

Introducing a Robotic Lumbar Puncture Simulator with Force Feedback: LP Sim

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Abstract

Purpose: Lumbar Puncture (LP) is widely used for spinal and epidural anesthesia or Cerebrospinal fluid (CSF) sampling procedures. As this procedure is highly complicated and needs high experience to be performed correctly, it is necessary to teach this skill to the physicians. Considering the limitation of number of usage of rubber models and advantages of Virtual Reality (VR) environment for digital training of skills, we tried to investigate the capability of VR environment to train the LP procedures.

Materials and Methods: Geometrical model of the lumbar area of L2 to L5 are extracted from fusion of MR and CT imaging modalities. Also physical model of resistance of each layers against needle insertion at lumbar area are investigated through specially designed sensorized handle for LP needle and recorded from a 41-year-old female patient. Then geometrical and physical models of lumbar area are fused together and the VR model of it, with insertion force rendering capability is extracted. Then the model is integrated with a haptic device and the complete VR environment is investigated.

Results: In this work we introduced a robotic Lumbar Puncture Simulator (LP Sim) with force feedback which may be used for training the LP procedures. Using the LP Sim, when a trainee inserts the needle inside the lumbar area at the provided virtual reality environment, he/she may feel the insertion forces against his/her movement inside the virtual lumbar area.

Conclusion: The LP Sim is a virtual reality-enabled environment, with force feedback, that provides an appropriate framework for training this skill.

Keywords: Lumbar Puncture; Force Feedback; Virtual Reality; Haptics; Simulation; Robotics.

1. Introduction

Lumbar puncture is one of the advanced and complicated clinical skills which needs high dexterity and experience of physicians to perform it correctly. To start lumbar puncture, a special needle called LP needle is used to insert in lumbar area between L2 to L5 vertebra. This needle should pass from several layers with different stiffness and biomechanical behavior which help physician to determine the layers from their resistance in front of inserting the needle inside them. Actually, physician may distinguish these layers from the force feedback which they sense during insertion of the needle inside the lumbar area. These layers include skin, subcutaneous fat, supraspinous ligament, interspinous ligament, ligamentum flavum, epidural space and meningeal layer (Dura mater).

The lumbar puncture is widely used for spinal and epidural anesthesia or CSF sampling. Spinal and epidural anesthesia has many advantages such as patient comfort, elimination of the risks of general anesthesia, shortening hospitalization, and postoperative pain control [1]. Also, postoperative nausea and vomiting, which are common problems with anesthesia, will be decreased [2]. Moreover, this technique can reduce acute and chronic pain in surgeries. Also CSF sampling is important in both diagnostic and therapeutic procedures. This method is used clinically to help diagnosing infections and also inflammatory, oncological and metabolic problems [3, 4].

Lack of experience in performing the lumbar puncture procedure may cause error in detecting and distinguishing the layers by physicians and cause wrong injection or sampling [1, 5-7]. To help solving this problem, several training model of lumbar area have been made by rubber and plastic materials to mimic the biomechanical behavior of lumbar area against needle insertion. Although the rubber models may make a proper environment for training of this procedure, they have several limitations to be used by physicians. The main limitations of them include: limitation in number of use, limitation in making rubber materials with exact stiffness and behavior same as bio materials of several layers of lumbar area, limitation of making stable behavior of each layer

during long time and finally limitation in assessment of this practice.

To overcome the limitations of rubber based training models, several researchers introduced Augmented Reality (AR) [8, 9] or Virtual Reality (VR) based simulators [10-16]. Specially for LP procedure, Farber *et al.* introduced a VR based LP simulator which used a Sensable Phantom Premium 1.5 device (3D Systems, SC, USA) with six degrees of freedom haptic feedback to steer the virtual needle and to generate feedback forces that resist needle insertion and rotation. They combine information from segmented data and original CT data which contributes to density information in unsegmented image structures. Also they applied an extended proxy based haptic volume-rendering approach to calculate forces both for preventing the needle to change direction after insertion and also calculation the resisting force against needle insertion [17]. Keri *et al.* combine a rubber based commercially available training model (Lumbar Puncture Simulator II, Kyoto Kagaku, Kyoto, Japan) for force sensation during insertion and a VR environment for visualization of the procedure in a graphical model. They real timely track the needle using an ultrasound machine (SonixTablet, Ultrasonix, Richmond, BC, Canada) which is equipped with an electromagnetic position tracker (GPS extension, Ultrasonix, Richmond, BC, Canada) [18].

