12th International Workshop on Innovative Simulation for Healthcare
20th International Multidisciplinary Modeling & Simulation Multiconference

2724-0371 © 2023 The Authors.
doi: 10.46354/i3m.2023.iwish.003

Lumbar puncture trainer for training acute care nurse practitioner students: goal of low cost

Nilsa Black-Mead[1,*], Haley Hoy[1], Cooper Gunter[2], Ishmael Domingo[2], Gary Maddux[2] and Bernard Schroer[2]

[1]College of Nursing, University of Alabama in Huntsville, Huntsville AL, 35899, USA
[2]Systems Management and Production Center, University of Alabama in Huntsville, Huntsville AL, 35899, USA

[*]Corresponding author. Email address: nmb0001@uah.edu

Abstract

This paper presents the development of a low cost lumbar puncture trainer for training acute care nurse practitioner students in the College of Nursing (CoN) at the University of Alabama in Huntsville (UAH). A mold box, L1-L5 vertebrae and a support structure were 3D printed. A plastic tube was inserted through the vertebral foramen of L1-L5 and suspended in the mold. Silicone rubber was then poured in the mold and Smooth-On Slacker added to give the silicone rubber a flesh like feel. The cast was bent around the 3D printed structure to partially expose the spinuos processes. After removing the plastic tube a combination of aluminium foil, foam and silicone rubber tubing was inserted into the vertebral foramen to simulate the ligamentum flavum, epidural space and dura mater respectively. This tubing provided two losses of resistance, as the needle exited the ligamentum flavum and the dura. The trainer has been used in a class of acute care nurse practitioner students with very positive feedback, including 1) realistic aspects, 2) opportunity to hone skills and make mistakes 3) consistence experiences with procedures, 4) exposure in controlled environment and 5) reduction in lab fees. The materials cost was $63.88. This paper describes the design constraints and requirements, detailed configuration of the tubing to achieve the loss of resistance, trainer assembly, implementation in the classroom, faculty and student feedback and lessons learned.

Keywords: Lumbar puncture trainer; low cost, acute care training

1. Introduction

A lumbar puncture (spinal tap) is a procedure performed on the lower back generally between the L3-L4 vertebrae (Figure 1) (Kluwer, 2022; Sturt, 2020). The lumbar puncture may be done 1) to collect cerebrospinal fluid (CSF) to test for infections, inflammation or other diseases, 2) to measure the cerebrospinal fluid pressure, 3) to inject spinal anesthetics, chemotherapy drugs or other medications or 4) to inject dye or radioactive substances into the cerebrospinal fluid to make diagnostic images of fluid flow (Mayo Clinic, 2022).

The lumbar puncture procedure starts with a local anesthetic into the lower back. A hypodermic needle is then inserted between the L3-L4 vertebrae, through the ligamentum flavum ligament, epidural space, dura mater membrane and into the subarachnoid space that contains the cerebrospinal fluid and cauda equine. All of these items are housed in the vertebral foreman (Figure 2).

The spinal cord extends down between L1 and L2. The bottom part of the spinal cord (beyond L2) is the cauda equine which gets its name from Latin for "horse's tail" because the nerves at the end of the spine cord resemble a horse's tail. Therefore, it is much safer to insert the needle between L3-L4.

The Tuohy needle is a thin, hollow hypodermic needle that is slightly curved at the end. The needle length varies between 18-22 gauges depending on the patient. Figure 3 shows the parts of an 18 gauge needle. The needle has a hollow core. Inside the hollow core is a stylet which converts the needle into a solid one, preventing the removal of a plug of skin. When the stylet is removed the cerebrospinal fluid will drip out and a small amount of the fluid is also collected.

The cerebrospinal fluid (CSF) pressure is measured with a manometer and is an estimate of intracranial pressure (pressure on the brain). A variety of conditions may increase pressure within the brain and/or obstruct the flow of CSF such as tumors, infection and abnormal accumulation of CSF within the brain or bleeding (Testing, 2021). The normal range of CSF pressure is 6-25cm H2O in adults (95% confidence) with a population mean of 18cm H2O (Lee and Lueck, 2014).

