



HAL
open science

Designing an accurate and customizable epiduralanesthesia haptic simulator

Thibault Senac, Arnaud Lelevé, Richard Moreau, Laurent Krähenbühl,
Florent Sigwalt, Christian Bauer, Quentin Rouby

► **To cite this version:**

Thibault Senac, Arnaud Lelevé, Richard Moreau, Laurent Krähenbühl, Florent Sigwalt, et al..
Designing an accurate and customizable epiduralanesthesia haptic simulator. 2019 IEEE Inter-
national Conference on Robotics and Automation (ICRA), IEEE, May 2019, Montreal, Canada.
10.1109/ICRA.2019.8794199 . hal-02170879

HAL Id: hal-02170879

<https://hal.science/hal-02170879>

Submitted on 12 Sep 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Designing an accurate and customizable epidural anesthesia haptic simulator

Thibault SÉNAC*, Arnaud LELEVÉ*, Richard MOREAU*, Laurent KRAHENBUHL*, Florent SIGWALT†, Christian BAUER†‡, Quentin ROUBY*

*University of Lyon, INSA Lyon, École Centrale de Lyon, CNRS, Ampère, F-69621, Villeurbanne, France,

†Département d'Anesthésie-Réanimation, Hôpital de la Croix Rousse, Hospices Civils de Lyon, Lyon, France,

‡Centre Lyonnais d'Enseignement par la Simulation en Santé, SAMSEI, Université Claude Bernard Lyon 1, Lyon, France

Abstract—Epidural anesthesia, despite being a relatively common medical procedure, remains quite demanding in terms of skills as it is mostly blind and thus heavily reliant on the haptic sensations. Although some training support solutions exist, anesthesiologists consider them mostly inefficient or impractical. A few attempts at creating a simulator for this particular procedure exist but each one lacks one of the important requirements of the procedure. This article introduces a haptic simulator featuring a more complete and realistic simulation of the procedure than we could observe in existing simulators. The simulator is composed of a generic electrical haptic interface coupled with a pneumatic cylinder.

I. INTRODUCTION

A. Medical context

Epidural anesthesia is a commonly used medical gesture performed mainly during childbirth delivery, but it is very complex and hard to learn. This is mainly due to the fact that the procedure is mostly performed blind, relying solely on haptic cues and their interpretation by the anesthetist. To perform such a gesture, the practitioner has to insert a Tuohy needle between two vertebrae while injecting a fluid using an epidural syringe. The Tuohy needle has to cross several physiological layers, namely derma, supraspinous ligamentum, intraspinal ligamentum, and ligamentum flavum, to finally reach the epidural space. Throughout the insertion, the anesthetist experiences an increasing resistance felt both from the needle insertion and from the fluid injection. This resistance reaches its maximum when the needle tip crosses the ligamentum flavum, and suddenly plummets, creating what is commonly called the *loss of resistance* (LOR) principle. It is this phenomenon that allows physicians to

know they reached the epidural space and this principle is specific to the epidural anesthesia procedure. Due to the relatively high forces exerted simultaneously on the needle and on the plunger of the syringe, the procedure is really demanding in terms of precision as the epidural space is usually only about 4 mm wide, and about 6 mm deep.

In consequence, this particular medical gesture has a quite steep learning curve and may require up to 90 attempts to be performed with a success rate of only 80% [1], which does not suffice for healthcare applications. The need for an efficient teaching tool has been strengthened by public institutes such as the French H.A.S. [2] (*Haute Autorité de la Santé*), which prescribes to "never do the first time on a patient".

B. State of the art

In the past years, some training solutions to support this teaching have been developed such as manikins or complete robotic simulators. Most of the proposed solutions have been listed and compared in [1], which considers 17 manikin based solutions and 14 computer based ones. According to this study, despite promising solutions, none of them responds to every training requirement. On the one hand, manikins generally offer an appropriate level of realism concerning the general look and feel of the back of the patient. However, steep prices, the lack of easy customization, the non-repeatability of the attempts, the lack of objective feedback for the trainers to perform a supervisory control, usually limit the practicability of these solutions. On the other hand, the computer based solutions lack realism in the patient back reproduction. Nevertheless, computer based simulators

allow for a deeper and easier customisation of the type of patient and objective assessment.

