Simulator for Regional Anaesthesia in Virtual Environments with Electric Nerve Stimulation

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Abstract

In this paper we present a virtual reality-based medical training application for regional anaesthesia procedures. The application consists of a simulation framework that employs new designed data structures representing an articulated virtual patient with anatomical features. The most essential component of the simulation is the electric impulse transmission. In a novel approach we enable the impulse traversal through inhomogeneous soft tissue to reach nerve cords and activate motor response. Additional components of the simulator are also described briefly: visualization techniques and interaction metaphors. A prototype had been implemented to demonstrate the usage of the simulator for a nerve block of the lower limbs. The resulting virtual reality-based simulation system is being evaluated by medical residents.

1. Introduction

Anaesthetics are used in everyday practice at hospitals for pain treatment and during medical procedures. They are used to temporary disable parts of the nervous system, i.e., the sensory and motor function of nerves are suppressed. Global anaesthesia is the most common form and renders the patient unconscious. This is an intentionally induced state that is used for most major surgeries. The sensory system is shut down so that no pain can be felt and the motoric system is blocked to inhibit movement during the procedure. However, a global anaesthetization is expensive, involves risks and prolongs the stay at a hospital for the patient. It means a considerable amount of stress for the organism and may be fatal if the patient is not in a good physical condition.

Regional anaesthesia (RA) is a less invasive alternative and can be applied in certain situations. With a specialized cannula, the anaesthetist can locate specific nerves to block selected regions of the body. The tip of the cannula emits electric impulses which cause a perceivable feedback (twitches of muscles) if it is in close proximity to the nerve. This procedure is done iteratively with position changes of the cannula until the desired nerve is located. Then the aneasthetics can be released through the cannula in order to temporary deactivate that nerve. Compared to global anaesthesia the human organism is much less stressed and the amount of aneasthetics can be significantly reduced. However, the localization of the nerves is a non-trivial tasks, since nerve cords can neither be adequately captured by medical imaging techniques nor can they be palpated. Additionally, there are patient-specific variations in the anatomical branching and location of nerve cords. Thus each procedure can differ and the anaesthetist has to rely on his experience and always perform a careful search process. Complications can occur and there exist some risks. For example, it must be avoided to touch a nerve cord with the needle tip which could lead to permanent damage. Furthermore, before applying the anaesthetics there is always a checking procedure to make sure the needle tip is not inside a blood vessel which would transport the anaesthetics directly to the heart and paralyze its muscle structure.

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With proper training and gathering of routine experience these risks can be minimized. But it is difficult to train this kind of procedure. Training on patients can be unethical and while cadavers can be used to learn the anatomy and to practice motor skills, the observable feedback to electric stimulation is missing.

The goal of this work is to provide a training framework for anaesthetists, so that they can get used to specific procedures of regional anaesthesia. By modeling rare scenarios and simulating complications, not only novices but also intermediate and experts can make use of the simulator application.

2. Related Work

Software-based medical simulators cover many different topics (e.g., minimal invasive surgery, brain surgery, and suturing). A survey can be found in [11]. We want to focus our overview on simulators dealing with regional anaesthesia and related techniques..

There are many needle simulators for different areas of applications, e.g., acupuncture [9], lumbar puncture [4, 6] and intravenous procedures [12]. These works are interesting in regards, to the soft-tissue simulation and deformation and because of the haptic force feedback approaches. There are also examples of simulators for regional anaesthesia and epidural blocking procedures [2, 5]. These two examples focus on the epidural region of the spinal cord where usually the focus is more on the haptic feedback of the needle and no electric stimulation is employed. One of the most recent simulators for regional anaesthesia [8] utilizes a commercially available three-dimensional anatomical virtual patient model dataset as basis [7]. Muscle contractions and limb movements are induced by a very basic geometry-based nerve stimulation that is not described in detail.

All these approaches provide good results and enable basic training. Still, one major restriction of most solutions is the use of static datasets. However, for the often performed peripheral blocks of limbs it is important to have movable datasets, i.e. an articulated patient model. Furthermore, the simulation is often simply based on a rule-set derived from empirical data and thus hard to extend to new regions or new datasets (of other patients).

Therefore we propose a universal method for electric impulse propagation which is the most essential part in regional anaesthesia simulation. Before introducing this new algorithm in section 5, we first describe the data acquisition in 3 and the simulator application in 4 which sets the context for the nerve simulation.

