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► To cite this version:

Hugo Talbot, Nazim Haouchine, Igor Peterlik, Jeremie Dequidt, Christian Duriez, et al.. Surgery Training, Planning and Guidance Using the SOFA Framework. Eurographics, May 2015, Zurich, Switzerland. hal-01160297

HAL Id: hal-01160297

<https://inria.hal.science/hal-01160297>

Submitted on 5 Jun 2015

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Surgery Training, Planning and Guidance Using the SOFA Framework

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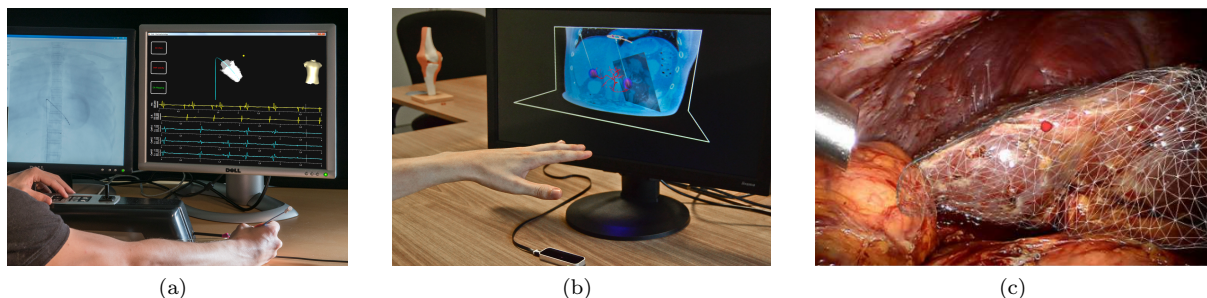


Figure 1: Simulation examples implemented in SOFA: (a) Virtual training in cardiac electrophysiology, (b) patient-specific planning of cryosurgery and (c) intra-operative guidance for laparoscopy.

Abstract

In recent years, an active development of novel technologies dealing with medical training, planning and guidance has become an increasingly important area of interest in both research and health-care manufacturing. A combination of advanced physical models, realistic human-computer interaction and growing computational power is bringing new solutions in order to help both medical students and experts to achieve a higher degree of accuracy and reliability in surgical interventions.

In this paper, we present three different examples of medical physically-based simulations implemented in a common software platform called SOFA. Each example represents a different application: training for cardiac electrophysiology, pre-operative planning of cryosurgery and per-operative guidance for laparoscopy. The goal of this presentation is to evaluate the realism, accuracy and efficiency of the simulations, as well as to demonstrate the potential and flexibility of the SOFA platform.

1. Introduction

The current medical curricula usually involve years of theoretical learning and the practical aspects of medical training are often underestimated. Nevertheless, surgeons and interventional radiologists are supposed to practice during an important amount of time to be considered as experts in their respective domains. Therefore, a high-fidelity medical training allowing for quantitative assessment without posing any ethical issues is of a paramount interest. Further, new

types of interventions have been proposed, either to reduce the patient's discomfort (pain, time spent in the OR and the hospital), or to aim at curing complex pathologies. While requiring a high degree of dexterity, the execution of these interventions is often significantly patient-specific necessitating detailed pre-operative planning and/or intra-operative guidance.

For training purposes, virtual simulators can provide a realistic and configurable environment where any surgical scenario can be reproduced and repeated

without any restriction and ethical issues. Moreover, they allow to assess the performance of the trainee, thus allowing to standardize the medical curriculum. When planning a surgery, patient-specific information is extracted from the pre-operative data. This can then be integrated in physics-based models in order to virtually evaluate the effect of the procedure and therefore assist the clinicians in the selection of the optimal therapy. Finally, computational models may provide additional valuable information directly during the intervention, e.g. an augmented view based on pre-operative data.

Despite the significant development in the field of medical simulation, some fundamental problems still hinder the acceptance of this appealing technology in day-to-day clinical practice. In particular, the multi-disciplinary aspect of medical simulation requires the integration, within a single environment, of leading-edge solutions in areas as diverse as visualization, biomechanical modeling, haptics or contact modeling. This diversity of problems makes it challenging for researchers to make progress in specific areas, and leads quite often to duplication of efforts.

In this paper, we present a versatile platform SOFA [FDD*12] capable of modelling a large set of physical phenomena occurring inside the human body. Three different applications have been chosen from a larger set of existing simulations, dealing with electrical, thermal and mechanical behaviour. Moreover, these simulations are dedicated, respectively, to the training, planning and guidance as shown in Fig. 1.