Some computer based solutions have been developed to help trainees learn the epidural anesthesia. We can highlight, for instance, the works of Manoharan *et al.* [3], Magill *et al.* [4], Dubey *et al.* [5] or Thao *et al.* [6], who developed haptic simulators for this particular procedure. These simulators however, provide an incomplete representation of epidural anesthesia. Concerning needle insertion, they often feature a custom haptic interface to reproduce a simplified version of the necessary haptic cues of the procedure. The procedure may, for example, be limited in terms of degrees of freedom, or only consider crossing the different physical layers without taking into account a potential bone contact. Regarding the LOR, the simulations are very simplified (if present), only using on/off solenoid valves.

In the literature, needle insertion modeling has been thoroughly studied. The insertion forces are often described as a sum of various contributions [7] which are: a constant cutting force, a friction force and an elastic force. Moreover, as the epidural space is located in the spine, one may hit a vertebrae during the insertion of the needle. In that case, simulators must reproduce the feel of an interaction with a hard body. Thereon, the most common approach is to use a proxy system (also called god object [8]). This solution is usually quite efficient and simple for surface exploration but has shown some limitations when it comes to representing collisions, as Kuchenbecker *et al.* [9] pointed out in their study. They therefore proposed using event based haptic feedback to generate a vibration cue when collision occurs. Then, once the contact is established and the transient vibration force has damped, it goes back to a classical proxy based approach to generate the resting force.

C. Required features

Regarding epidural anesthesia simulator, Vaughan *et al.* [1] has exposed the requirements for a perfect epidural anesthesia simulator. According to them, the simulator has to be customisable and should contain a haptic interface paired with a 3D interface. Finally, the study insists that the simulator should emulate not only the needle insertion forces, but also the LOR felt using a syringe. However, most of the current simulation options only reproduce what is called 100% LOR, which is encountered only in the "average" and "easy" cases.

D. Contributions of this study

In this paper, we introduce an haptic training simulator for epidural needle insertion covering the requirements proposed in [1]. It features a customizable needle insertion haptic simulator coupled with a LOR syringe haptic simulation. The simulator uses a off-the-shelf haptic interface handling the reproduction of the needle insertion, and a pneumatic cylinder which reproduces the classical LOR syringe behaviour during this kind of procedure. The novelty lies in the use of a pneumatic cylinder fitted with a servovalve to precisely reproduce the LOR forces, instead of a simple solenoid valve in existing solutions. Also, an enhanced model of needle insertion is introduced in order to take into account the potential contact with bones. This simulator reproduces realistic epidural anesthesia procedures, records data to assess the trainee level, and allows the repeatability of the attempts. This paper is organized as follows. Section II introduces the way this simulator has been designed. Section III depicts the experimental setup for validation. Section IV reports the results and provides a discussion. Finally, some concluding remarks and future directions are provided in Section V.

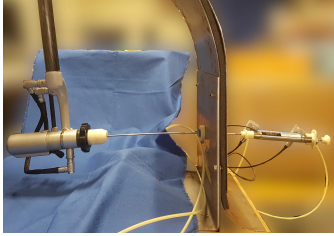
II. THE SIMULATOR AND ITS IMPLEMENTATION

In this simulator, the haptic electric interface reproduces the haptic cues generated by the needle insertion only. The pneumatic cylinder is employed to emulate the syringe which is used to detect the end of the procedure through the LOR approach.

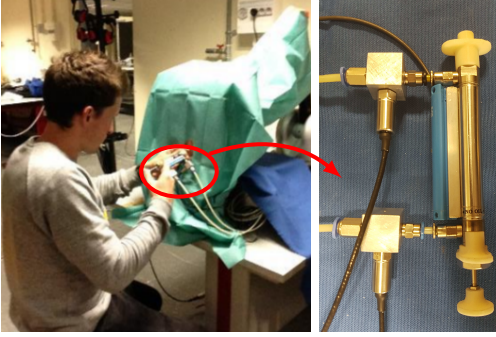
A. Prototype setup

A latex based human back phantom is used, to reproduce the back of the patient. Some landforms represent the vertebrae. As the choice of the insertion point is out of the pedagogical objectives of this simulator, the needle insertion location is static. The prototype features a Virtuoso™ 6D [10] from Haption® as the haptic interface for the Tuohy needle driving. The needle is reproduced by a plain metallic rod which is attached to the tip of the haptic interface and crosses the fake patient back. An Airpel® anti stiction double acting pneumatic cylinder (M9D50.0UT1 [11]) with a shape close to the real LOR syringe, represents the latter and is attached to the "external" end of the rod. In order to keep the instrumentation of the cylinder as light as possible and as small as possible, we opted for a magnetic position sensor (MPS-064TSNU0 [12]) from