Figure 1. Lumbar puncture between L3-L4 (L1 is top vertebra).

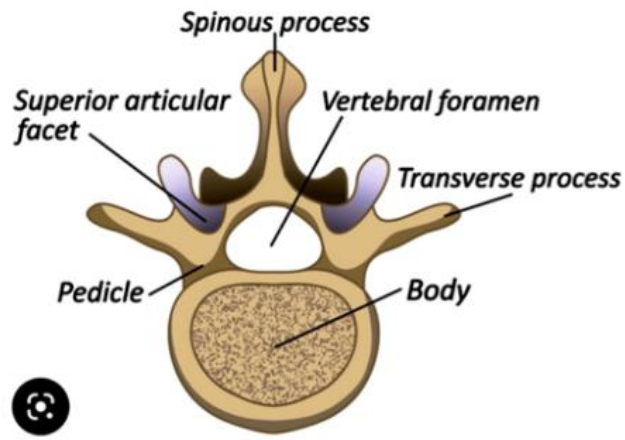

Figure 2. Lumbar vertebra cross section.

Figure 3. Lumbar puncture needle.

The lumbar puncture needle pierces in order: skin, subcutaneous tissue, supraspinous ligament, interspinous ligament, ligamentum flavum ligament, epidural space, dura mater membrane, arachnoid mater membrane and finally the subarachnoid space (Figure 4) that contains the cerebrospinal fluid and cauda equine.

A lumbar puncture can be performed with the patient in a lateral recumbent or prone position, or even sitting upright. However, the lateral recumbent position is preferred when not using fluoroscopic guidance as during prone positioning. In addition, lateral recumbent and prone positioning allows for a more accurate opening pressure measurement. Therefore, a slight bend, or arc, in the lumbar puncture trainer will better simulate real life by enlarging the space between L3-L4.

The ligamentum flavum (Latin for yellow ligament) is a short, thick ligament that connects the laminae of adjacent vertebrae from C2-S1. The function of the ligamentum flavum is to maintain an upright posture and preserve the normal curvature of the spine. The dura mater is a thick membrane that surrounds the spinal cord and is the outermost of three layers of membrane called the meninges. It surrounds the arachnoid mater which contains the cerebrospinal fluid. A loss of resistance or a pop is generally felt when the needle exits the ligamentum flavum and dura mater.

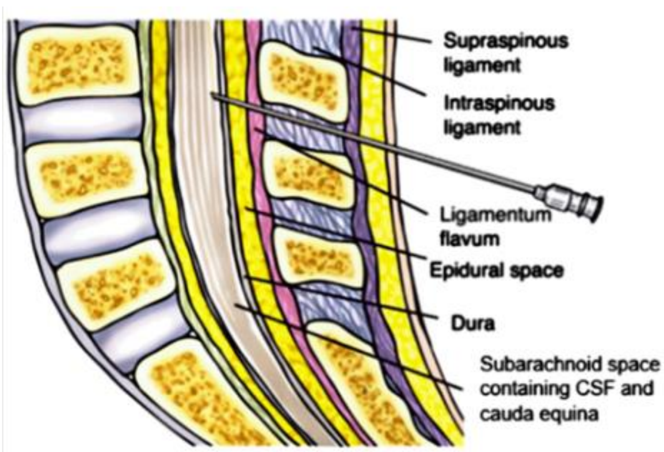

Figure 4. Insertion of lumbar puncture needle (Procedure Guide, 2022).

Vaughan et al., (2020) evaluated the need for epidural and spinal simulators and compared the differences between computer based and manikin based simulators. Dynamic Disc Designs has developed a variety of very realistic lumbar spine models for training healthcare professionals (Dynamic Disc Designs 2020). Gaubert et al., (2021) showed significant improvement after lumbar puncture simulation training (p<0.0001). Vrillon et al., (2022) used virtual reality in lumbar puncture training.

Pedersen et al., (2017) reported that trainees are three times more likely to fail in insertion compared with specialists. To deliver local anesthetics to the epidural space practitioners need to learn the correct identification of the epidural space and the catheter. The identification of the epidural space is achieved by the loss of resistance technique.