Despite valuable works in this area, none of them used the real insertion forces data to simulate the LP procedure. In this work, first we measured the real needle insertion forces during an LP procedure and then used it as a physical model in our developed LP simulator. This simulator, which we named it as "LP Sim" is a robotic training system with force feedback capability. We prototype it by developing a new geometrical and physical model (based on measured insertion forces data) as a VR environment and integrate it with a Novint Falcon haptic device (Novint Technologies, Inc., NM, USA) to simulate the mechanical behavior of the lumbar area against needle insertion.

2. Materials and Methods

To simulate the mechanical behavior of the lumbar area against needle insertion, two main parts should be investigated. The first part is geometrical model of the total lumbar area and internal organs and layers and the second part is physical model of the area and each layer. Geometrical model means the 3-dimensional geometry of total area with details of each layer. We investigate them through fusion of Magnetic Resonance (MR) Imaging and Computer Tomography (CT) scanning of the lumbar area of a 41-year-old female subject. This study was performed in accordance with the declaration of Helsinki and subsequent revisions and approved by the ethics committee of Tehran University of Medical Sciences. MR imaging is used to determine the soft tissues and CT scan modality is used to determine the vertebrae in L2 to L5 area. In each modality 6 steps have been investigated to reconstruct the 3-dimensional geometry of the area. These steps include segmentation of each slice to segment each layers and vertebrae, 3D reconstruction of each layer and vertebrae to generate cloud of points of them, mesh generation of each area to reduce the number of points which should be considered in 3D dimension and finally render and texture of each area to make a geometrical 3D model of the area with a graphical texture of near to real one. The MRI image of our patient had in-plane resolution of 1.5 mm and her CT had the spatial resolution of 0.5 mm in all direction. We fused them both with resolution of 0.5 mm for vertebrae and 1.5 mm for soft tissues. [Figure 1](#) shows the procedure of making the geometrical model of lumbar area in this study.

Regarding the second part of model which is the physical model of total area with details of each layer, we should investigate the mechanical behavior of each layer against insertion of LP needle. To investigate this model we design and fabricate a sensorized handle

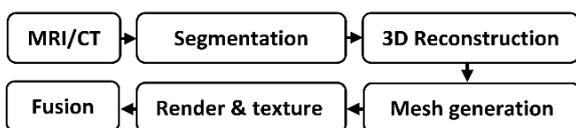


Figure 1. Procedure of making the geometrical model of lumbar area in L2 to L5 section

which could grasp the LP needle and measure the interaction forces of needle insertion between physicians' fingers and the LP needle. This is the force which we should investigate and feedback to the fingers of trainers to know the insertion force of each layer. The point is that the interaction forces between physicians' hand and the LP needle are equal to the insertion forces between LP needle and lumbar area. This device has a cantilever one directional load cell of L6J1 from Zemic company (Zemic Europe B.V., Netherland) with capacity of 10 N and claimed accuracy of ± 2.8 mN which is extremely enough to record the LP insertion forces which have the order of more than 1000 times of the error of this load cell. The load cell is installed in the handle of measuring device and we use a 24 bit analogue to digital converter (Fararoo Paya Co., Tehran, Iran) to record the interaction forces with sampling rate of 1 kHz. The insertion forces are measured from the same person from whom we take the CT and MR imaging to make the geometrical model. Depth of insertion are recorded by infrared tracking system of Parsiss (Parseh Intelligent Surgical Systems Co., Tehran, Iran) with claimed accuracy of ± 0.1 mm which is enough in comparison with accuracy of our imaging data to reconstruct the lumbar area. We mapped the recorded position data to the interaction forces measurement which had been synced together.