SICK[®] and two miniature pressure sensors (EPRB-1 [13]) from TE[®]. A dSpace[®] DS1103 controller commands a Festo MPYE[®]-5-M5-010 B servo-valve to control the air mass flow rates entering this cylinder. An Arduino Uno ensures the communication between the haptic interface and the pneumatic cylinder controllers. The prototype, manipulated by a trainee, is visible in Fig.1.



(a)



(b)

Figure 1: (a) Prototype viewed from the side (b) Complete prototype and pneumatic cylinder setup

We added some mechanical parts to bring the prototype closer to a real case in term of look and feel. A set of 3D printed parts dresses the pneumatic cylinder to resemble a real syringe. Moreover, a curved plate represents the back of the patient.

The control laws concerning the pneumatic cylinder were written with Simulink. A real-time user interaction with them is performed with ControlDesk. The haptic interface application was developed in C/C++ using the Haption API coupled with a physical simulation engine based on the ODE library [14], and with a virtual 3D environment.

B. Pneumatic cylinder control

1) *Objectives:* The aim of the pneumatic cylinder is to reproduce the forces resisting to the injection of a

fluid throughout the insertion of the needle. The main objectives are:

- clearly reproducing the LOR phenomenon, creating different resistant forces according to the physiological layer simultaneously crossed by the virtual needle,
- allowing the user to empty (and potentially refill) the syringe.

The pneumatic cylinder is fitted with a servo-valve instead of a simple solenoid valve, to reproduce a larger variety of haptic cues during the LOR experience. Indeed, the variability of the patient morphology implies various force levels as well as various speeds of transition when the force plummets at the end of the procedure. Also, it is necessary to emulate the emptying/re-filling of the virtual syringe through the pneumatic cylinder and its control law.

2) *Cylinder control:* To implement the LOR behavior, two control laws were needed, as well as an algorithm selecting the right law and switching them in a stable fashion. The first control law needed to produce a resistant force (as the real syringe which hardly empties itself as long as the needle has not reached the epidural space) and the second control law had to keep the plunger at a set position (to set the plunger at the right positions during the procedure). We apply the control laws defined in [15], [16] based on the A-T transform [17] and a backstepping approach to control either the position or the pneumatic force generated by the system. We then added a switching algorithm that selects the control law to activate in real-time. To ensure that the system remains stable during the whole procedure, we use an average dwell time approach to set a minimum switching time between the two laws in our switching algorithm [18]. It guarantees that the laws stay active long enough for the whole system to remain stable.

C. Haptic interface control

1) *Objectives:* The main objective of the electric haptic interface is to reproduce the forces encountered when inserting a needle in tissues. According to Okamura *et al.* [7], one can describe the insertion forces in soft tissues (muscles, ligaments and skin in particular) as a sum of the following contributions:

$$\vec{F}_{needle} = \vec{F}_{stiffness} + \vec{F}_{friction} + \vec{F}_{cutting} \quad (1)$$

where $\vec{F}_{stiffness}$ represents the force corresponding to the puncture of a tissue, $\vec{F}_{friction}$ the force generated

by the friction between the tissues and the needle and $\vec{F}_{cutting}$ the force at the tip of the needle once the tissue has been punctured. In our case, the stiffness part is impactful mostly before the needle has punctured the derma. The cutting force depends on the tissue the needle tip crosses, and the friction force grows with the distance traveled inside the tissues. This behaviour is suitable for a standard insertion, where the needle only crosses ligaments, muscles or skin for example but it has to be enhanced to represent some bone contact.

