

# Ray-Casting-Based Evaluation Framework for Needle Insertion Force Feedback Algorithms

Andre Mastmeyer<sup>1</sup>, Tobias Hecht<sup>1</sup>, Dirk Fortmeier<sup>1,2</sup>, Heinz Handels<sup>1</sup>

<sup>1</sup>Institute of Medical Informatics, University of Lübeck

<sup>2</sup>Graduate School for Computing in Medicine and Life Sciences, University of Lübeck

mastmeyer@imi.uni-luebeck.de

**Abstract.** Segmentation of patient data often is a mandatory step for surgical simulations featuring haptic rendering. To alleviate the burden of manual segmentation we chose direct haptic volume rendering based on CT gray values and partially segmented patient data. In this study, the fields of application are lumbar puncture and spinal anesthesia. We focus on a new evaluation method driven by ray-casting to define paths from the skin to the spinal canal. In a comparison of our reference system AcusVR to a newer algorithm, force outputs are found to be similar in 99% of the tested paths.

## 1 Introduction

Surgical training systems let surgeons improve skills effectively without any risk. Among others, preoperative planning, anatomic education and training of surgical procedures are the focus of these systems. Technically, the real-time performance for volume visualization, tissue deformation and haptic feedback are of major interest. Regarding the necessary virtual patients, the manual preparation mainly comprises the tedious contouring of organs and structures in CT patient data.

In [1] needle insertion simulation is presented as a challenging field of research with many aspects ranging from mimicking stiffness, cutting and friction forces at the needle tip and shaft to needle bending in real-time.

Haptic feedback in virtual environments has been qualitatively evaluated by [2], the techniques presented there are of key importance for regional anesthesia simulation [3]. However, quantitative evaluation of the proposed algorithms still remains a gap to be filled.

Previously from our group, AcusVR [4, 5] has been published being a realistic and valuable tool for the simulation of needle punctures using a Sensable Phantom 6DOF (Fig. 1). Its major bottleneck is the complete expert segmentation of patient image data. Alternatively, we propose direct haptic volume rendering using partially segmented data [6]. Haptic transfer functions and the segmentation of only a few structures try to provide a mock-up of a complete segmentation, where voxel classification based on a heuristical transfer function set-up fills the gaps between the delineated structures.

Here, we focus on the thorough evaluation of the latter approach by automatically generating a large number of plausible puncture paths.

The paper is organized as follows: First, we describe the data used. Force calculation is briefly reviewed as presented in [6, 7]. Afterwards, we describe the ray-casting method used to evaluate force outputs. Evaluation is done quantitatively by comparing force output from the (modified) reference system AcusVR and the new (modified) approach.

## 2 Methods

One standard abdominal CT patient scan with isotropic voxel size 1.0 mm and 240 slices is used (Fig. 4(a)). The complete segmentation of the virtual patient including bone, ligaments, spinal canal, inter-vertebral disks, fat, muscle, skin and liver is available and used for haptic rendering [4, 5]. The AcusVR system [5] is our gold standard to which we compare force output. The system used here only needs a subset of the segmentations for force output.

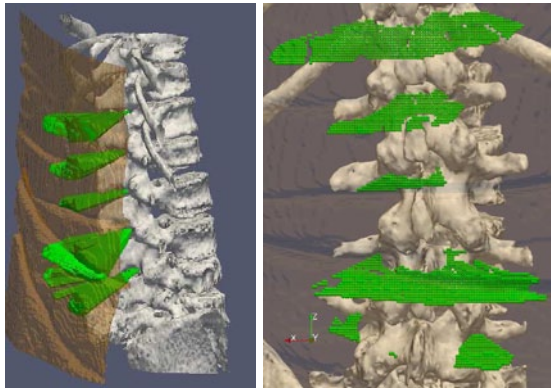
In proxy based haptic rendering [6, 7], the device tip  $\mathbf{x}_t$  is attached to a virtual spring with stiffness parameter  $k$ . On the other end the spring is held back by a proxy  $\mathbf{x}_p$  that sticks to an organ surface. The force between tip and proxy is depended on their Euclidean distance and is given by Hookes law. The calculation for haptic feedback runs at 1000 Hz (Fig. 3).

