Lumbar Puncture Simulation: Perception and Modeling

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***Abstract*— The collection of cerebrospinal fluid via lumbar puncture is a key diagnostic tool for various neurological conditions, including meningitis, encephalitis, and subarachnoid hemorrhage [1]. Performance of lumbar puncture with adequate technique can significantly reduce patient complications. To enhance the learning experience for novice practitioners, our study introduced an experiential device that simulates the tactile sensations and resistance encountered during a real lumbar puncture. The device utilizes simple mechanical structures and a force-feedback model to provide users with a realistic and immersive experience, enabling them to accurately identify the optimal puncture site, perceive the needle's trajectory, and develop kinesthetic awareness of relevant anatomical landmarks. Our research focuses on optimizing user experience and facilitating the acquisition of essential lumbar puncture skills to improve procedural confidence and reduce the risk of needle misplacement.**

I. INTRODUCTION

Lumbar puncture (LP) remains the gold standard in cerebrospinal fluid (CSF) sampling for diagnosing a range of central nervous system (CNS) diseases[2]. This essential clinical skill, pioneered by Heinrich Irenaeus Quincke in the 19th century, continues to play a vital role in neurological assessment beyond its diagnostic utility. LP's applications extend to spinal anesthesia, intrathecal drug administration (e.g., chemotherapy), tumor management, intracranial pressure monitoring, and CSF drainage [3]. Mastering proper LP technique is paramount for clinicians, as it significantly reduces the risk of complications and enhances patient safety.

Recent research suggests that patient positioning significantly influences LP success and safety. Studies have demonstrated that the lateral decubitus position, characterized by knee flexion and neck flexion, offers several advantages compared to the sitting position[4]. Notably, it facilitates the identification of anatomical landmarks and potentially contributes to more reliable opening pressure measurements [5]. Furthermore, reducing head extension during the procedure has been shown to reduce the risk of post-dural puncture headache (PDPH), a common complication associated with LP [6].

The best puncture point of lumbar puncture is usually located between the third and fourth vertebrae, and the spinal needle needs to pass through the skin, subcutaneous tissue, supraspinous ligament, interspinous ligament, ligamentum flavum, epidural space, dura, and arachnoid then arrived at subarachnoid space to obtain CSF samples [7]. There is usually a clear sense of breakthrough when the needle is inserted into the skin and through ligamentum flavum.

Informed by the critical role of proper positioning and tactile feedback in successful LP, we developed a mechanical tactile device. This tool allows users to practice identifying the optimal puncture site (typically between the third and fourth lumbar vertebrae) by simulating the movement and sensation of needle insertion. The device accurately replicates the resistance encountered during skin penetration and the distinct tactile sensation of traversing the ligamentum flavum, providing users with a realistic and valuable training experience.

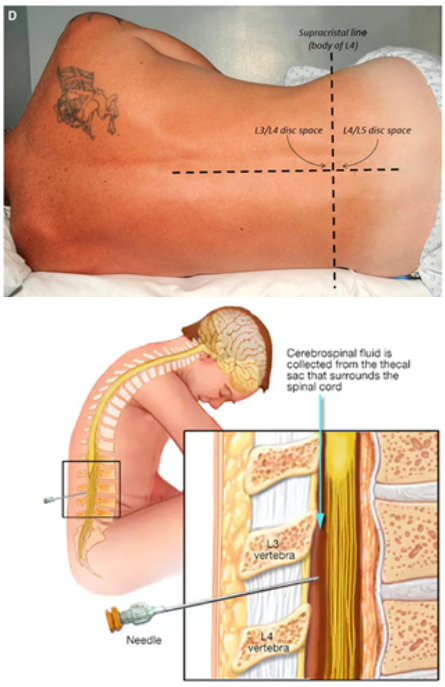

Fig. 1. Figure on the left shows the patient in the left decubitus position and the horizontal dotted line indicates the spinal process [5]. Figure on the right shows the needle being inserted into the spine [6].