To reproduce the haptic cue corresponding to a contact between the needle and a bone, we referred to [9] which provides various desired force patterns to reproduce whenever a contact occurs. Out of these patterns, we chose to re-use the one based on a decaying sine as it is presented as being relatively simple, identifiable as a solid-solid contact for the user, and quite realistic. The trajectory is the following :

$$\vec{F}_{contact} = -Ae^{\ln(0.01)t/d} \sin(2\pi ft) \vec{v}_{in}, \text{ for } 0 < t \leq d \quad (2)$$

with A being a nominal magnitude, d the duration of the pattern, f a set frequency, and \vec{v}_{in} the velocity vector before hitting the surface. Moreover, once the needle collides with a bone, the needle tip cannot slip from the contact point. It has to be pulled back. Lastly, once the needle has started to cut through tissues, we consider that it remains on a set straight trajectory. This trajectory may be considered as curved in some cases depending on the type of needle used. However in our case, with the pierced tissues being relatively dense and because of the form of the needle tip, the trajectory remains relatively straight. Each of the previously forces are further detailed in the following part.

2) *Implementation:* The Virtuose 6D is designed to operate mostly using a proxy based/virtual mechanism system. In this type of simulation, a virtual object is attached to the haptic interface. This virtual object receives the position of the interface handle and sends back forces to the interface through a virtual mechanism (usually a mass, spring, damper mechanism, as show in Fig.2). These forces may be reaction forces when the virtual object touches another another object in a virtual scene, or forces rendering the gravity or some viscosity. This kind of approach is widely used to reproduce virtual object contacts as it ensures the stability of the interface as long as the stiffness and the damping are appropriately chosen [19], it limits vibrations and it has low CPU usage [8].

In this application, the Virtuose 6D control soft-

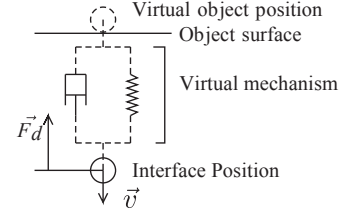


Figure 2: Example of a proxy and virtual mechanism on a contact situation

ware features two ways to generate the desired force applied by the haptic interface on the fake needle. On the one hand, we make use of the aforementioned proxy virtual object approach to model the virtual needle. The latter interacts with several other 3D virtual objects in order to generate each part of the needle insertion forces: the various physiological layers, two vertebrae and a plane to generate the stiffness ($F_{stiffness}$) part of the reaction force. The friction force has not been implemented so far, as it did not seem crucial on initial examination. On the other hand, some haptic cues require fast force patterns to be fully efficient (typically $F_{stiffness}$ or $F_{contact}$) as they are based on a sensation of vibration. To reproduce these cues, we superimpose the corresponding force patterns directly on the haptic interface.

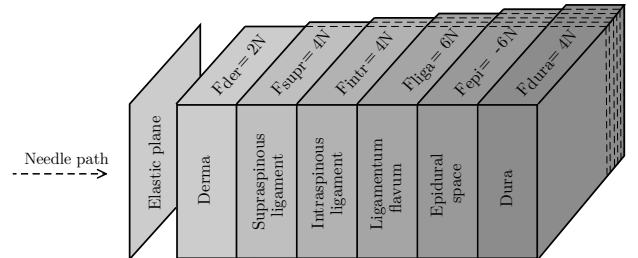


Figure 3: Diagram of the 3D model used to replicate the intervertebral space with force values of each layer from a standard case

To implement the cutting force we used nested boxes, as shown in Fig.3, to generate a constant force opposed to the current motion of the virtual object. According to Okamura *et al.* [7], the force is created as follows:

$$\vec{F}_{cutting} = F_{layer} \cdot \frac{\vec{v}}{\|\vec{v}\|}, \text{ if } \|\vec{v}\| > \epsilon, \quad (3)$$

with F_{layer} being the sum of each force from each layer crossed and ϵ a velocity threshold to trigger this force behavior. We used a nested environment instead of stacked spaces to avoid any issues at the interfaces between each layer, where one could cross either an

empty zone or a heterogeneous area which would create undesirable high force variations. Concerning the stiffness force, according to Okamura *et al.* [7], it has the following formulation:

$$\vec{F}_{stiffness} = (a_1 \cdot z + a_2 \cdot z^2) \cdot \vec{n}, \quad (4)$$

\vec{n} being the normal to the plane the needle is starting to cross, a_1 and a_2 two positive constants, and z the distance between the object center and its orthogonal projection. This force is computed using the virtual object position but is applied directly to the haptic interface without going through the proxy because we need the feel of a rupture of the capsule when the needle has entered enough.