### 2.1 Direct haptic volume rendering

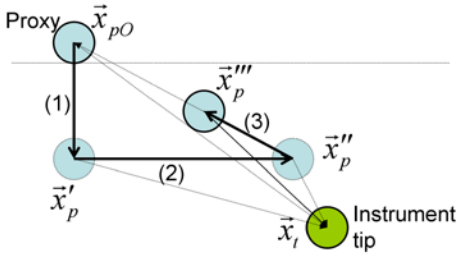
In the method proposed by [6], transfer functions are used to obtain the haptic parameters, if missing a segmented structure at the needle tip. An axial slice



**Fig. 1.** The haptic device and workbench.



**Fig. 2.** Reference paths (green), skin (tan) and bone (white). In lumbar puncture only the lower groups of paths are relevant, while in spinal anesthesia the upper three groups are also interesting. Left: paths targeting the spinal canal. Right: path starting points on the skin.

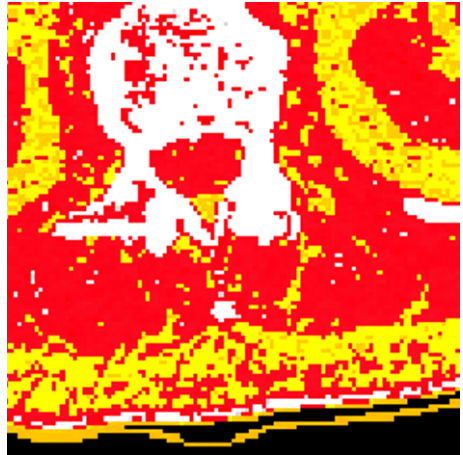


**Fig. 3.** Proxy-based haptic rendering recapitulated: (1) The proxy position  $\mathbf{x}'_p$  for the surface penetrability along the normal vector of a virtual surface is determined. (2) The position  $\mathbf{x}''_p$  tangentially to the surface is calculated. (3) A viscosity term retracts the proxy to the position  $\mathbf{x}'''_p$ .

(see axial slice in Fig. 4(b)) shows plausible tissue classifications between large volume structure such as skin (orange), fat (yellow), muscle (red) and bone (white). In these classes different haptic parameters are valid. However, the small volume and key structures spinal canal and inter-vertebral disk as well as the flavum ligaments fall falsely into the domain of the large volume structures. Consequently, manual segmentations are still provided for these structures.

## 2.2 Evaluation method framework

In our new evaluation framework we define a large number of plausible puncture paths automatically, which are used to steer the needle tip back and forth (“reference paths”) assuming constant velocity (Fig. 2). Hence, absolutely reproducible force outputs are obtained for comparing different haptic force calculation algorithms. A high number of paths consisting of two points are automatically defined to reflect successful user experience.



**Fig. 4.** An axial slice of the reference data: (a) original gray values, (b) visual transfer function applied with tissue classes air (black), skin (orange), muscle (red) and bone (white).

For this aim, ray-casting is used to determine the visibility of the spinal canal from the perspective of the source structure, i.e. the skin. The algorithm checks whether a direct line to the spinal canal can be drawn without touching impenetrable structures such as bone. In other words, we apply the ray-casting technique driven by the 3D-Bresenham algorithm [8]. The Bresenham algorithm features integer arithmetic operations to draw a line from source to target voxels. In our implementation, line-of-sight connections from each skin voxel line to each spinal canal voxel are drawn. For all rays starting from a skin voxel, the shortest path shorter than our needle length (75 mm) is selected as a “reference path”. Taking into account not only one shortest path at a source voxel would exponentially increase the computational burden with little insight gain for the study. The ray-casting algorithm is implemented in CUDA-C and runs in parallel on NVIDIA graphics hardware.

In this study, we end up with 4038 automatically defined paths (Fig. 2) that reflect trainee experience with the system, i.e. starting from the skin they reach the spinal canal target within needle length and do not collide with bony structures. Force rendering of bone has been changed in the newer haptic algorithm due to a new force feedback device, thus comparison results would systematically be biased on bone touching paths. With our new Sensable 6DOF HighForce device much higher forces can be exerted as in the original AcusVR set-up (22 N vs. 7 N).

At every position of the reference path at the needle tip two force outputs are calculated:

1. by the algorithm used in AcusVR and
2. by the method using a partial segmentation and gray values based transfer functions.

As measures to compare the force output values we show the “mean of squared errors” (MSE) and “maximum absolute error” (MAE). For statistical assessment of the errors found the  $p$ -value from two-sided t-tests is used.

### 3 Results

In Tab. 1 the errors for the force outputs along the paths are shown for the two error measures, MSE and MAE. Due to the large amount of errors, we show tail and head of sorted error lists. In the left resp. right half of the table the worst resp. best case paths of this study are given.

For MSE the worst case paths show small but significantly different force feedback from the reference system AcusVR (Fig. 4(a)). In these cases, closer investigation shows air gaps in the assumed complete segmentation, which the original AcusVR algorithm is sensitive to while the newer algorithm is not affected. These flaws can be easily corrected by filling the spurious gaps in the segmentation. The worst maximum absolute errors are not significant (Figs. 5, 4(b), 4(c)).