Han et al., (2020) developed a simulator for thoracic epidurals. The spine segment and discs were 3D printed. A plastic tube simulated the spinal cord. The ligament flavor was simulated by wrapping a thin layer of silicone molding material around the plastic tube. This assembly was then inserted in the vertebral canal of the printed model. Ballistic gel created a cylinder of soft tissue surrounding the spine.

Leaf et al., (2020) developed a pediatric lumbar puncture trainer using a 3D printed lumbar spine and ballistic gel. The trainer allowed for ultrasound guidance of the needle. A silicone tube simulated the spinal cavity. A connection to an IV (intravenous) bag allowed opening pressure adjustment and measurement.

The College of Nursing (CoN) at the University of Alabama in Huntsville (UAH) and the UAH Systems Management and Production Center (SMAP) have been working for several years developing a variety of trainers. One of these projects has been the development of a lumbar puncture trainer for training acute care nurse practitioners.

The CoN and SMAP had previously design a prototype lumbar puncture trainer (Lioce etal, 2021). This lumbar spine segment was not encapsulated in this prototype. After further evaluation and testing several areas for improvement were identified, including 1) bending of the lumbar spine segment to enlarge the open space between L3-L4 and to more realistically simulate the patient's position during the lumbar puncture, 2) improved covering to conceal the vertebrae, 3) feel of the encapsulated vertebrae spinous processes, 4) tubing to simulate the ligamentum flavum and dura mater and 5) needle insertion to sense the two pops.

This paper builds on the initial prototype to construct a lumbar puncture trainer that addressed these areas for improvement. Specifically the paper describes the design constraints and requirements, detailed configuration of the tubing to achieve the loss of resistance, trainer assembly, implementation in the classroom, faculty and student feedback and lessons learned.

2. Materials and Methods

The following design requirements for the lumbar puncture trainer were established based on the previous prototype and further discussions with the faculty in the College of Nursing:

- Full scale L1-L5 vertebrae embedded in the trainer.
- Slight bend (arc) in the trainer to simulate patient leaning forward and consequently enlarging the space between L3-L4.
- Simulate two pops or loss of resistance, as the needle exits the ligamentum flavum (Centeno 2022) into the epidural space and then exits the dura mater into the subarachnoid space, or spinal canal.
- Only the dura mater tube contains liquid simulating cerebrospinal fluid (CSF).
- Ligamentum flavum tube can be a partial tube and can rest against the interior walls of the vertebral foramen.
- There should be space between the ligamentum flavum and dura mater to simulate the needle traveling through the epidural space to the dura mater.

- Easy to use, maintain and clean.
- Relative low cost.

The most significant design constraint was the diameter of vertebral foramen of 5/8 inch (15.875mm). The AP (anteroposterior) diameter of a normal lumbar spinal canal varies from 15-27mm (Nadalo, 2017). This diameter dictated the maximum diameter of the tubing that simulated the ligamentum flavum.

Several relevant measurements were:

- Distance from surface of skin to ligamentum flavum ligament of 45-55mm (Doherty and Forbes 2014).
- Distance from ligamentum flavum to the dura mater of 7mm (Doherty and Forbes 2014).

Individual L1-L5 vertebrae STL (stereolithography) files were obtained from Embodi3D.com. The developer was "BioGuy." The dimensions of the prototype lumbar puncture trainer mold box were based on the dimensions of the L1-L5 vertebrae. The mold box was made with Legos and placed on a glass base (Figure 5). A 16mm (5/8inch) diameter plastic tube was inserted through the five vertebral foramen and hung in the mold box. A wooden dowel kept the plastic tube horizontal during casting.

A silicone rubber from Smooth-On (Smooth-On, 2022) was selected to cast the part. Dragon Skin is soft, stable, strong, flexible, and stretchable. It is often used to create silicon makeup appliances, skin effects, medical prosthetics, life-like skin castings, and other movie special effects. Smooth-On Slacker was added to change the feel of the silicone rubber to a softer and more flesh-like. The selected mixture ratio was 1Part A Dragon Skin FX-Pro: 1 PartB Dragon Skin and 1/2PartS Slacker.