Following the investigation of the geometrical and physical model of the L2 to L5 area and fusing them, we made a 3D graphical environment of lumbar area which integrate both geometrical and physical model of the lumbar area. We call it the Virtual Reality (VR) environment of the LP Sim trainer which used VC++ (Microsoft Corporation, NM, USA) for force feedback management and Unity real-time development platform and game engine (Unity Technologies, CA, USA) for geometrical model reconstruction part. The next step was to integrate this environment with a haptic device to interact the insertion force against of inserting the needle from each point of the lumbar area. We used the "Falcon" haptic device to implement our model in real interaction with the trainers' hand. The first step of this integration was to calibrate the interaction forces of the Falcone device in each three directions of X, Y and Z and at different points of the workspace. To do this step, we attached a 6 dimensional load/torque cell of Nano 17 (ATI

Industrial Automation Co, NC, USA) to the end effector of falcon device from one side and to a Cartesian adjustable platform from other side. Then we used the device Software Development Kit (SDK) and command the device to exert force in 3 dimensions at each selected points of its work space. The selected points were selected in its total work space of $10*10*10\text{ cm}^3$ with distance of 20 mm between each other in each Cartesian direction. It leads to 216 calibration points at total reachable workspace of 1000 cm^3 of the Falcon device. At each point of the investigated area, we change the haptic forces with resolution of 0.5 N in each direction. The total range of force calibration at each direction and at each point was -10 to +10 N. We investigate it for each direction at each point. The results show that we may fit a linear model of force calibration with slope of near 1 N/N. The pool of $216*3$ slopes of calibration line in 216 points and 3 directions at each point shows the standard deviation of 0.27 N/N. This value for the near midline workspace of the Falcon, which is a cube of $2*2*6\text{ cm}^3$ and we used it for LP simulation, was reduced to 0.04 N/N. So we assumed that in our targeted workspace, which is midline of our calibrated cube, at each point and at each direction, the demand force (commanded from official SDK of Novint Falcon) and actual force is equal with each other and we do not add any calibration matrix for our used falcon device during this study.

Following calibration of the haptic model of the Falcon device, our virtual reality model and the haptic device were ready to integrate through software which was developed based on VC++ integrated development environment for force feedback management. Also a physical model of a LP needle was designed, fabricated and integrated to the end effector of the Falcon device for most real feeling of the LP procedure for trainers.

Performance of the system was evaluated in 2 phases. First, the objective parameters of position and force feedback were evaluated during a LP procedure with LP Sim. We used a “Nano 17” external load cell which was attached to the falcon end effector and the “Parsiss” tracking system to measure the position of the end effector during the LP procedure and compare it with the real measured data which was obtained from a real patient. At the second phase, the subjective

parameters of Graphical Quality (GQ), Needle Motion tracking quality (NM), Interaction Force quality (IF) and Similarity with Real patient (SR) are evaluated using a questionnaire form with a 5-point Likert scale of Excellent (5)- Above Average (4) – Average (3)- Below Average (2) - Very Poor (1). The form was filled by 5 expert anesthesiologists who were expert in LP procedures.

3. Results

This technical investigation leads to introduce a Lumbar Puncture Simulator (LP Sim). This system may be introduced in two main parts of software and hardware.

3.1. Software

The software of the LP Sim includes force rendering/control module and graphical rendering engine. Technical specifications of each module are summarized in [Table 1](#).

Table 1. Technical specification of the software modules of the LP Sim

Base graphical rendering module	Unity
Control loop velocity for image rendering	25 Hz
Base force rendering/control module	VC++
Control loop velocity for force feedback	500 Hz

[Figure 2](#) shows the graphical environment of lumbar area of L2 to L5 which has been developed for LP Sim. Trainer may select the level of transparency of several layers prior to vertebra and try to increase his/her level of dexterity step by step by decreasing the level of transparency of the mentioned layers.

3.2. Hardware

Hardware of the LP Sim includes the Falcon device with model of LP needle at its end effector, a display, a processor unit and a base platform. These components are shown in [Figure 3](#).