II. MECHANICAL DESIGN

This device is built of linear guide rails with sliders, motors, timing wheels and belts, and Arduino board and motor drivers. The device has two degrees of freedom, which allow the user to move the sliding block in the X and Y direction as defined in figure 2, which refers to the direction of inserting the needle into the spine and the direct along the patient's spine, respectively. Other structural parts, from the base support, motor and idle wheel housing, and mounting blocks to the pushing block, were designed in SolidWorks and 3D printed. Since the 3D printing material lack the strength to form threads, most structural parts were fastened using screw-nut mechanism, except the connection between the guide rail slider and the mounting blocks since the guide rail slider has threaded holes. The entire device is clamped

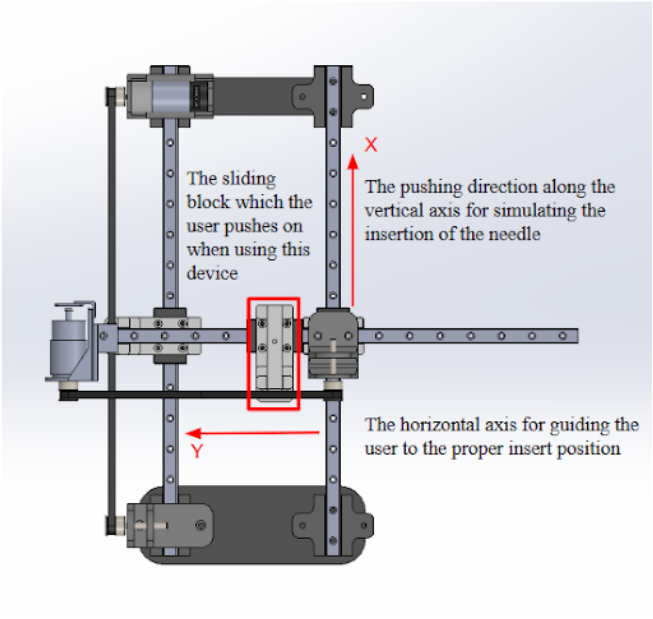

Fig. 2. Definition of axis and introduction to the device's basic function

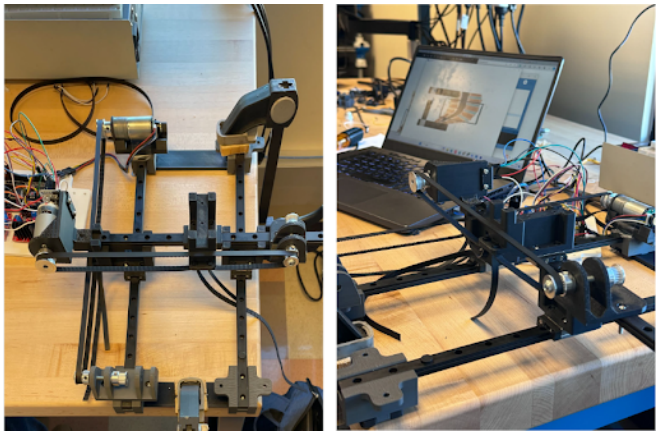

Fig. 3. Left: The actual device; Right: the device with the virtual environment displayed in the laptop

onto the work desk after the assembly has been completed to provide a stable platform. The actual device is shown in figure 3, along with the virtual environment. Two isometric views and an exploded view of the device assembly are shown in figures 4 and 5.

This following paragraph will introduce the structure of the haptic device. From the bottom, two parallel guide rails form the basis of the device and act like the railway to allow motion of the moving components in the X direction. Base supports were assembled to each end of the parallel guide rails, which limit the motion of the insertion mechanism in the X axis and provide mounting platform for other components, such as the housing for the X direction motor and idle wheel. The parallel rails are then fixed by assembling the base support onto the 3D printed boards at the bottom. The third linear rail, which is perpendicular to the parallel rails and allow motion of the sliding block in the Y direction, is

