Remote Haptic Collaboration for Virtual Training of Lumbar Puncture

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***Abstract*—A remote haptic collaboration system for lumbar puncture learning and training has been proposed. The study built a physical model for the simulation of interaction force between the needle and different tissues and developed a new protocol for real-time force feedback data transmission. Based on the processing delay and preprocessing interpolation, the negative effects on remote haptic perception caused by network communication can be reduced to a minimum. Experiments were carried out to justify the proposed method. The experimental results show that (1) our physical model agrees well with the reality lumbar puncture; (2) the integrity of received data has been ensured by means of interpolation preprocessing. Our system can provide a good realism and real-time stability for the remote learning and training of lumbar puncture teaching.**

***Index Terms*—virtual reality; lumbar puncture; haptic interaction; remote collaboration; force feedback**

I. Introduction

A lumbar puncture (LP) is a diagnostic and at times therapeutic procedure that is performed to collect a sample of cerebrospinal fluid for biochemical, microbiological, and cytological analysis. Lumbar punctures may also be done to inject medications into the cerebrospinal fluid, particularly for spinal anesthesia[1] or chemotherapy. Lumbar punctures can also be used as a treatment for elevated intracranial pressure, such as occurs with cryptococcal meningitis, by removing fluid and decreasing the pressure. Lumbar punctures require a high level of precision and skill from the physician. While inserting the lumbar needle into the epidural space between the vertebral bones of the lower back and into the fluid filled spinal canal, the physician must be greatly careful so as to not perforate the dura matter, a tough fibrous layer that covers and protects the spinal cord and its nerves, as this would result in complications such as spinal headache and the cerebrospinal fluid (CSF) leak that can lead to life threatening infections on rare occasions [2]. However, as soon as the needle enters the epidural space, force feedback from the needle tip can be felt which is called “loss of resistance”. Currently, in medical school, the students gain experience by performing the procedure on real patients, while a trained teacher stands by and instructs medical students as they perform the procedure. Although successful lumbar puncture skill can be learned through that method, the disadvantages are obvious especially for the patient, because unnecessary pain, tissue damage, or injury would be caused by the student’s incorrect operation.

Ongoing progress in the area of virtual reality [3-5] and computer-enhanced simulation is now providing a new training method overcoming most of the deficiencies associated with live-patient training. Computer Haptics is a rapidly emerging area of research that is concerned with the techniques and processes associated with generating and displaying the touch and feel of virtual objects to a human operator through a force reflecting device [6]. Haptic collaboration involves multiple users, each with their own haptic device and they manipulate objects collaboratively in a shared virtual environment where the users can interact. Our system (Figure 1) allows the medical teacher and the training student to interact and collaborate in real-time while sharing the same virtual world, thereby achieving hands-on guidance

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of "loss of resistance" effect. Force feedback, which physicians almost entirely rely on to perform the LP procedure, is provided to the user via a haptic device. The student can practice the procedure at any time without the fear and anxiety of performing an LP on a real patient.

In this study, we have designed a remote haptic collaboration system for simulating LP. Firstly, we built a physical model for the simulation of interaction force between the needle and different tissues. Then we proposed a new force feedback real-time data transfer protocol in the application layer of the TCP/IP network, which is based on the remote haptic collaboration features. Finally, we carried out experiments to validate the effectiveness of the physical model and the proposed protocol.