A wooden structure was fabricated to hold the lumbar puncture pad vertically. The structure had a slight arc to realistically simulate the patient leaning forward and to provide more space for the needle insertion. Plastic zip ties were attached to maintain the arc.

Figure 6 is a photo of one of the prototypes. The prototypes were evaluated by nurse practitioner students in an acute care class during the summer of 2022. The prototypes only included either a 14mm plastic tube or a 14mm silicone rubber tube for the students to evaluate one pop. With the bend in the pad the vertebrae spinous processes (Figure 4) were noticeable and could be readily palpated.

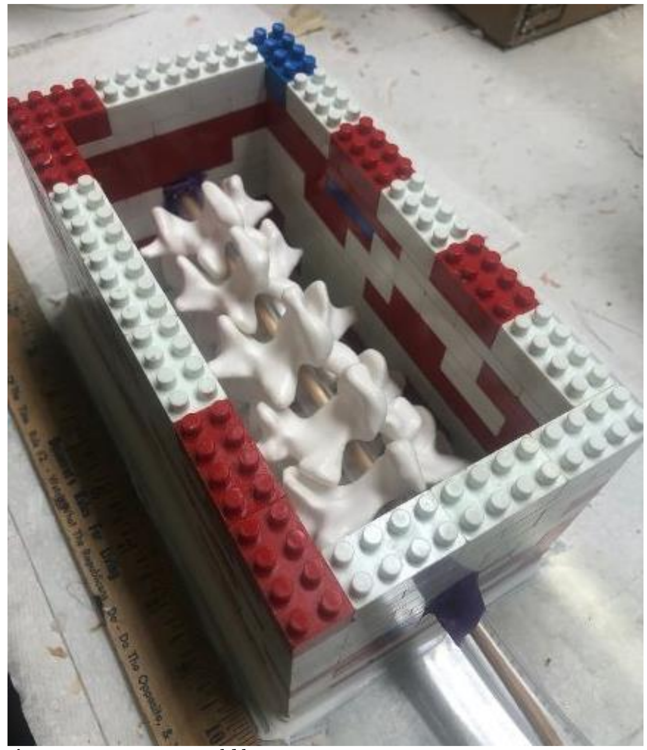

Figure 5. Prototype mold box.

Figure 6. Prototype lumbar puncture trainer.

3. Results and Discussion

Figure 7 is a 3D printed model of the final mold design that was printed on a Prusa-i3 MK3S with PLA (polylactic acid) filament. A 16mm (5/8inch) diameter plastic tube was inserted through the L1-L5 vertebral foramen and inserted in the mold before casting. A

1/2inch dowel was inserted through the tube to keep the vertebrae horizontal during casting.

A 3D printed part was made to replace the prototype wooden structure in Figure 6. Zip ties were used to hold the cast part around the structure (Figure 8).

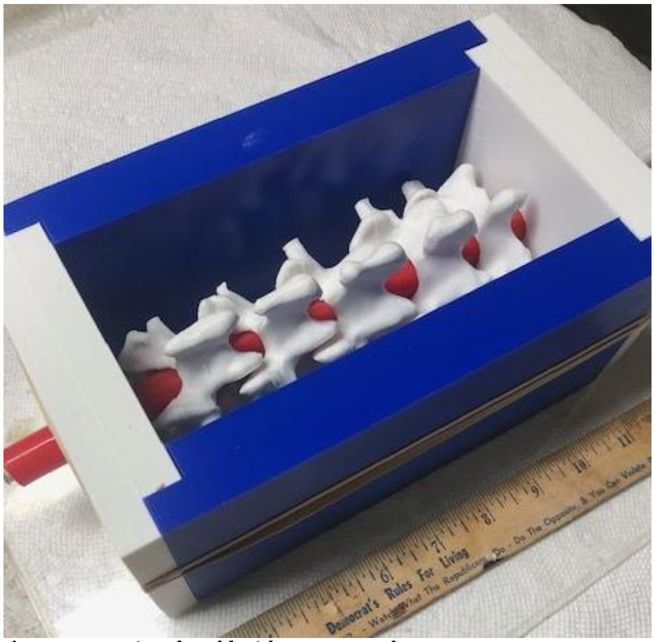

Figure 7. 3D printed mold with L1-L5 vertebrae.