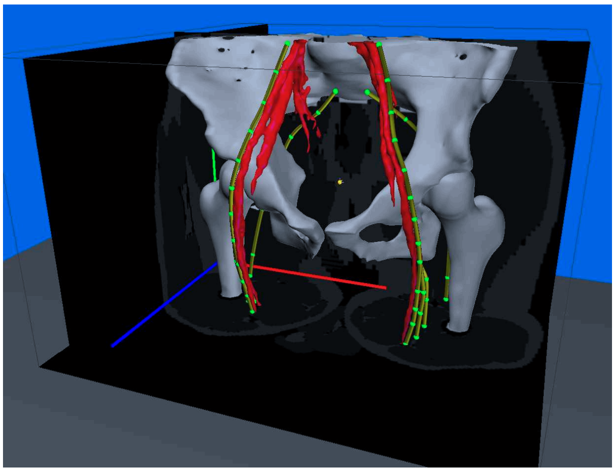

Figure 1. Example of virtual patient model for the hip region. 3D modeled virtual nerve cords are shown together with DICOM slices of MRI data, an adjusted skeleton geometry and blood vessels that have been extracted from an angiography MRI scan.

3. Virtual Nerve Cords

3.1. Medical Image Acquisition & 3D Modeling

Current medical imaging techniques can not visualize peripheral nerve cords. Therefore they cannot be extracted via contour algorithms from MRI scans [17]. Because of this we provide tools for manual modeling of nerve cords. Other anatomical structures, e.g., bones, blood vessels and muscles are used for orientation during the modeling process (see Fig. 1). These structures can either be extracted with state of the art segmentation algorithms from provided MR images or already available geometries can be adjusted and combined with the other structures to construct a virtual patient model. The adjustments can be as simple as translations and scalings of a whole geometry, but some non-trivial transformations such as scalings of specific geometry parts and other non-linear deformations may be required as well. Additional to polygonal objects, the MR images themselves can also be displayed to support the modeling process.

To create nerves or similar structures, e.g., lymph and blood vessels, the user only has to set new spline control points using an input device that can either be a six degrees of freedom (6DoF) device or a simple two-dimensional mouse [19]. If a control point has been selected before creating a new spline, the latter will connect this existing point and a new created one. Otherwise, the spline will connect two new points that are automatically created by the system. Whether control tangents have to be provided by the user depends on the selected interpolation technique. Linear interpolation and Catmull–Rom interpolation require no user input, as the tangents for a control point in the latter case are computed from its neighbours, and are not required at all for

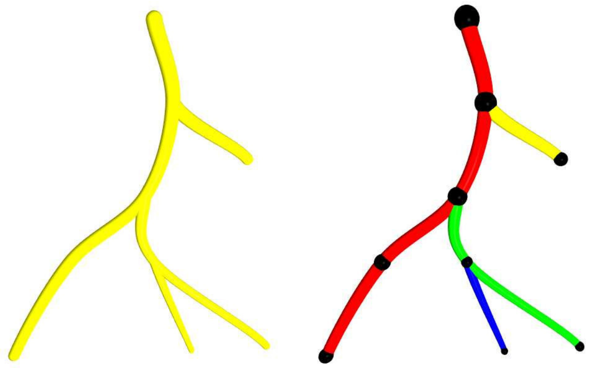

Figure 2. Example of the virtual nerve data structure: schematic illustration of a nervous system on the left side and the corresponding hierarchical data structure for simulation on the right side.

linear interpolation. Therefore, a combination of automatic computation of tangents (Catmull–Rom) and manual definition (Hermite) for selected points is the fastest and most efficient way.

3.2. Virtual Nerve Data Structure

We use a hierarchical tree data structure for modeling and simulating peripheral nerve cords [19]. Within this data structure, nerve sections are represented by functional nodes and spline curves. Each spline curve is defined by control points attached to movable anatomical structures, e.g., bones and muscles.

The data structure representing the virtual nerves is divided into two different levels (see Fig. 2). Each node holds a list of splines while each spline in turn features two control points. Control points are shared between neighboring splines to create continuos curves and branches. Since each node has exactly one parent and an arbitrary number of children, a hierarchical tree structure is built. Nerves which innervate muscles (other types of nerves are irrelevant for our purpose) end at the adjacent muscle with a *myoceptor*. This anatomical entity translates the electric impulse to muscle stimuli. In our data structure, these nerve ends are represented by specialized control points. In summary, to represent the peripheral nervous system the data structure consists of nerve nodes (for traversal in simulation), nerve splines that in turn are defined by nerve control points and associated tangents. The latter are used as parameters for standard interpolation techniques, e.g., Hermite spline interpolation, to compute curve segments between two neighbouring control points and thus build a spline curve that interpolates all control points.