The contact force is computed according to (2) and also applied directly to the haptic interface, using the position and velocity of the coupled virtual object. At the beginning of the procedure, we attach the virtual object to a virtual line which is aligned with the orientation of the fake needle (which coincides with the virtual needle), in order to keep the needle trajectory straight. We let the virtual mechanism generate the forces needed for the users to realize that they are locked on this straight trajectory. Finally, we parameterized the virtual hard object so that it can roll without slipping. When coupled with the set straight insertion trajectory, this helps users realize they are stuck on a bone when the virtual object contacts one.

III. EXPERIMENTAL SETUP AND FIRST TESTS

A. Objectives

First, we tried the prototype with skilled anesthetists to make sure the simulation was accurate enough. It allowed us to apply some necessary adjustments to some simulation parameters, such as the values of F_{layer} or the resistant force created by the pneumatic cylinder. Once the parameters were set to obtain realistic simulations, we proceeded to recording of complete procedures. The aim of the first experimental study was to know whether it would be possible to differentiate an experienced user from a novice through the use of this simulator.

B. Test settings

We set up three kinds of patients for the first test sessions. The first patient type was the average patient, which represents an "easy" case and serves as a basis from

Table I: Patient types

Patient	Derma length (cm)	Epidural space length (mm)	F_{dura} (N)	LOR speed
Average	1.0	6.0	8.0	average
Overweight	3.0	4.0	6.0	slow
Calcified	1.0	4.0	14.0	quick

which we derived the others. The parameters changed for the other patient types were: the length of the derma layer, the length of the epidural space layer, the value of F_{dura} , and the LOR speed (*i.e.* the speed of transition between the highest resistant force in the ligamentum flavum to the lowest one in the epidural space). The patient characteristics are provided in table I. Their dimensions derive from measures on MRI images, the forces from an article by Tran *et al.* [20] and the rest from the knowledge and feedback from the skilled anesthetists working on the project.

The procedure of the test was:

- 1) quickly present the aim of the epidural anesthesia and the risks it bears,
- 2) show an example of the correct way to perform the procedure (the main objective was to introduce the right way to handle the syringe),
- 3) let the subject perform the procedure himself without recording so they can get an idea of the forces they will have to face,
- 4) record at least one attempt on each patient case we implemented.

The tests were done with a relatively low number of subjects, namely 2 experts and 6 novices.

IV. EXPERIMENTAL RESULTS

A. Data analysis

Once a few tests were recorded, we analyzed the data featuring a total of 24 variables: including in particular the mean and variance of both velocity and acceleration of the haptic interface handle along three axes, the mean and variance of both velocity and acceleration of the cylinder plunger. We also recorded the number of bone contacts, needle insertions, the insertion angles, the proportion of syringe volume used, as well as the overshoot which represents the distance traveled inside the epidural space. We also developed an indicator ($syrrate$) based on the amount of syringe emptied relative

to the distance traveled by the needle in the back. The formula for this indicator is:

$$syr_{rate} = \frac{\text{Proportion of syringe emptied}}{d} \quad (5)$$

with d being the distance travelled by the haptic interface from the puncture of the derma to the end of the procedure along the elastic plane normal vector. Finally, we recorded whether the attempt ended up puncturing the dura or not as a way to describe whether it was a success or a failure.

As a first result we decided to analyse the success rate per patient type, the velocity of the needle tip along the insertion path, and finally the aforementioned syr_{rate} to try differentiating a novice user from an experienced one.

B. Results

The experienced users who tried the simulator were quite satisfied with the overall realism of the proposed simulator. Some room for improvement was highlighted in some areas such as bone contact, ability to steer the needle while in the derma and some variability in the space between each vertebrae. The results shown in Fig.4 highlight some patterns that separate the unskilled users from the trained experts. The success rate shows that the only users who failed were the unskilled ones. The overall results show around 60% of success rate for the novices. Their success rates are better on the calcified/average cases and worse on the overweight ones. This indicates that the LOR speed played a great role in how the unskilled users detected the epidural space. This strengthens the need of a customisable LOR speed instead of the existing binary 100% LOR.

Concerning the speed, the data show that the experts perform the gesture with a relatively low but constant speed, regardless of the patient type. The unskilled users showed a much more variable speed that greatly depends on the patient type. Hence, the consistency in speed may indicate a stronger mastery of the procedure.