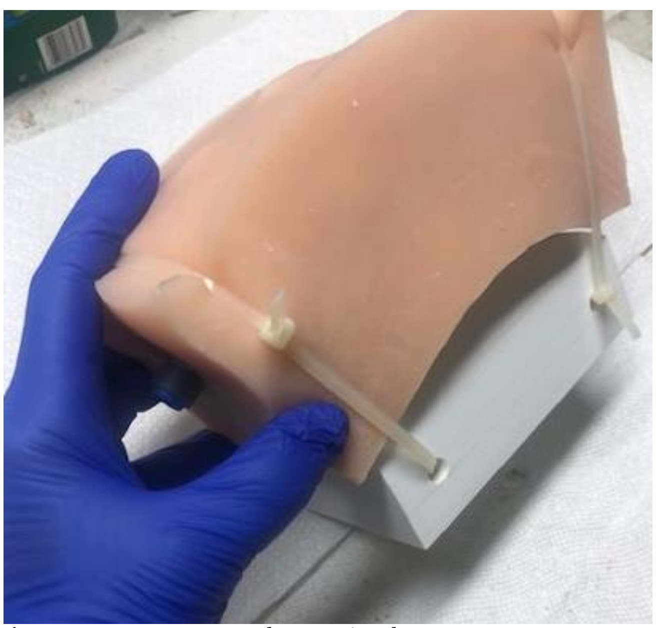

Figure 8. Cast part connected to 3D printed support structure.

Nine design configurations (Figure 9 and Table 1) were evaluated to obtain the pops as the needle exits the ligamentum flavum filament, travels through the epidural space and then exits the dura mater membrane. As previous stated a significant design constraint was the available space to insert the configuration through the subarachnoid space (Figure 4). Therefore, Configuration9 was included which was identical to Configuration8 only with a smaller 11mm O.D. silicone straw.

The tubing was compressed in several of the configurations to fit within the available space. The CoN selected Configuration8 followed by Configuration9 and Configuration7. All selected configurations had aluminum foil tape (4.8mil thick) for simulating the ligamentum flavum and a 2mm foam sheet for the epidural space. The silicone straw in Configurations8 and 9 was a softer silicone than the tubing in Configuration7.

Because of the difficulty in inserting Configuration8 tube assembly, Configuration9 was the final tubing selection. This configuration was the easiest to insert in the L1-L5 vertebral.

In the final design the foam surrounded approximately half of the silicone tube while the aluminum foil was wrapped completely around the tube to firmly secure the foam. The foil was self sticking which eliminated the problem of maintaining the position of the foam.

Figure 9. Design configurations.

Table 1. Design configuration parameters.

Configuration	Ligamentum flavum/ Dura mater	OD	ID	Epidural Space*
1	Silicone tube	16mm	12mm	2mm
	Silicone tube	10mm	8mm	

2	Silicone tube (half)	16mm	12mm	2mm
	Silicone straw	14mm	11mm	
3	Two ply film	10mil thick		2mm
	Silicone tube	10mm	8mm	
4	One ply film	5mil thick		2mm
	Silicone tube	13mm	10mm	
5	Silicone straw	14mm	11mm	2mm
	Plastic straw	9mm	8mm	
6	Silicone tube	13mm	10mm	none
	Plastic straw	9mm	8mm	
7	Aluminum tape***	4.8mil thick		2mm
	Silicone tube	10mm	8mm	
8	Aluminum tape***	4.8mil thick		2mm
	Silicone straw	14mm	11mm	
9	Aluminum tape***	4.8mil thick		2mm
	Silicone straw	11mm	8mm	

Notes:
*Foam sheet is only partially placed around the tube on the side of the needle insertion to simulate the epidural space.
**1mil=0.001inch. 25.4mm=1inch.
***Aluminum foil tape 72mm wide in roll.

Figure 10 shows the trainer in a nursing class. The trainer had been covered with a sterile drape, the needle inserted, the needle stylet removed and a manometer being attached to the needle.

Figure 10. Lumbar puncture trainer in classroom.