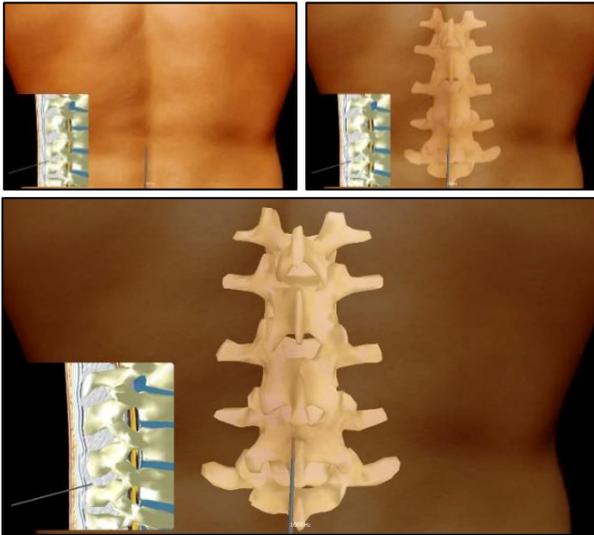


Figure 2. Graphical environment of lumbar area of L2 to L5 with 3 levels of transparency from minimum (up-left) to maximum (down) at LP Sim. A sectional view of the needle insertion and layers are shown at the left-down corner of the screen



Figure 3. Components of the LP Sim hardware including: 1-Falcon 2- Model of LP needle, 3- Processor unit 4- Display and 5- Base platform

Technical specifications of the LP sim hardware are summarized at [Table 2](#).

Performance evaluation of the force and position rendering in comparison with real data which we were obtained from a real female 41-year-old patient, showed average error of less than 4 percent. [Figure 4](#) shows the result of our measurement of real data in comparison with the LP Sim performance during LP needle insertion.

[Figure 5](#) shows how a trainee uses the LP Sim to train the lumbar puncture procedure. Using this system, when the needle is inserted to the tissue, its

direction will be kept fixed during entire procedure and the user could not change the needle directions. So at LP Sim before inserting the needle to the lumbar area, the user may change the point of insertion but could not change its direction. After inserting to the tissue, the direction of movement should be kept fixed along needle predefined direction. We do it through inserting maximum available force, against movement at perpendicular direction of the assumed needle. The point is that in our scenario, the falcon will apply forces only against movement. It means that if the user do not move the needle, the force will be zero, if he/she tries to move it at perpendicular direction of the assumed needle, the force will increase up to 10 N to keep it in its predefined direction and if the user moves the needle in its own direction, the falcon will exert the insertion force against movement based on needle insertion depth and measured pattern of insertion force from real patient which is illustrated in [Figure 4](#).

Result of evaluating the subjective parameters of the LP Sim, including graphical quality, needle motion tracking quality, interaction force quality, and similarity with real patient are illustrated in [Figure 6](#).

Table 2. Technical specifications of hardware of the LP Sim

Workspace	10×10×10 cm ³
Maximum Force Capabilities	10 N
Position Resolution Measurement	0.1 mm
Force Feedback Resolution	0.5 N
Force Feedback Frequency	500 Hz
Operating System	Windows 8
Dimension	50×40×30 cm ³
Weight	5.5 Kg
Processor	1.8 GHz
Graphics Card	128Mb 3D
DirectX Version	DirectX 9.0c
Memory	2 GB RAM
Display	12", HD
Max Power Consumption	70 Watt
Input Power Frequency	50-60 Hz
Input Voltage	100-240 VAC