2. Training

Virtual training prevents medical students from early manipulation of real patients. The development of simulation used for medical training usually requires important computational power, since realistic behaviours are key to deliver a high-fidelity experience to the trainee. Further, the quality of interaction with

the simulator (usually via visual and haptic rendering) is also of a paramount importance. All these constraints make the development of training systems time-consuming, i.e. expensive, thus limiting the deployment of virtual simulators in standard medical curriculum.

The first application based on the simulation framework SOFA is an interactive training system for interventional electrophysiology procedures (see [TSD*14] for details). The simulation deals with virtual ablation of a cardiac arrhythmia which is caused by an abnormal electrical activity in the myocardium (heart walls). We consider a right-ventricular (RV) extrasystole, i.e. ventricular tachycardia caused by ectopic foci. An ectopic focus is an abnormal pacemaker area (outside of the sinoatrial node) that initiates abnormal self-generated beats.

The procedure starts by inserting the catheters from the femoral vein up to the RV under fluoroscopic imaging. Once inside the ventricle, an electrophysiology mapping is performed by exploring the endocardial surface with catheters to map the activation patterns. These patterns allow to locate the ectopic focus responsible for the arrhythmia. Each pathological region found by electrophysiology mapping will eventually be ablated using RF: heating the cardiac tissue next to the ectopic focus leads to cellular death, thus suppressing the related abnormal beats. Until now, residents in cardiology train on patients by separately learning each step of the procedure under the supervision of a senior cardiologist.

In order to shorten the training period and to allow a virtual training on complex patient cases, we propose a training system based on the simulation of the cardiac electrophysiology, as illustrated in Fig. 2. The phenomenological model from Mitchell Schaeffer [MS03] thus reproduces the human electrophysiology using physiological parameters. To reach real-time performances, the model is implemented into GPU [TMD*12] using the CUDA toolkit. Furthermore, the complexity of the procedure highlights the importance of interacting with the electrophysiology *in silico*. We therefore propose interactive features reproducing the clinical gestures: extra-cellular potential measurements, reconstruction of the endocardial surface, mapping of ventricular activation times, RF ablation as well as electrical stimulation using the catheter. A tracking device is connected to the simulation, so that trainees can use real catheters to interact with the simulated heart.

This simulator has been recently evaluated by seven cardiologists (four novices and three experts). The average grade given to this virtual experience amounts to 2.50 out of 3, which is very encouraging.

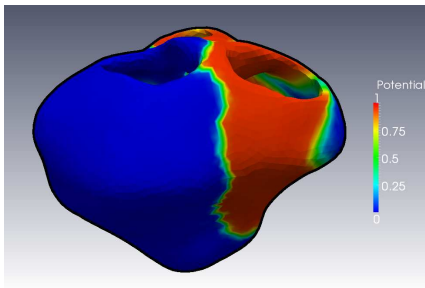


Figure 2: Transmembrane potential activity simulated using the Mitchell-Schaeffer model.

3. Planning

Beyond training, clinicians ask for innovative tools that can assist them in the pre-operative planning of an intervention. Using the patient information acquired before the operation, physics-based simulations allow to simulate the effect of a therapy with no risk to the patient. The clinicians can thus virtually assess different strategies and select the optimal procedure. Compared to a training simulation, a planning system requires a high accuracy to ensure reliability. Constrained by the time elapsed between the pre-operative acquisition and the intervention, the computation must also be efficient.

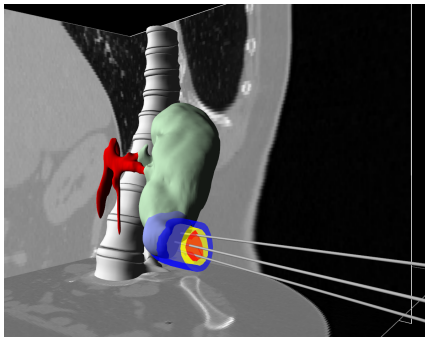


Figure 3: Virtual isotherm surfaces (0°C in blue, -20°C in yellow, -40°C in red) obtained after a cryoablation cycle using three cryoprobes

The second application implemented in SOFA is a tool allowing for interactive cryosurgery planning [TLBDC14]. The cryosurgery or cryotherapy consists in destroying cancer cells by extreme cold delivered at the tip of a needle-like probe. Only guided by CT or MR images, radiologists might carry out several treatment cycles to freeze the entire tumor to a temperature of 233K to 248K. This technique has been applied to treat many kinds of tumors, such as breast cancer, primary or metastatic liver neoplasms, renal, lung, pancreas, and prostate cancer. The volume of the iceball must be slightly larger than the volume of tumor to ensure the effectiveness of cryosurgery but minimize freezing damage to nearby healthy tissue. To guarantee an optimal tumor ablation, a very careful planning must be performed to define the best position for each probe as well as the type of probe. This planning is currently done qualitatively, based on experience, and can take several hours, with a result that is often different for the expected one.