Several approaches were evaluated to provide liquid to the subarachnoid space. One approach was to use an elevated IV bag and gravity feed the liquid. The height of the IV bag determined the cerebrospinal fluid pressure. An alternative approach was to insert the IV bag in a 500ml pressure infuser bag. A pressure infuser bag is mainly used in medical procedures to speed up an infusion. Squeezing the infuser bulb caused air to enter the bag bladder which in turn added pressure on the liquid in the IV bag and consequently a larger infusion rate. The infuser bag has a pressure gauge to monitor the air pressure of the bladder.

Figure 11 is the configuration with the pressure infuser bag. This configuration shows the lumbar spine segment without the Dragon Skin casting.

Figure 12 shows the insertion of the Tuohy needle and the manometer for measuring the simulated cerebrospinal fluid pressure in the inner tube (simulated subarachnoid space).

Figure 11. Configuration using the manometer.

Figure 12. Needle injection and insertion of manometer.

The materials costs for the lumbar puncture trainer were 1) $15.72 for the 3D printed mold box with tubing and 2) $48.16 for the Dragon-Skin pad, the encapsulated 3D printed L1-L5 vertebra, 3D printed support structure, tubing and miscellaneous. The mold box is reusable. The costs do not include labor, infuser bag, IV bag and items on the lumbar tray. The time to setup the mold, pour the dragon skin and insert the tubing was approximately one hour. The trainer cost is considerably less than a commercially available trainer.

The detailed materials costs were:

Mold box (reusable)	
3D printed mold box in PLA	$14.97
Tubing	$0.75
Total mold box cost	$15.72
Trainer	
3D printed L1-L5 in PLA	$4.53
3D printed structure in PLA	$5.25
Dragon Skin/Slacker	$37.08
Tubing	$1.00
Zip ties	$0.15
Rubber plug	$0.15
Total trainer cost	$48.16

4. Conclusions

The trainer has been used in a class of nineteen acute care nurse practitioner students and two nurse practitioner instructors.

Faculty comments were:

- Very complimentary of the realistic aspects of the trainer.
- Significant advantage in the use of the trainer was that students were exposed to a serious procedure in a controlled setting with no risk to the patients.
- From a curricular perspective the use of simulation for common procedures ensures that students have consistent experiences with procedures with faculty present to supervise and correct techniques.
- Trainer allowed nursing students to hone their skills and even commit mistakes in a controlled learning and risk free environment without harming patients. This safe realism is one of the greatest benefits of these simulators.
- The faculty had asked that the trainer have an arc to simulate the patient leaning forward. By doing so the spinous processes were visible and the space between the L3-L4 vertebrae was enlarged to improve the ability of inserting the needle into the subarachnoid space.

Student comments were:

- Complimentary of the realistic aspects of the trainer. During training the trainers were covered with surgical drapes. Consequently, students, were only exposed to the lumbar area around L2-L5 to simulate the real world environment.
- Appreciation of the opportunity to practice a skill before performing it in a clinical setting.
- Cost saving aspects since additional fees were not charged because of the lower cost of the trainer.

The most difficult limitation was the selection of the tubing to create the pops, or loss of resistance, as the needle exits the ligamentum flavum and dura, coupled with the constraint of the diameter of the vertebral foramen. A related challenge was adding a foam material between the ligamentum flavum and dura to simulate the epidural space and the insertion of the tubing assembly into the vertebral foremen. Surprising there was no negative feedback on the loss of resistance as the needle exits the ligamentum flavum and dura.

A related limitation was the insertion of the tube assembly through the vertebrae that had been encapsulated in the silicone rubber. The casting of the silicone rubber around the vertebrae reduced the diameter of the opening. Furthermore, the aluminum foil wrinkled causing a larger diameter of the tubing assembly. A solution to the problem was to enlarge and round the vertebral foreman of L1-L5 in the CAD design. Typical vertebral foreman are oblong. Preliminary calculations indicate that the diameter of the vertebral foreman needed to be approximately 22mm.

The addition of the Smooth-On Slacker to the Dragon Skin FX-Pro greatly improved the flesh feel of the trainer. After some experimentation a mixture of 1PartA: 1PartB: 1/2PartS provided the ideal feel.