By abstraction both geometric and functional characteristics can be reused for other anatomical cords such as blood vessels or lymph vessels.

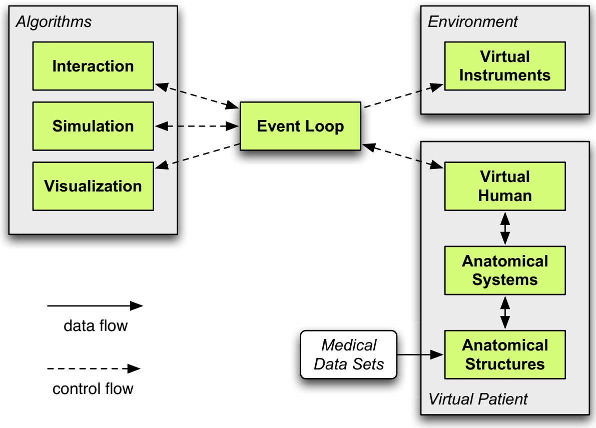

Figure 3. System architecture of the simulator with its components, showing the separation of algorithms and data.

4. Simulator Application

Our system enables simulation of regional anaesthesia procedures in virtual reality and is based on previous work [18, 3]. The application is implemented within the virtual reality toolkit ViSTA [1] and makes use of several modules for collision detection, virtual humanoids, interaction and visualization. First we provide an overview of the system architecture and then describe some selected components in more detail. The simulation algorithms are afterwards described in Section 5.

4.1. System Architecture

The system architecture (see Fig. 3) has been designed to separate data structures from algorithms. This contributes to extensibility and interchangeable datasets for patient-specific data. In previous work we have already proposed a systematic approach to separate functional anatomy from static data in different data structures: anatomical systems and anatomical structures, respectively [21]. An event loop in the application layer monitors interactions, issues collision detection between virtual instruments and the virtual human, triggers simulation tasks and propagates changes to the visualization algorithms.

4.2. Visualization

In order to enable explorative analysis and to interactively render geometric representations of the virtual patient and the instruments we provide visualization algorithms. For deformable skin surfaces we use vertex blending [10]. To get an anatomic view, the alpha channel of the skin geometry can be modified to see through to geometric representations of visualizations of virtual bones, musculature, vessels and nerves.

For virtual nerve cords we provide two approaches.

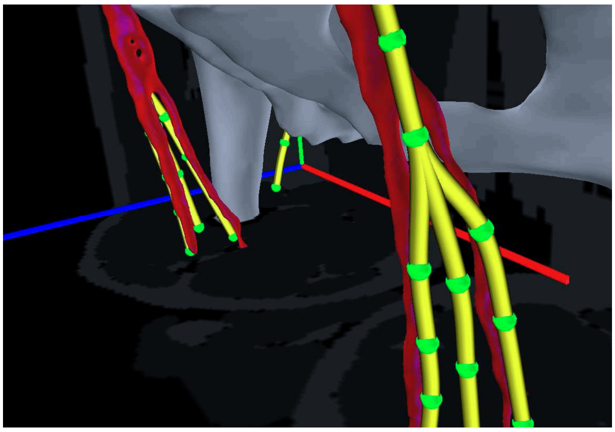

Figure 4. Visualization of nerve cords with shaded tubelets for fast rendering of complex structures. Additionally, the control points of the nerve splines are visualized as green spheres.

Polygonal lines can be used for thin nerve cords and are also a very fast visualization technique. To adequately represent thicker cords we use so-called tubelets [15] which are accelerated and shaded by programmable graphics card (see Fig. 4)

To show muscle twitches (that are caused by electric nerve stimulation) and that are propagated through fat tissue to the skin surface we use morphing algorithms. Two geometries are used: the first represents the anatomical region of interest with the muscles relaxed, the other shows the fully contracted state. According to the triggering of nerves and the calculated contraction state of the muscles, we morph the meshes in between these two extremes to produce reasonable intermediary results.

