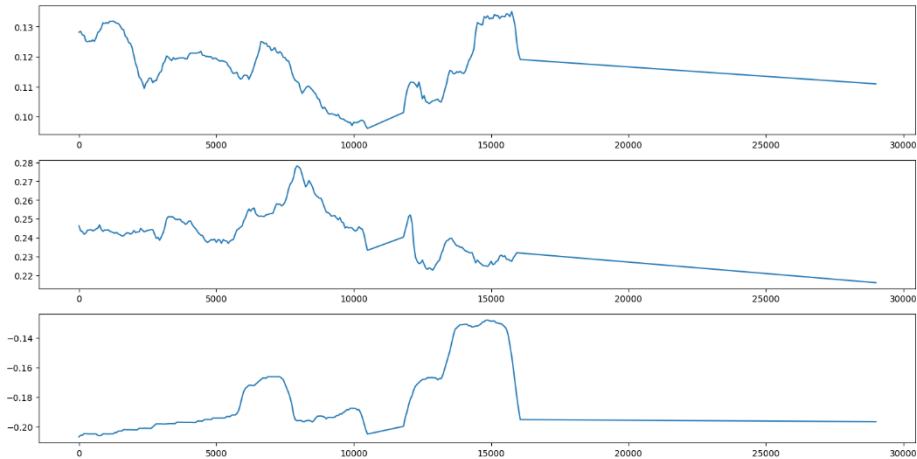


Figure 7: coordinates (X,Y,Z) of needle extremity in the global frame if reference

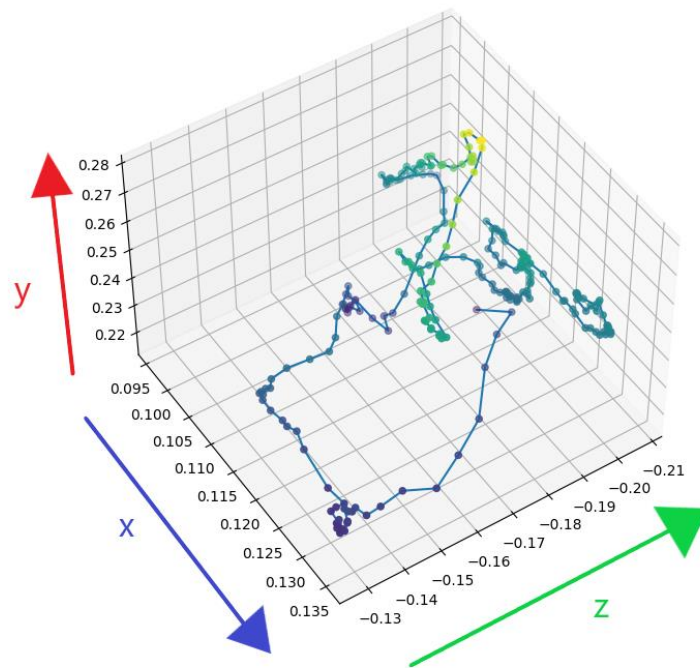


Figure 8: 3D graph of the simulated needle's point's position

From the 3D plot and the variation along each axis, we can say that the variations are contained within the margins of length expected by the veterinarian which are between 5 to 6 centimetres (Figure 8), considering that there are also parasitic lateral movements around the insertion axis and that there is some margin around the actual needle

insertion movement. To detect any error in this procedure, we created a function that computes, for each point of the needle tip calculated, the distance between this point and the handle. We checked this distance had no variation in length.

4.3 Principal component analysis

In order to extrapolate a one-dimensional direction profile for the needle and focus on insertion force along this axis, we used a method called principal component analysis to isolate a direction along which to project each point. The Principal Component Analysis (PCA) is a reduction method applied on a dataset to identify the principal components along which the data is differentiated and therefore distinguishable. It computes the eigenvalues and eigenvectors of the dataset's covariance matrix to identify the principal components [9]. This method is widely used in data science for linear regression, which is the goal we pursue here.

We implemented the PCA with the estimated point of insertion coordinates (cf. section 4.2). To calculate this point, we found the first variation of the force and defined it as the needle point of insertion (figure 9 bottom).