The lumbar puncture trainer can also be used for epidural training with only a slight change to the tubing configuration by removing the ligamentum flavum. An epidural is a procedure that involves injecting a medication into the epidural space to provide pain relief (Figure 4). For epidurals the needle only exits the ligamentum flavum (only one pop) and then into the epidural space. Epidurals are used during labor and childbirth (over 60% of epidurals) and during and after some types of surgeries.

The low cost of the lumbar puncture trainer allowed for the construction of six trainers for use in a typical class size of sixteen. Each training station also had a 3D printed model of the L1-L5 spine segment for visualization. Each student had considerable hands on time to hone his/her skills.

Six lumbar puncture trainers have been fabricated for training nurse practitioner students in the fall 2023 class. Five of the trainers had the tubing Configuration9. Trainer6 had Configuration8 with the larger 14mm OD and 11mm ID. The vertebral foremen were enlarged to 22mm. An additional benefit of the 11mm ID provided a larger area for a correct needle insertion.

In conclusion the lumbar puncture trainer provides the nursing students with safe realism, one of the greatest benefits of simulation.

Acknowledgements

This project was supported by The University of Alabama in Huntsville (UAH) Systems Management and Production Center and The UAH College of Nursing.

References

Centeno, C. (2022). What is the ligamentum flavum? Why should you care. *www.regenexx.com*. Mar 25.

Doherty, C. and Forbes, R. (2004). Diagnostic lumbar puncture. *Ulster Medical Journal*, 83(2), 93-102.

Dynamic Disc Designs. (2020). Lumbar models. *Dynamic Disc Designs*, www.dynamicdiscdesigns.com.

Gaubert, S., Blet, A., Dib, F., et al. (2021). Positive effects of lumbar puncture simulation training for medical students in clinical practice. *BCM Education*, 21, article 18.

Han, M., Portnova, A., Lester, M. and Johnson, M. (2020). A do-it-yourself 3D printed thoracic spine model for anesthesia resident simulation. *PLoSONE*, 15(3).

Leaf, P., Tena, R., Sampson, L., Kuntz, H. and Young, T. (2020). IDEA Series: 3D-printed pediatric lumbar puncture trainer. *Aademic Life in Emergency Medicine.* www.aliem.com.

Lee, S. and Lueck, C. (2014). Cererospinal fluid pressure in adults. *Journal Neuroophthalmol* 34(39), 278-83, Sep.

Kluwer, W. (2022). Lumbar puncture. www.uptodate.com, Wolters Kluwer Inc.

Lioce, L., Budisalich, K., Gunter, C., Myler, M., Maddux, G. and Schroer, B. (2021). Application of 3D printing in the development of lumbar puncture and epidural simulators. *Proceedings 2021 Annual Modeling and Simulation Conference (ANNSIM21).* Fairfax VA. Jul.

Mayo Clinic (2022). Lumbar puncture (spinal tap). *www.mayoclinic.org*.

Nadalo, L. (2017). Spinal stenosis imaging. *Medscape*. www.mayoclinic.org.

Pedersen, T., Meuli, J., Plazikowski, M., Buttenberg, M., et al. (2017). Loss of resistance: a randomized controlled trial assessing four low fidelity epidural puncture simulators. *European Journal of Anaesthesiology*, 34 (9), 602-608, Sep.

Procedure Guide (2022). Lumbar puncture (spinal tap) technique and overview. *The Procedure Guide*. www.theprocedureguide.com.

Smooth-On (2022). Dragon Skin FX-Pro. *Smooth-On*. www.smooth-on.com.

Sturt, K. (2020). What to expect from a spinal tap. *SpineUniverse.* www.spineuniverse.com.

Testing, T. (2021). Cerebrospinal fluid (CSF) testing. *www.testing.com.* Nov.

Vaughan, N., Dubey, V., Wee, M. and Isaacs, R. (2020). A review of epidural simulators: where are we today. *Core*, www.core.ac.uk.

Vrillon, A., Marabel, L., Ceccaldi, P., et al. (2022). Using virtual reality in lumbar puncture training improves students learning experiences. *BCM Medical Education*, 22, article 244.