Medical training simulators for bilateral sagittal split osteotomy and regional aneasthesia in virtual environments

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Abstract:

Regional anaesthesia and bilateral sagittal split osteotomy are both clinical procedures which require profound theoretical knowledge and specific motor skills for successful accomplishment. As training opportunities are rare and can be harmful for patients, we started the development of two virtual reality-based surgical training simulators. While visualization is an important topic on its own, here the research challenges are predominantly interaction and real-time simulation. More specifically, solutions for realistic haptic feedback, multi-layer tissue deformation and simulation of crack propagation have to be found. In this article we present the chosen methods and some preliminary results.

Keywords: virtual reality, physics simulation, regional aneasthesia, bilateral sagittal split osteotmoy, medical training, haptics, patient-specific modeling

1 Problem

Training opportunities for surgical situations are limited. Prop-based training, cadavers and animals all have shortcomings. Learning on patients is time-consuming, instructor has to be present, and bears risks. For minimal invasive "keyhole" procedures numerous simulators have been developed. However, only few open surgery simulators exist. In this paper we focus on two distinct types of procedures: bilateral sagittal split osteotomy (BSSO) and regional anaesthesia (RA).

The BSSO represents a major surgical procedure in maxillofacial surgery. Today`s most commonly used technique has been developed by Obwegeser and Trauner in the modification according to Dal Pont [1, 2]. It permits relocation of the mandible in all three planes of space in various ways. After surgically freeing the jaw corpus and ramus of the mandible, a predetermined breaking point is created on the lower mandible. For this purpose a bone saw or Lindemann's cutting burr is used to mark the planned osteotomy line and hereafter deepened until the outer hard bone layer is completely severed. Chisels with different sizes are now inserted into the prepared line, which is then carefully broadened by twisting the tools. The drilling and the subsequent controlled splitting of the jaw bone are the most important and also most critical steps of this operation. In cases where complications occur during the division, the mandible and the contained neurovascular bundle could be damaged beyond repair. Consequences could range from necessity of a temporary intermaxillary fixation to a complete irreversible paralysis of the bottom lip and chin. Therefore, we aim at developing an interactive simulator (BSSOSim) which provides a training tool to learn the basic manual skills but also to rehearse difficult scenarios. The crucial surgical steps of drilling and breaking will be the focus of the simulation.

The second simulator's primary goal is to provide a needle-interaction training environment for regional anaesthesia (RA). Needle simulation is an important topic and has a broad field of applications in clinical procedures, e.g., biopsies, injections, neurosurgery, brachytherapy cancer treatment and RA. We focus on RA because training opportunities are limited and there is a lack of available virtual reality-based (VR) RA simulators. RA requires profound theoretical knowledge and repeated performance to gain sufficient manual skills for successful accomplishment of such procedures [3]. Although, there is widespread utilization of simulators to learn and improve medical skills in general and sophisticated full-scale simulators for general anaesthesia, the use of such mannequins for RA training is limited by nonreflecting the patient variance, inaccurate representing of biological tissue, and physically wearing from repeated use. In an interdisciplinary approach, we therefore launched the Regional Anaesthesia Simulation (RASim) project (http://www.rasim.info/), which is composed of subject-specific data set creation and VR-based simulation [4].

2 Methods

Both simulators are based on VR-technology, with a real-time, human-in-the-loop physical simulation. Necessary preconditions for a life-like simulation are anatomical data sets. Thus we first describe acquisition and modelling in section 2.1. and then give an overview of the simulators systems in 2.2.

2.1 Data sets and training scenarios

For the BSSO simulator, anatomical models will be extracted from cone beam CT-Scans, which are already done in context of routine preoperative diagnostics and planning. These data sets will function as the foundation for models used in the XFEM simulation and visualization. One requirement is the segmentation of the data into jaw-bone and surrounding soft tissue. The extraction of the neurovascular bundle will be done indirectly by the segmentation of the mandibular canal. The mandible anatomies strongly differ among patients. Therefore, another important aspect of the project will be the collection of operation scenarios which should have a large variety with respect to the morphology, the bone architecture and the course of the neurovascular bundle. In this context, we will outline standard situations, namely comparatively simple operations, as well as special scenarios.

To provide the RA simulator with subject-specific data and to support various training scenarios, a content creation pipeline has been established [4]. Because routine diagnostic scans could not be used, the database is built with inputs based on non-invasive magnetic resonance imaging (MRI) and customized magnetic resonance angiography (MRA). For *imaging* the scanner protocols have been adjusted together with radiologists [5] to improve the contrast of morphology in MRI scans and to visualize blood vessels in MRA without contrast agent. Tissue types, that are relevant for the simulation (e.g., skin, fat, muscle, blood vessels and bones), are segmented in a *data processing* step. For 3D *nerve modeling*, we have created a tool to construct spline-based virtual nerve cords interactively with control points in virtual environments [6]. To import datasets into the *VR simulator*, the physician can choose a subject in a *selection* step. In a *3D nerve instantiation step*, the spatial configuration of the nerve cords can be (optionally) varied randomly in order to obtain a unique virtual patient for each training session. Parts of the data base and pipeline (especially the nerve modelling) will be reused for the BSSO simulator.