Significant errors concentrate in a certain area in the lower right part of the back of the patient. This was exactly the area from where paths collide with unexpected air cavities (Fig. 4(a)).

**Table 1.** Comparison of force output values calculated by AcusVR to new algorithm variant. Asterisks indicate significantly different force feedback ( $p < 0.05$ ). Plus signs mark paths where air holes are present in the segmentation. MSE means “mean squared error”, MAE denotes the “maximum absolute error”.

Worst Paths			Best Paths		
Rank in Metric	MSE [ $\text{N}^2$ ]	MAE [N]	Rank in Metric	MSE [ $\text{N}^2$ ]	MAE [N]
4038	0.5403*+	4.4955	9	0.0044+	0.535
4037	0.5364*+	4.4932+	...	...	...
4036	0.5349*+	4.4926	6	0.0042	0.5262
4035	0.5239*+	4.4871	5	0.0041	0.5233
4034	0.5135*+	4.4846+	4	0.0041	0.5116
4033	0.5103*+	4.4785	3	0.0040	0.5116+
...	...*+	...	2	0.0036	0.5004
4021	0.4337	4.4495	1	0.0032	0.5+

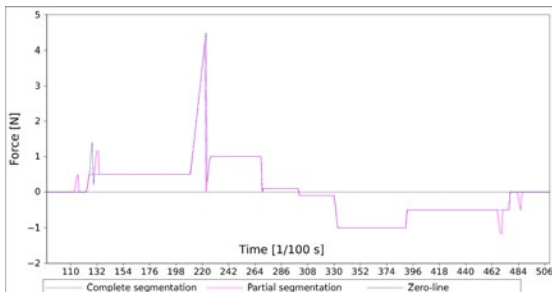
Using CUDA for path calculations takes only 3 minutes of time instead of over 15 minutes in a CPU implementation.

On average we found MSE resp. MAE to be  $0.053 \pm 0.077 \text{ N}^2$  resp.  $1.7817 \pm 1.293 \text{ N}$ . Statistically significant errors are present in only 0.6% of all paths.

## 4 Discussion

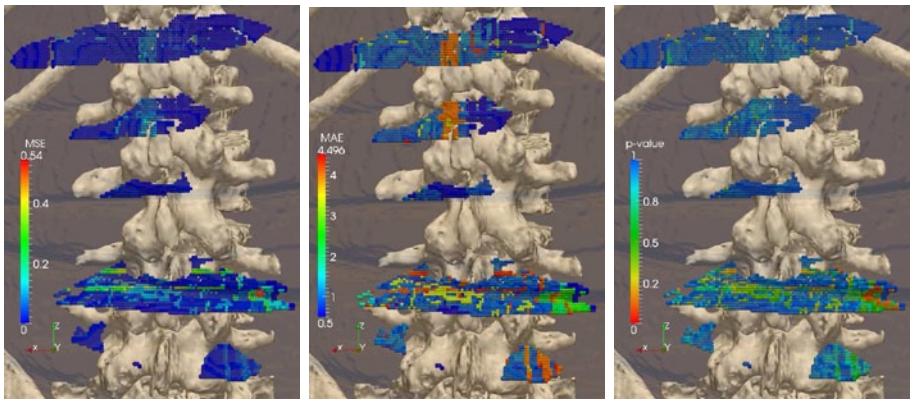
In [6] a new approach has been presented that considerably reduces the segmentation preparation workload from days to hours.

Evaluation there was only carried out on 12 manually selected paths. In this paper, an evaluation framework producing a large number (4038) of automatically generated, densely packed paths is used. This new tool even stronger underlines direct haptic rendering to be a valuable method. Important structures such as ligaments are clearly reproduced by the simulation and for unsegmented structures errors are small. As shown the high number of test paths helps to further prove the validity in comparison to the reference system AcusVR. Generally speaking, the ray-casting based quality check is a good concept for the



**Fig. 5.** Force curves for erroneous path with high maximum absolute error: AcusVR calculated force (blue) vs. newer algorithm (magenta): The force outputs for the paths are very similar despite of outlier errors near the skin and at the ligamentum peak.

**Fig. 6.** Color coded errors of reference paths: (a) MSE, note that the maximum errors hide on the very right in a fold of the skin marked with a red circle (b) MAE and (c)  $p$ -value.



development of haptic algorithms in general. In future, we will use the proposed evaluation methodology to further improve the algorithms, check quality at other surgical sites and test for inter-patient applicability of the used heuristics.

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