4.3. Interaction

Besides anatomical realism, one of the most important requirements is an intuitive interaction interface. Therefore, the interaction algorithms support a range of different input devices (e.g., VR-devices like tracking systems and a 6DoF mouse, and also keyboard and a 2-D mouse) and allow to record a session during training for later evaluation. This allows to navigate through the virtual environment and to change the view relative to the virtual patient. A picking metaphor allows to interactively manipulate the posture of the virtual patient and thus provide better access for the insertion of the needle. Customized haptic input devices are used for palpation [20] to localize the needle insertion site realistically and are also used for needle operations. As a first approach, we give a very rudimentary haptic feedback once the virtual needle has entered the body. This is based on the virtual proxy approach [13] and the use of constant material properties for fat tissue and muscle tissue. The properties of the virtual needle (e.g., impulse strength and impulse duration) can be changed via a two-

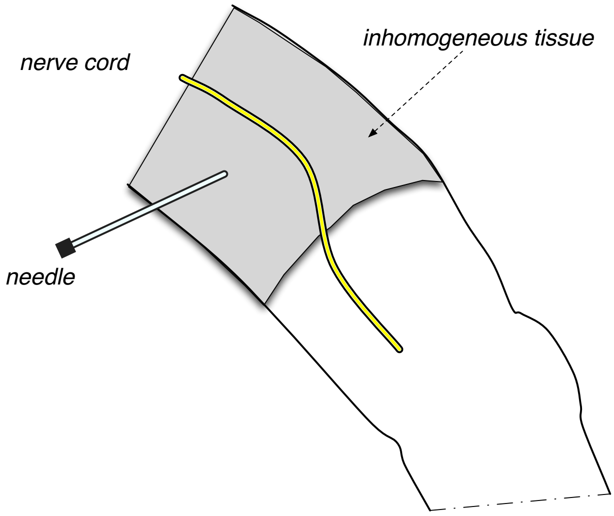

Figure 5. The electric impulse emitted from the needle tip must be simulated through the soft tissue and the intensity at nearby nerve cords must be calculated.

dimensional graphical user interface in order to support a systematic search process for the nerve.

5. Nerve Impulse Simulation

The simulation algorithms operate on the data structures described in Section 3.2. Our novel approach simulates the electric impulse transmission through soft tissue, the traversal through nerve cords and the resulting muscle activation.

5.1. Electric Impulse Transmission in Soft Tissue

The electric impulse transmission is one of the most essential parts of regional anaesthesia and must be simulated properly. When the needle is inserted in a region of inhomogeneous tissue the propagation of electric impulses must be simulated. It must be determined if nearby nerve cords are reached (see Fig. 5) and the intensity of the electric impulse must be calculated. Depending on the intensity the nerve cords will depolarize and transmit a signal, which leads to motor (muscle) response. We have implemented two different algorithms: (1) a rule-based approach [8] and (2) a novel approach based on electric distance.

The *rule-based approach* first checks with collision detection whether the needle is inside the body of the virtual patient. Then the shortest geometric distance between the needle tip and nearby nerves is determined. The intensity of the electric stimulation is estimated in an inverse proportional relationship to the length. This approach only works well in homogeneous areas, where different types of tissue have similar electric resistance.

The calculation of the so-called *electric distance* is more accurate and is used in the second approach. The algo-

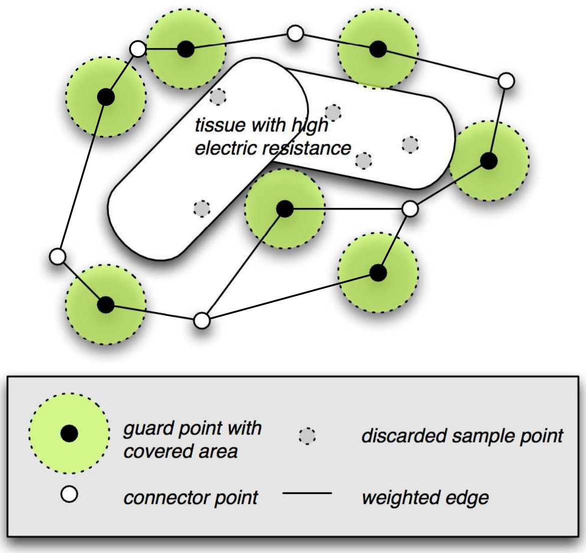

Figure 6. Example of the sample points distribution for the electric distance calculation.

rithm determines the shortest path of electrons through inhomogeneous tissues. First it creates a special search data structure (called roadmap) that is used by path finding algorithms [16]. Sample points are randomly distributed within the area around the needle. Accepted samples (i.e., inside the virtual body) either cover a volume around them (called guards) or are used to connect guard nodes with each other (called connectors). The desired percentage of coverage, the radius of the sphere of a guard (the extent of the volume it represents) and the maximum distance between guards and connectors are parameters that define the quality of the simulation, and also influence processing time. From these samples, a bi-directional graph can be generated [16, 14], whose edge weights are closely related to the electric resistance of the tissue between the nodes (see Fig. 6).