Finally, the experts tend to have a much higher syr_{rate} (indicator defined in (5)) than the novices, showing that they usually use a greater portion of the cylinder length (d being constant for a given patient type). This might be a way for the skilled users to gather as much haptic information as possible. This may help them guess the current position of the needle tip with much more precision, besides detecting the LOR. Typically, they

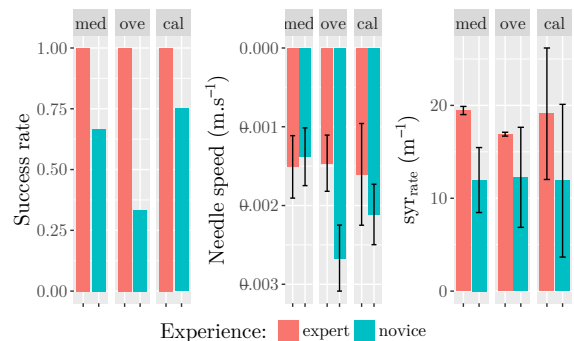


Figure 4: Needle speed, syr_{rate} and success rate achieved depending on the patient type on separated by experience of the user (med: average, cal: calcified, ove: overweight) with two populations : novices and experts

are able to differentiate each crossed layer, from the force feedback provided by the syringe. Furthermore, concerning the novices, the standard deviation of the syr_{rate} is also quite high. This shows a wide variety of use. It is noteworthy that the low number of experts attempts may have caused the very high standard deviation for the calcified case.

V. CONCLUSION, PERSPECTIVE AND FUTURE WORK

In this paper, we introduced a realistic and customisable haptic simulator dedicated to the hands-on training on the epidural anesthesia procedure, based on the ideal simulator depicted by Vaughan *et al.* [1]. The overall results of this first study are quite encouraging and indicate that such a simulator might be realistic enough to provide an efficient training tool in the future. However some areas need improvements, such as introducing a very distinct feel of cutting through the ligamentum flavum which, according to our experts, feels like friction and cracklings. Moreover, according to their feedback, when the needle is in the ligamentum flavum, the syringe plunger feels like it is locked. Finally, we would like to perform an automatic classification of the user once the tests are completed. This requires many more trials to generate a training set for such an algorithm.

VI. ACKNOWLEDGMENT

Authors would like to thank the Neuro-immersion tech facility of the CRNL (Centre de Recherche en Neurosciences de Lyon) for their material support and the ANR (French National Research Agency) for financing SAMSEI project (ANR-11-IDFI-0034) under the supervision of Pr. X. Martin.