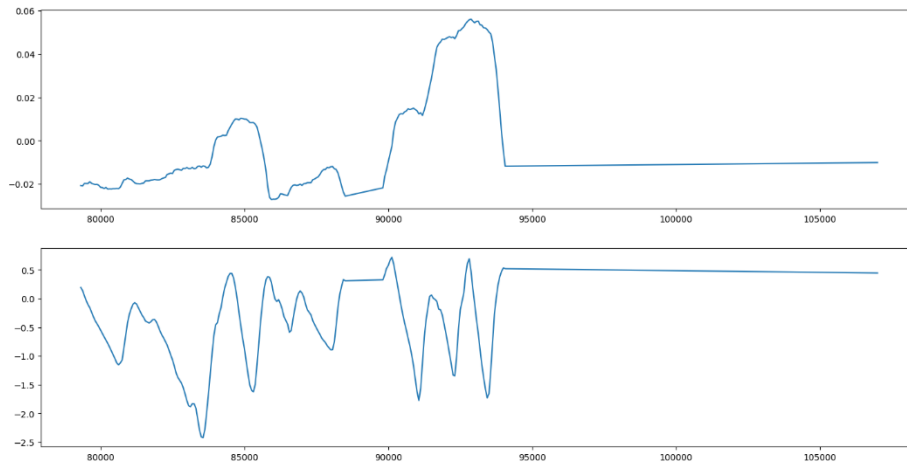


Figure 9: (top) Graph of the projected position along the principal component over time (bottom) Graph of the force insertion profile F_z along the needle axis over time

Most data treatment coding languages –mainly Python and Matlab - have built-in methods to implement the PCA. Here we used `numpy.linalg.svd` from NumPy, the fundamental package for scientific computing in Python. Once we implemented the PCA, we can directly plot the projected data and its variations during the timeframe (figure 9 top).

5 Discussion

5.1 PCA Limitations

As we can observe on (see figure 10), the results of the PCA are far from the expected results as we have variations on a length of almost twelve centimeters for the one-dimensional movement. Also, it would be expected for the needle to progress along the axis only to be pulled out when the procedure is done, hitting a plateau whenever the veterinarian stops to force the needle through a tissue that presents a resistance. Instead, this plot shows a needle that would be inserted then pulled back to be inserted further again. The problems to solve here are to use force, torque and position data together to create a more accurate insertion force profile, that compensates lateral movements of the needle.

5.2 3.2. Force modifications

As we can observe on (see figure 9) that the force does not render the idea of three resistance plateaus but more of isolated peaks of exerted force from the veterinarian. This seems counter intuitive to a simple rectilinear movement, however, as previously said, the movement isn't rectilinear. Indeed, watching the video one can observe the operator moves the head of the needle around while trying to feel where and how to insert the needle at every step of the way.

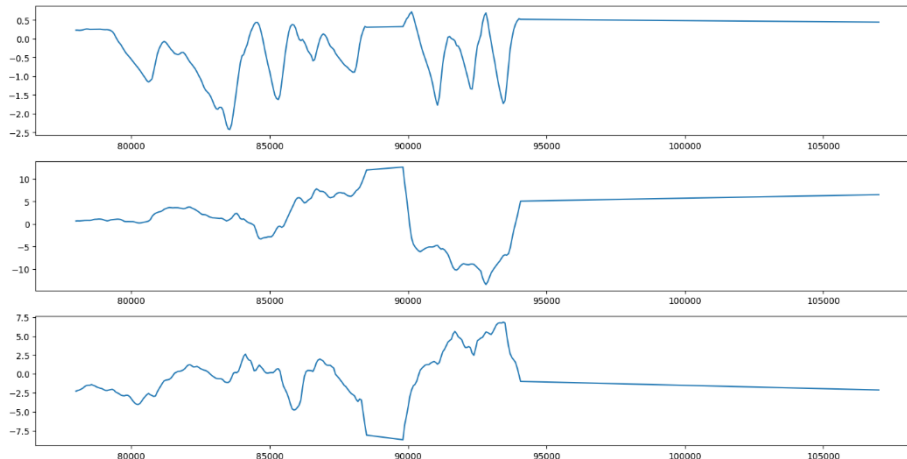


Figure 10: Graph of the force (F_z) along the needle axis and torques normal to the needle (T_x , T_y) over time