The construction of such a roadmap cannot be performed in real time and thus is pre-calculated. In a second step, the built data structure can now be used to determine the shortest path in terms of electric resistance from the tip of the needle to the nerve whose control points are part of the samples. This step is performed iteratively in each simulation cycle during the search process with the needle.

5.2. Nerve Stimulation, Impulse Transmission and Muscle Activation

A nerve is stimulated and thus releases an impulse once the electric depolarization due to the electric impulses is big enough to induce an action potential. The threshold for such a depolarization is about 20mV or more. Since the time for the recovery of a nerve cell is known, it can be easily calculated how many times the nerve will fire during a specific time period. Now it is important to determine which muscles are affected by these impulses. This is achieved by traversing through the nerve hierarchy. Since nerve cords may split and rejoin, a depolarization at a certain region can cause different amounts of impulses at different muscles. It is known that the intensity of the effect at the muscles is related to the amplitude of the nerve impulse. Unfortunately, there is no specific information about this relationship, as it varies from person to person due to their own individual physical properties. Thus, we use empirical values that are within a plausible interval defined by medical experts.

It should be noted that by the stimulation of nerve cords also sensoric nerves are innervated. This is not yet covered by the simulator because the motor feedback is also dominantly used for observation during the real procedures.

6. Results & Discussion

For the simulation of lower limb nerve blocks [3] datasets of the hip region (see Fig. 1) have been created by anatomical experts using segmented scans [17] in combination with the modeling tools provided by Ullrich *et al.* [19]. Furthermore, the simulator is developed in close collaboration with medical residents and anatomical experts. Preliminary evaluations and discussions of prototypes (see Fig. 7) have already shown high interests of the medical community in using such a tool.

To compare the two approaches for the simulation of electric impulse transmission we discuss their advantages and weaknesses respectively. The rule-based approach is only accurate in areas with homogeneous tissues. The main advantages are the uncomplicated setup and the fast execution time. However, the approximation becomes bad with inhomogeneous tissues and can lead to wrong results. The second approach based on electric distance is designed to return accurate results in inhomogeneous tissue. Choosing good parameters for the sampling and the pre-calculation are some negative points but contribute to reliable results.

Future work will concentrate on further improving accuracy, doing extensive evaluations with medical staff and extending the simulator to new regions.

7. Summary

We have presented a training simulator for regional anaesthesia that is implemented in a virtual environment. A flexible data structure encapsulates and separates functional anatomy, physiological data and geometry extracted from medical imaging data. This modular setup of the data structure and the abstraction from the simulation algorithms allows to exchange patient-specific datasets and to extend the simulator to new regions for other procedures. Due to the limitations of current medical imaging technology an accurate individual patient model can not be created be-

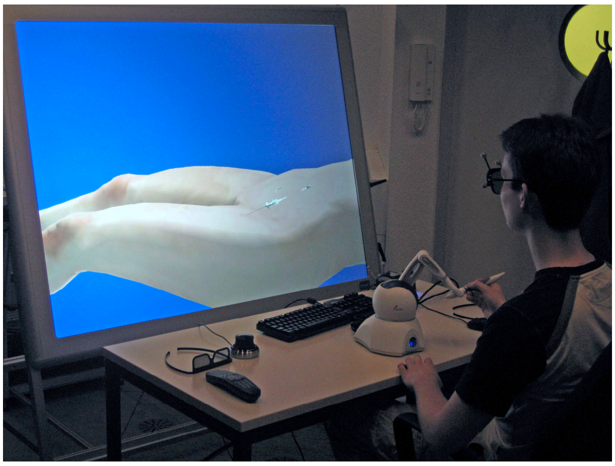

Figure 7. Simulator prototype running on a VR desktop environment with stereoscopic visualization and a haptic input device.

fore an actual procedure. However, the datasets are aimed to be anatomical plausible and are verified by anatomical experts. Therefore the simulator is meant to be used as a training tool and not intended for rehearsal of a procedure with the current state of a specific patient. In summary, we provide a flexible training environment with virtual reality by using multimodal representations (both visual and rudimentary haptic), with intuitive interactions and a plausible simulation.

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