REFERENCES

- [1] N. Vaughan, V. N. Dubey, M. Y. Wee, and R. Isaacs, "A review of epidural simulators: Where are we today?" *Medical Engineering & Physics*, vol. 35, no. 9, pp. 1235–1250, Sep. 2013. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S135045331300057X>
- [2] J.-C. Granry and M.-C. Moll, "État de l'art (national et international) en matière de pratiques de simulation dans le domaine de la santé," Haute Autorité de la Santé (HAS), Tech. Rep., 2012.
- [3] V. Manoharan, D. van Gerwen, J. J. van den Dobbelsteen, and J. Dankelman, "Design and validation of an epidural needle insertion simulator with haptic feedback for training resident anaesthesiologists," in *Haptics Symposium (HAPTICS), 2012 IEEE*. IEEE, 2012, pp. 341–348.
- [4] J. C. Magill, M. F. Byl, M. F. Hinds, W. Agassounon, S. D. Pratt, and P. E. Hess, "A Novel Actuator for Simulation of Epidural Anesthesia and Other Needle Insertion Procedures," *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare*, vol. 5, no. 3, pp. 179–184, Jun. 2010. [Online]. Available: <https://insights.ovid.com/crossref?an=01266021-201006000-00009>
- [5] V. Dubey, N. Vaughan, M. Y. K. Wee, and R. Isaacs, "Biomedical Engineering in Epidural Anaesthesia Research," in *Practical Applications in Biomedical Engineering*, A. Andrade, Ed. InTech, Jan. 2013. [Online]. Available: <http://www.intechopen.com/books/practical-applications-in-biomedical-engineering/biomedical-engineering-in-epidural-anaesthesia-research>
- [6] D. Thao, A. T. M., and S. M. A., "Development and Evaluation of an Epidural Injection Simulator with Force Feedback for Medical Training," *Studies in Health Technology and Informatics*, pp. 97–102, 2001. [Online]. Available: <http://www.medra.org/servlet/aliasResolver?alias=iopressISSNISBN&iissn=0926-9630&volume=81&spage=97>
- [7] A. Okamura, C. Simone, and M. O'Leary, "Force Modeling for Needle Insertion Into Soft Tissue," *IEEE Transactions on Biomedical Engineering*, vol. 51, no. 10, pp. 1707–1716, Oct. 2004. [Online]. Available: <http://ieeexplore.ieee.org/document/1337139/>
- [8] C. B. Zilles and J. K. Salisbury, "A constraint-based god-object method for haptic display," in *Intelligent Robots and Systems 95: Human Robot Interaction and Cooperative Robots, Proceedings. 1995 IEEE/R.S.J International Conference on*, vol. 3. IEEE, 1995, pp. 146–151.
- [9] K. J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving contact realism through event-based haptic feedback," *IEEE transactions on visualization and computer graphics*, vol. 12, no. 2, pp. 219–230, 2006. [Online]. Available: <http://ieeexplore.ieee.org/abstract/document/1580456/>
- [10] "Virtuose™ 6d - HAPTION SA." [Online]. Available: <https://www.haption.com/fr/products-fr/virtuose-6d-fr.html>
- [11] "Double-Acting Archives." [Online]. Available: <http://airpot.com/product-category/product-lines/pneumatic-actuation/airpel-anti-stiction-air-cylinders/metric-models/double-acting-metric-models/>
- [12] "MPS-064tsnu0 | Magnetic cylinder sensors SICK." [Online]. Available: <https://www.sick.com/ag/en/magnetic-cylinder-sensors/position-sensors/mps-t/mps-064tsnu0/p/p230381>
- [13] "Miniature Ratiometric Pressure Transducer | EPRB Series | TE Connectivity." [Online]. Available: <http://www.te.com/usa-en/product-CAT-PTT0007.html>
- [14] "Open Dynamics Engine - Browse /ODE/0.13 at SourceForge.net." [Online]. Available: <https://sourceforge.net/projects/opende/files/ODE/0.13/>
- [15] N. Herzig, R. Moreau, T. Redarce, F. Abry, and X. Brun, "Nonlinear position and stiffness Backstepping controller for a two Degrees of Freedom pneumatic robot," *Control Engineering Practice*, vol. 73, pp. 26–39, Apr. 2018. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0967066117302812>
- [16] T. Senac, A. Lelevé, and R. Moreau, "Control laws for pneumatic cylinder in order to emulate the Loss Of Resistance principle," in *IFAC 2017 World Congress*, ser. Proc. of the 20th World Congress of the International Federation of Automatic Control. Toulouse, France: IFAC, Jul. 2017. [Online]. Available: <https://hal.archives-ouvertes.fr/hal-01506823>
- [17] F. Abry, X. Brun, S. Sesmat, and E. Bideaux, "Non-linear position control of a pneumatic actuator with closed-loop stiffness and damping tuning," in *European Control Conference (ECC)*, Zürich, Switzerland, 2013, p. 1089. [Online]. Available: <http://www.nt.ntnu.no/users/skoge/prost/proceedings/ecc-2013/data/papers/0463.pdf>
- [18] J. P. Hespanha and A. S. Morse, "Stability of switched systems with average dwell-time," in *Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No.99CH36304)*, vol. 3, 1999, pp. 2655–2660 vol.3.
- [19] N. Diolaiti, G. Niemeyer, F. Barbagli, and J. K. Salisbury, "A criterion for the passivity of haptic devices," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*. IEEE, 2005, pp. 2452–2457.
- [20] D. Tran, King-Wei Hor, A. Kamani, V. Lessoway, and R. Rohling, "Instrumentation of the Loss-of-Resistance Technique for Epidural Needle Insertion," *IEEE Transactions on Biomedical Engineering*, vol. 56, no. 3, pp. 820–827, Mar. 2009. [Online]. Available: <http://ieeexplore.ieee.org/document/4760227/>