2.2 Simulators

In the planned BSSO training application, the operator sees a virtual setup of a jaw surgery on an immersive display, e.g., an L-Bench. Furthermore, she operates surgery tools by means of a combined input/output device enabling interactive drilling and breaking of the mandible. An important goal of the simulator is the training of specific motor abilities which are needed for a positive outcome of the split osteotomy. Therefore, one prerequisite to the system is a reproduction of the real interaction with a high degree of realism (see Fig. 1b). For this purpose we utilize a haptic input/output device with 6 degrees of freedom (6DOF) (see Fig. 1a). The end effector of the device is mapped to the grip of the currently used virtual tool (e.g., bone saw or drill). Through these virtual tools the operator is not only able to, e.g., put pressure on the virtual jaw, but also concurrently feel its resistance. The necessity of highly realistic interaction requires a high quality real-time simulation of the occurring physical effects, including the force exchange between tool and bone and the induced structural changes of the latter. The bone splitting can be described from an engineer’s point of view as a crack propagation problem. Hence, we chose the extended Finite Element Method (XFEM) [7], which is well suited to the modelling of this kind of problem. Unlike the classical FEM, XFEM does not need an alignment of the FEM grid with discontinuities and singularities. This is an important advantage as the positions of the discontinuities and singularities change during the crack propagation. In the classical FEM, a permanent, expensive remeshing is required in order to follow the crack; this is not required within the XFEM [8].

For RASim a prototype has been developed for the femoralis block in the inguinal region. First, the user has to localize important anatomical landmarks by palpation with a virtual hand. The extended index finger is used as a ``sensor" and can be moved over the skin surface of the virtual patient (Fig. 1d) with a PHANTOM Omni Haptic Device. Afterwards, the virtual hand is replaced by a virtual needle, which is coupled to the input device and can be moved and rotated freely outside the virtual patient (Fig. 1c). Once the skin surface has been penetrated, the movement (of the virtual needle) is currently restricted to the injection direction (i.e., along the axis of the needle shaft). At any time during the training procedure a virtual aspiration can be triggered by the trainee, to check whether the needle tip is inside a blood vessel. To simulate needle interaction and electric impulse transmission, a novel approach based on electric distances has been developed. Hence, if a virtual nerve cord is within emission range of the needle tip, corresponding muscular motor responses are displayed in real-time. The amplitude of the electric impulses can be controlled by a 2D-GUI. In case of missing motor feedback, either the needle can be relocated or the user can switch back to palpation mode to search for a better insertion site. Once the trainee has reached the desired target area, the needle can be fixed and individual anatomical layers can be turned transparent to offer a review opportunity to gain better insight.

Fig. 1: a) 6DOF Haptic Feedback Device. b) Demonstration of the tool movement for the split step in the BSSO procedure. c) RASim prototype with an anatomical dataset of the hip region and a generic upper leg to show animated muscle responses. d) RASim used for virtual palpation.

3 Results

Because the BSSO project has been initiated recently, there are no preliminary results yet. However, in ongoing work shared components of both projects have been identified and are being aggregated in a medical simulation library.

The RASim content creation pipeline has been used for five subjects so far. We plan to extend the database with more cases and also work on other body regions. MRI and MRA data were obtained from five individuals from the inguinal region. Relevant data were successfully extracted employing our new software. Further differentiation of anatomical structures was realised using an ontology subdividing and describing tissue types as well as cavities. As nerves cannot be sufficiently captured, virtual nerve cords were modelled according to a hierarchical data structure along anatomical landmarks. The simulator utilized this data and consistently applied the developed modules for collision detection, virtual humanoids, interaction, and visualization. Needle interaction and electric impulse transmission was simulated realistically. The RASim prototype has been systematically evaluated with ten residents and consultants using a 24-item questionnaire on a 5 point Likert-scale ranking between 1 (best) and 5 (worse) [4]. Furthermore, in this study, our subject-specific data sets have been compared with a current state-of-the-art commercial dataset (Zygote, USA, http://www.3dscience.com), that consists of geometry and textures representing the anatomy of a male subject The user study showed an overall acceptance (1.8 ± 1.6) with the ease of use of the simulator. Also the anatomy and identification of landmarks were highly rated (2.2 ± 1.6), both for our and the Zygote data sets. Further, we did not reveal any advantage of the commercial dataset. Despite the use of a 3D navigation, 90% of the participants stressed the importance of the incorporation of sophisticated haptic feedback allowing the tactile perception of tissue resistance.

4 Conclusion & future work

The evaluation of the RASim prototype stressed the need for haptic feedback in surgical training applications. Therefore, we are currently working on haptic simulation with support for a novel bi-manual interaction for concurrent palpation and needle guidance in the RASim project. For realistic feedback with multiple tissue layers we are adapting a constrained-based needle simulation approach [9]. For the BSSO trainer 6DOF haptic rendering and physics simulation based on XFEM are utilized and have to be optimized for the real-time requirements. Both described training simulators employ commercially available VR-Technology. Being standardized, it is possible to use the same hardware for multiple training applications and thereby reduce costs and at the same time increase accessibility. Due to the haptic feedback the simulators will not only be suitable to learn medical concepts, but also to increase the specific motor skills needed for the target interventions. To further facilitate education and training, operation guides and evaluation criteria will be integrated into the simulators. The content creation pipeline aims to minimize the effort of integrating patient-specific data into training simulators. It is a first step towards the usage of training simulators, beyond educational purposes, for rehearsal of difficult real interventions. Additionally, as ultrasound guided RA is an emerging technique, we plan to include this aspect into the RASim trainer by adapting the work of Vidal et al. [10].

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