Our simulation relies on the Pennes' model [Pen48] to compute the evolution of the temperature field. As for the electrophysiology simulation, a GPU code is employed to improve performances. Coupled with the

Leap motion technology, the radiologist can place virtual needles and evaluate their effect within clinical time. Synthetic (in water) and experimental validations have been performed proving that our approach is relevant.

4. Guidance

Beside the surgery training and planning, another major need from clinicians is surgical guidance. While the practitioner is performing the operation, a guidance system provides enriched visual feedback. This is especially useful with the emergence of minimally invasive surgery (MIS) where the visual information is often strongly limited. It can be used for example to avoid critical area such as vessels or to highlight the position of a tumour during its resection. In the MIS technique, the clinician does not interact with organs directly as in the open surgery, but manipulates instruments inserted through trocars placed in small incisions in the wall of the abdominal cavity. The surgeon can observe these instruments on a display showing a video stream captured by an endoscopic camera inserted through the navel. The main advantage of the method resides in reducing pain and time recovery, in addition to reducing bleeding and risks of infection. However, from a surgical standpoint, the procedure is quite complex since the field of view is considerably reduced and the direct manipulation of organs is not possible.

With the advances in surgical vision [MHMB*13] and the capability to compute virtual organs pre-operatively, Augmented Reality (AR) has been considered as a suitable technology to counteract the limitations of MIS and lead the community to propose innovative methods bringing AR in surgery [NSMM11]. However, most of previous work consider the organs as rigid or subject to cyclic motion, thus neglecting the elastic behavior of the tissues. Making such a strong assumption necessary leads to significant errors.

Based on the SOFA framework, we introduce an application dedicated to augmented reality. Based on mechanical constitutive laws, the simulation estimates, in real-time, the position of the internal structures of the liver (vessels and tumors) by taking into account liver deformations [HDP*13]. Our framework relies on the corotational model and takes into account the liver heterogeneity and anisotropy due to veins and arteries. This model is driven by external forces that arise from a partial 3D motion estimated on the liver surface from a stereo video stream. The physics-based guidance was tested on multiple datasets. It has been first assessed through an experimental protocol to quantitatively validate the accuracy of the approach. We proved that the error between the estimated and actual positions of an artificial tumor

implanted in a phantom liver remains below 5 mm, i.e. lower than current surgical margins. Second, the same validation protocol has been used on porcine liver and the same accuracy was measured. Finally, visual assessment on an in-vivo human liver shows the capability of our framework to ensure long-term augmentation in a real environment with the presence of specular lights, beating heart, respiratory motion and instrument occlusions.

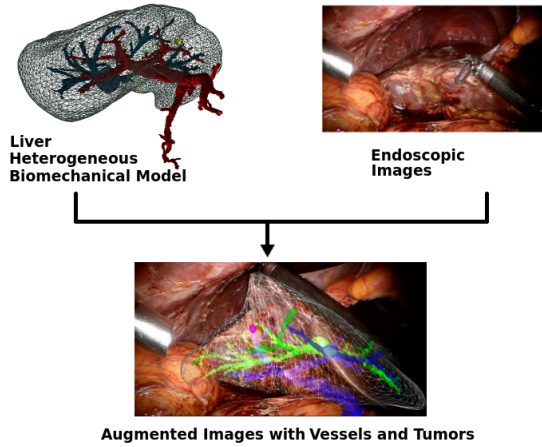


Figure 4: Augmented reality for laparoscopic liver surgery. The purpose of AR in surgery is to visualize internal structures such as tumors, superimposed on the video stream, in 3D and in real-time.

Furthermore, the automatic definition of appropriate boundary conditions (such as surrounding ligaments) as well as the semi-automatic approach for the initial alignment of pre- and intra-operative data [PHRC14] have recently been integrated to the framework, and tested on three patients (offline).

5. Conclusion

It has been demonstrated previously that physics-based simulations provide an interesting solution in medical training thanks to its flexibility and risk-free environment. Similarly, simulations can be effectively employed in patient-specific operation planning as well as they can be used to provide additional information in advanced guidance.

In this paper, we presented three simulations implemented in the same SOFA platform, but each represents a different application related to medical training, planning and guidance, respectively. We believe, that using a single platform significantly facilitates and accelerates the development of new simulations. Moreover, it allows for efficient re-using of components: e.g. the mechanical model of vascularized liver

can be employed for other organs and structures such as kidney or brain, requiring only partial modifications. Thus, the unified platform seems to be the efficient solution, allowing for significant reductions in time, effort and cost, needed for development and maintenance of complex simulations in health-care.

Acknowledgements

The authors would like to thank all the SOFA contributors.

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