If we look at the torque while the force is at a local minimum, we can see that a strong torque is measured most of the time (figure 10). This can be explained by the fact that the operator turns the needle while not moving. And this torque when impacting the force may cause this irregular profile. As a way of correcting those irregularity and

creating a more accurate insertion force profile, we cancel the torque which would normally translate as:

$$(-Tx + Ty) \times l$$

where l is the needle's length.

By summing its opposite projection to the force:

$$F = Fz + (Tx - Ty) \times l$$

This operation gives us the following force profile (figure 11):

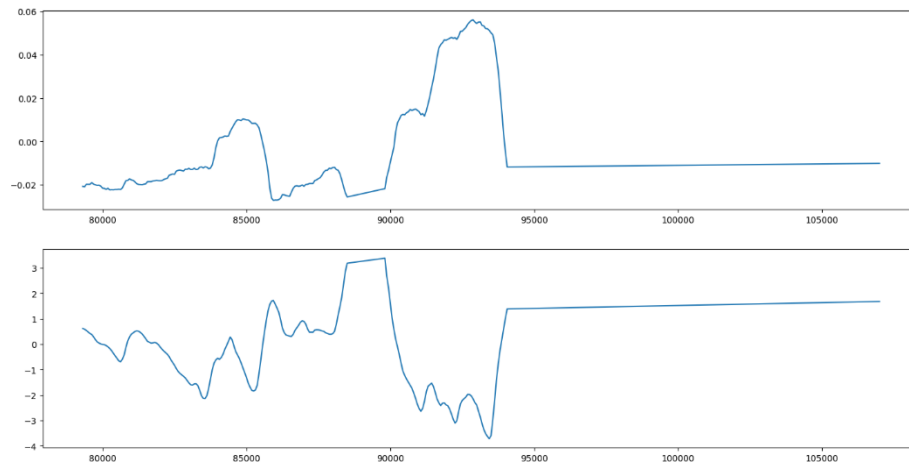


Figure 11: (top) Graph of the projected position along the principal component over time (bottom) Graph of the force with torque compensated over time.

When analysing the movements, we can set an approximative time gap of five seconds between the skin and the second resistance encountered and a fifteen seconds gap between the skin and the third resistance. Therefore, we have peaks of force that are coherent with the three timestamps of insertion and resistance met during the operation (as seen on figure 11). The uncertainty on the data is the peak of force that indicates a traction of the needle by the skin. Although the epidural space has a negative pressure, the needle does not seem to be in the epidural space. This irregularity might be caused by a poor filtering of the torque, as we can see very high torque at this point.

6 Conclusion

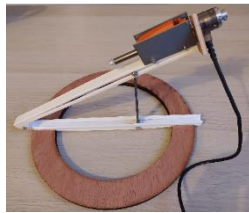
Despite being able to measure force and torque on the needle with a highly sensitive sensor, performed by an expert anaesthesiologist able to compensate the tool weight variation, it was not straightforward to extract the force profile along the needle insertion axis. Nevertheless, the calculated force profile (figure 11) can be used to measure or train students haptic sensitivity, for example with simple 1D haptic devices.

We can further improve the correction to create the three proper peaks although we know data accuracy is counter balanced by expert perception: from previous studies

[10], we know that, once inserted in a simulator, force profiles need to be tuned by experts before they trust the simulation and actually use it with trainees. The following step is then to check this first force profile with the experts.

7 Future Work

Based on this preliminary work, we have conducting new research on two tracks. The first one is measuring the same epidural procedure at the vet school with a cow, to get a force profile with a significant different physiology.



The second one is to build a new haptic device to train vet students to improve their performance with ligaments perforation. A first prototype has been built (see photo on the left) with an ATI Nano 17 6D force sensor and a FAULHABER linear DC servomotor LM1247-020-12. The displacement and the force feeling are smooth. It has to be evaluated now with vet students.

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