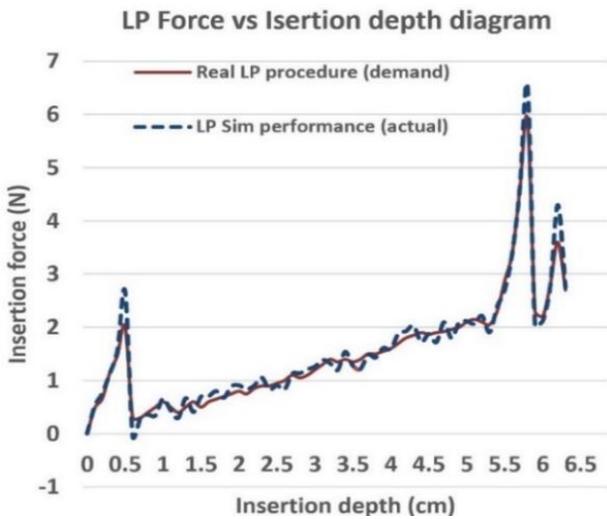


Figure 4. LP insertion force versus insertion depth of a real procedure in comparison with the LP Sim performance



Figure 5. Use of LP Sim by a medical skills trainee

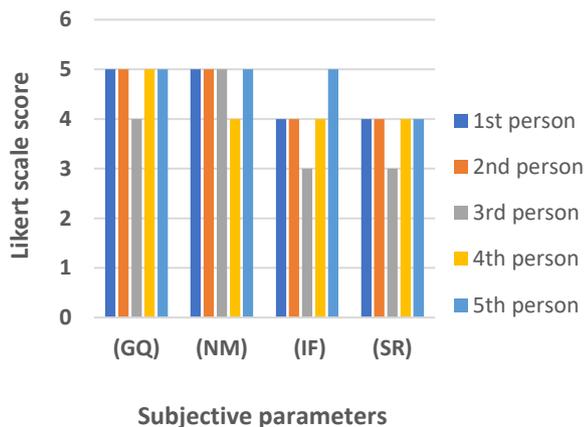


Figure 6. Likert score of subjective evaluation of the LP Sim by 5 experts, including parameters of Excellent (5) – Above Average (4) – Average (3)- Below Average (2) - Very Poor (1)

4. Discussion

We investigated the LP Sim in this report as well as the rationale of our focus on this field of medical education. The physics and graphics of the LP Sim have great credibility and are comparable with other method of LP procedure training. In this system, when a trainee inserts the needle inside the lumbar area at the virtual reality environment, he/she may feel the insertion forces against his/her movement inside the lumbar area. Although the interaction forces trend of the LP Sim are same as real forces which have been measured from a real patient; as we measure these data from only one patient, we do not have enough evidence to consider these data as a reference data of general LP procedure. We need to measure more data, categorize them, and compare them with each other considering several necessary parameters of age, gender, Body Mass Index (BMI) and special deformity to make a categorized LP insertion force versus insertion depth data.

As the direction of needle will be kept constant during insertion, for the LP Sim, we considered a predefined direction of 10 degrees cephalad in sitting situation of patient. This is a recommended degree for starting the insertion in standard sitting situation of patient, but if a physician do not observe the guidelines, it may affect the LP procedure result and it is necessary for a simulator to add 3 degrees of freedom to reorient the direction of needle before inserting to the lumbar area. So this is a limitation for the current version of the introduced LP Sim which has a constant orientation of the needle.

Evaluating the subjective parameters of the LP Sim for graphical quality and needle motion tracking quality showed near excellent quality and interaction force quality and similarity with real patient was above average.

5. Conclusion

Virtual reality is experiencing an exponential increase in its popularity [19-21] because of the emergence of high-performance computers and graphics engines. Development of a Robotic LP trainer may be a step toward a more effective

preclinical curriculum based on virtual reality for clinical skills training. The preliminary investigation of the LP Sim shows that its graphical quality, needle motion tracking, interaction force rendering and feedback quality, are acceptable as a virtual reality environment for training the lumbar puncture procedure. Further performance assessments and evaluation of this newly developed system are necessary and are currently under study.

A necessity to improve the impact of this system in clinical skills training methods is to increase the number of geometrical and physical model of the lumbar area for several classification of patients considering their age, gender, BMI and special deformity of lumbar area. At the current stage we only use one sample image and insertion force data and it could not be considered as a generalized model. The geometrical model may be more generalized by using an Atlas based model which may be reconstructed from images of many real patients either statistically or probabilistically.

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