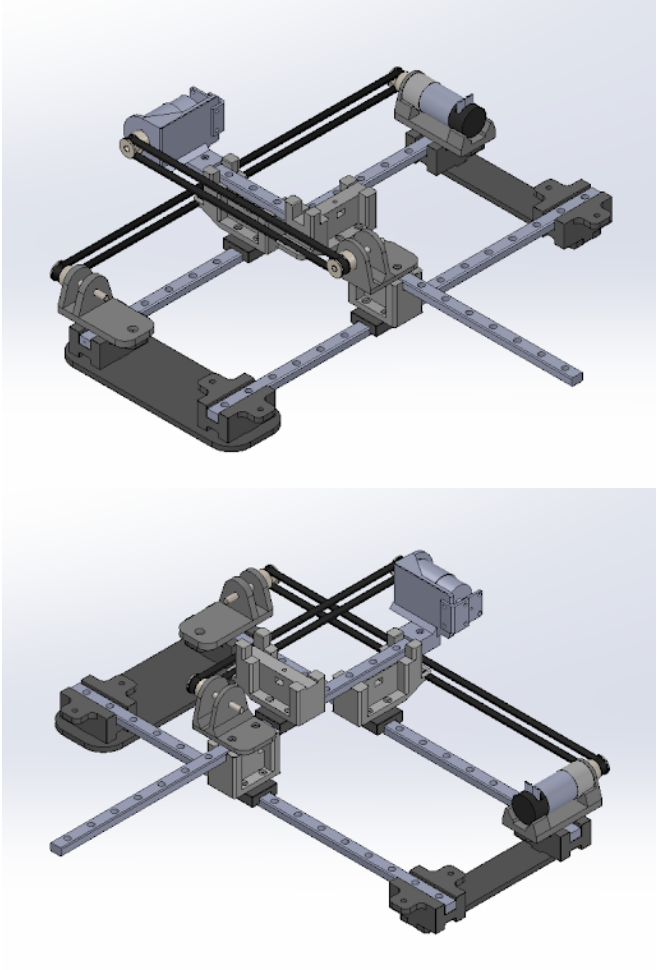

Fig. 4. Isometric views of the device

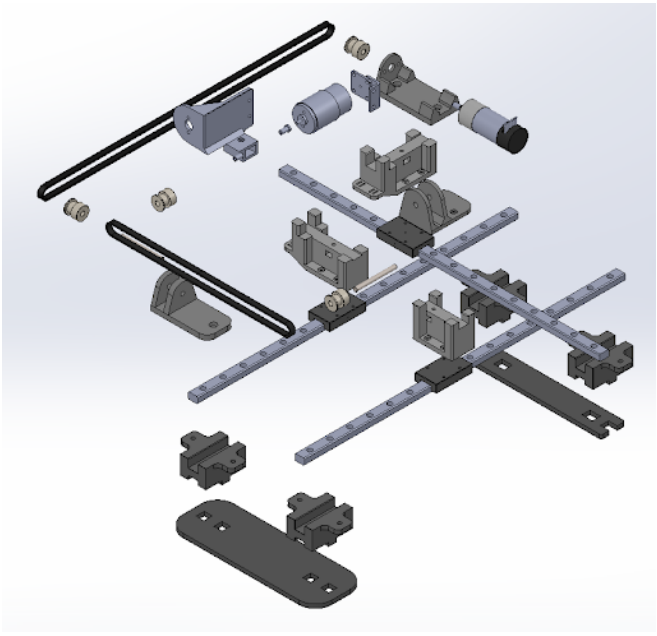

Fig. 5. An exploded view of the device, screws and nuts used for fastening parts not shown

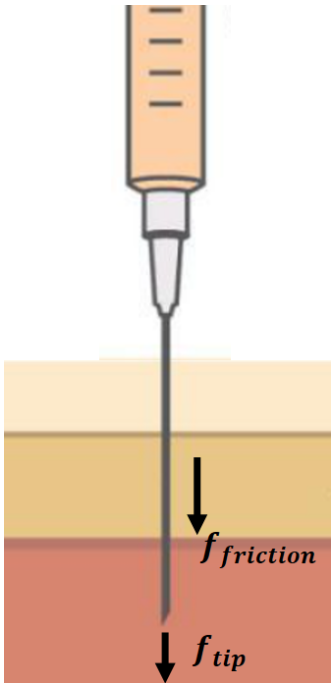

Fig. 6. Force applied on the needle

assembled into the device via two mounting blocks fastened on the sliders of the parallel guide rails. This third rail houses the timing wheel mechanism including the housing for the idle wheel, the sliding block where users will hold during use, and the Y direction motor and its housing.

The purpose of timing wheels and belt is to allow motors in X and Y direction to generate force and haptic feedback to the user, as well as recording the position of the sliding block using the motors' encoders. Referring to the isometric views in figure 3, the X direction belt is tied onto the left mounting block and the Y direction belt is tied onto the sliding block, which allows easy adjustment of belt tension.

III. Force Rendering

A. Force on the inserting direction

The layers of tissue penetrated by the needle are skin and fatty tissue, followed by the supraspinous ligament, intraspinous ligament, the tough ligamentum flavum, the dura mater and finally the spinal cord. In the model, the tissue layers are simplified to five layers, which are out of skin, skin, fat, ligament lincluding the supraspinous ligament and intraspinous ligament, dura including the tough ligamentum flavum and the dura mater and the layer of bone.

The magnitude of the force can be obtained by the system based on the position of the needle tip and the length of the needle inserted in the tissue[8]. The force applied to the needle consists of three components as shown in figure 6 The function to calculate the inserting force is given by (1).

$$f = \begin{cases} f_{tip} + f_{friction} + f_{mechanic} & v > 0 \\ f_{keepdir} & v \leq 0 \end{cases} \tag{1}$$

$f_{mechanic}$ is the moving friction of the mechanical structure which needs to be offset. $f_{keepdir}$ is set to make the moving smoother. As the belt is not exactly tightened, there will be a small sliding when the motor changes the direction which will cause vibration. The magnitude of $f_{keepdir}$ is small and with the same direction as when the velocity is greater than 0, thus the motor will not change the direction when the needle is not moved. $f_{keepdir}$ is set to 0.001N in the model.

The force tip f_{tip} is the reaction force applied to the tip of the needle when the needle is penetrating through tissues. Its magnitude is related to the elasticity of tissues. The mass-spring model represents the interaction between the needle tip and viscoelasticity tissues. As there is no force when the needle is not been pushed. There will be feedback only when there is velocity. The force tip was given in equation (2)

$$f_{tip} = -k \cdot x \tag{2}$$

where k is the tissue elasticity, x is the displacement of the needle.

The friction of the needle is due to tissue adhesion and damping which could be given by the Karnopp model. The Karnopp friction model includes static friction within a certain interval and moving friction depending on the velocity of the needle. If the needle velocity v is smaller than the threshold velocity Δv, there is no relative displacement between the needle and the tissue, and the friction is calculated by the first line of equation 3. Otherwise, there is relative displacement and the friction model will contain coulomb friction.

$$f_{friction} = \begin{cases} -bvl & v < \Delta v \\ -C - bvl & v > \Delta v \end{cases} \tag{3}$$

where b is the tissues' viscosity coefficient, l the length of the needle penetrated in the tissue, v is the needle velocity, C is the coulomb friction, and Δv is the threshold velocity. By referring to studies [9] and testing on the device, Δv is set to 0.01 m/s. The tested result of coefficients of different layers[10] and the distance[11] of the layers are shown in Table I.

TABLE I
LAYERS AND THE RELATED COEFFICIENTS

layers	end of layer(mm)	k/elasticity(N/m)	b/viscosity coefficient (Ns/m^2)	C
out of skin	5	0	0	0
skin	7	330	2.1	0.3
fat	14	0	1.0	0.3
ligament	30	550	3.0	0.5
dura	35	980	3.3	0.6
puncture aim	48	0	1.6	0.2
bone	55	2370	0	0

B. Headings, etc

C. Force on detecting the bone

In performing a lumbar puncture, a spinal needle is inserted between the lumbar vertebrae L3/L4, L4/L5 or L5/S1. To find the correct region of vertebrae interval, texture haptic feedback is given. A friction of damping model is rendered when the user is in the area of bone to give a rough touch. The damping model is given by equation (4).

$$f_{bone\_texture} = \begin{cases} -c \cdot sgn(v) & |v| > 0 \\ 0 & v = 0 \end{cases} \tag{4}$$

where c is the damping coefficient, v is the needle velocity. The function $sgn()$ is given by equation (5).

$$sgn(x) = \begin{cases} -1 & x < 0 \\ 1 & x > 0 \\ 0 & x = 0 \end{cases} \tag{5}$$

When the user gets to the correct region, they should feel free to move. The force model should set with offset of mechanical friction as equation (6).

$$f_{vertebrae_interval} = \begin{cases} f_{mechanic} & v < 0 \\ -f_{mechanic} & v > 0 \end{cases} \tag{5}$$

IV. RESULTS

A. Experiment Procedure

The purpose of the experiment was to let the participants to operate the device and comment on the effectiveness of the haptic feedback. For each trial of the experiment, the sliding block representing the needle would start at the origin and the motor in the Y direction would output a force through the belt mechanism to guide the user to move the sliding block to the proper location. The Y direction motor would stop generating the force once the sliding block is in the proper region to perform the insertion.

After reaching the proper region for insertion, the participant then began to push the sliding block in the X direction to insert the needle into the patient's body. As the needle tip is penetrating different layers of the skin, the device would generate different magnitudes of reaction force to simulate the resistance encountered by the needle. Once the simulated needle tip reaches ligamentum flavum, the user would feel a significantly larger resistance from the device as the simulated needle is puncturing the membrane. Once the participant pushes the sliding block beyond the region representing the ligamentum flavum, the reaction force from the device would suddenly decrease to simulate the sense of breakthrough when the needle punctures the ligamentum flavum. The sense of breakthrough informs the participant that the needle tip has reached the proper location to gather CSF samples.

In real practice, the needle would not go further once reaching the proper region to gather CSF samples, as inserting the needles deeper could damage the nerves and hit the spine. But for the purpose of demonstrating the capability of the program to command the motor to generate reaction forces according to the sliding block's location, the participants were asked to push the simulated needle further until it hits the spine in the virtual environment. Once the simulated needle hits the spine in the virtual environment, the device would generate a large reaction force against the user if the participant continues to push down deeper, simulating the sense of pushing against a very hard surface.

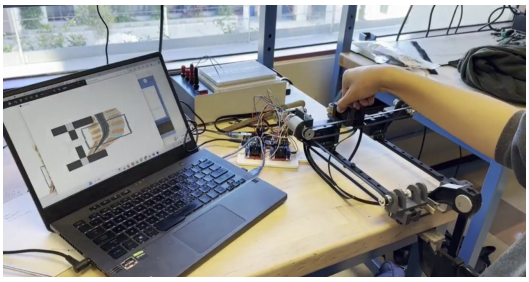

Fig. 7. User pushing the sliding block into the simulated body, virtual environment shown on the laptop

	strongly disagree	disagree	neutral	agree	strongly agree
I can feel the sense of puncture	0	0	0	0	6
I can feel the guidance to the proper location	0	0	0	2	4
I can feel the resistance when penetrating the skin	0	0	0	1	5
I can feel the strong resistance from hitting the bone	0	0	0	0	6

TABLE II

FEEDBACK FROM PARTICIPANTS ON DIFFERENT ASPECTS OF THE HAPTIC FEEDBACK

B. Experiment Results

A total of six person participated in the experiment and they were asked the following questions after completing the experiment: whether they can feel the sense of breakthrough once they puncture the ligamentum flavum; whether the force generated by the Y direction motor is helpful in guiding them to the proper location to insert the needle; whether they can feel the different levels of resistance when penetrating through different layers of the skin; and whether they can feel a strong resistance when the needle tip hits the bone in the virtual environment and they continues to push further. The answers were recorded based on five scales from strongly disagree to strongly agree. The result is listed in table II.

V. DISCUSSION

From the results displayed in table II, all participants reported that they can clearly feel the sense of puncture and the sense of the needle hitting the bone in the virtual environment, while for the other two aspects of the haptic feedback, although the reported sensation is not as strong as the aforementioned ones, are still clearly sensible to the participants. The result shows that haptic feedback, especially the sense of puncture after the simulated needle has penetrated the ligamentum flavum, is very helpful in terms of informing the user to stop pushing the needle. For future work, the device should be equipped with better power sources to ensure all electronics receive enough power, which would improve the accuracy of the Hall effect encoders. The control algorithm could also be modified, for example, to constraint the movement in the Y direction once the insertion has begun, to make the simulation more realistic.

VI. CONCLUSIONS

In this paper, we present a novel mechanical device designed to simulate the tactile sensations and resistance experienced during a lumbar puncture. This device aims to enhance training for medical practitioners, enabling them to better identify the optimal puncture site and develop a kinesthetic understanding of relevant anatomical landmarks. The research focuses on creating an immersive, realistic experience to improve procedural confidence and reduce the risk of needle misplacement. The device's development and effectiveness were demonstrated through experiments and feedback from participants, highlighting its potential as a valuable training tool in medical education. There are also some drawbacks in our device, such as in the user study, some people think the vibration guidance is some what confusing. In future work, we could modify the feedback method used to guide users to the correct position, such as providing a guiding force that points in the right direction, instead of using vibration.

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