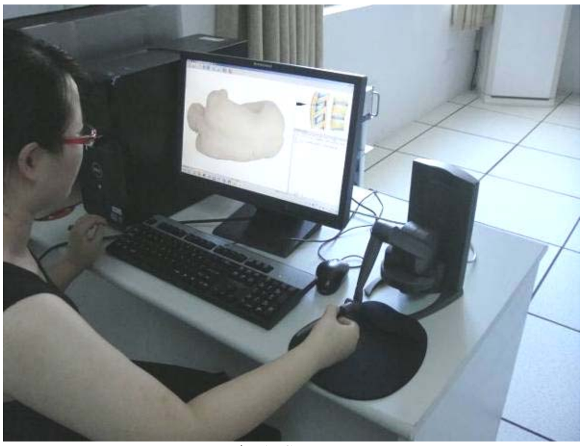

Fig.1: System at use

II. Related Work

There are several works in the area of LP simulation. A three-dimensional simulation of lumbar puncture was developed at Millersville University [7]. In [8], a spine needle biopsy training system was presented which used a haptic device to simulate needle insertion on a mannequin. A display of the CT volume with needle path was shown on a monitor. Colin Sutherland [9] proposed a haptic-based simulator for ultrasound-guided percutaneous spinal interventions, which composed of a haptic device to provide force feedback, a camera system to display video and augmented computed tomography overlay, a finite element model for tissue deformation and ultrasound simulation from a CT volume. A lumbar puncture training system presented by Farber et al. used a PHANToM Premium 1.5A haptic device [10]. The system combined original CT data with label data to facilitate the haptic feedback of structures that had not been segmented. These studies have provided a valid, efficient, and safe method to learn the LP procedure, but less attention has been paid to the interaction teaching between remote teacher and student. So we focus here on remote haptic collaboration.

To use collaborative haptics in LP training application over a real network, we need to overcome the stability problem. Because the presence of random and unpredictable network delays, packet loss, out-of-sequence packets, and other issues seriously affect the sense of user immersion and the overall user experience with remote haptic collaboration systems. Therefore the effective transmission of haptic data is a new research area that presents a number of challenges to the underlying network. Time delay compensation techniques have been studied widely in the area of bilateral teleoperation. Sankaranarayanan [11] used objective measures to compare tuned PD, wave variables, and time domain passivity controllers, which were subject to real-time delays from the Internet, based on similar experimental parameters. Another study [12] was concerned with the integration of wave transformations in the communication stream to produce distributed multi-user haptic cooperation systems, where the lifted state space model was developed to compute the maximum stable gains for the user feedback loops, and to coordinate virtual objects distributed over the network. Kammerl [13] extended the underlying perceptual model of the deadband approach by incorporating psychophysical findings into human force-feedback discrimination during the respective hand movements of operators. Meng Yap and Lee [14] developed a novel force collaboration and position synchronization algorithm to support wireless networked haptic interactions and the new peer-to-peer architecture could support haptic interactions over wireless IP networks. Lee [15] proposed guaranteed stable multi-user haptic cooperation in the presence of variable delays based on a passive integrator, which was suitable for point interaction in static virtual environments. In their architecture, each user simulated and interacted with its own local copy of the shared virtual environment and used a spring connection among the local copies with local damping. All of these analytical investigations focused on the use of control theories to address real-time remote haptic collaboration, rather than using network transmission protocol theories to solve the problem. In general, control theory based methods induce high computational cost as these methods normally result in large number of matrices and differential equation solving.

III. System Architecture

In our study, we used a PHANTOM Desktop device [16] produced by SensAble Technologies, which is capable of six input degrees of freedom and three output degrees of freedom. This device allows the user to touch and manipulate virtual objects. Therefore the so-called "loss of resistance" effect can be well simulated. The force feedback is calculated on a local PC, with which the haptic device is connected via the parallel port and the output occurs immediately to the device. When the medical teacher manipulated their local PHANTOM Desktop, the force was transmitted through the network to a remote PC terminal. Then, the training student could feel the "loss of resistance" effect via their local PHANTOM Desktop. In the same way, the incorrect operation of the training student can be immediately corrected by the remote teacher. Thus, users at both ends of the network could experience remote haptic

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interaction and collaboration.

The architecture of our system is shown in Figure 2. The physical simulator is to provide a physics-based simulation of the interaction between the needle and virtual patient. The results of physical simulation are displayed through graphic rendering and haptic rendering. For the purpose of realistic haptic feeling, the network controller is designed to acquire stable output to mitigate or eliminate the adverse effects of unpredictable network delays, packet loss and out-of-sequence packets.

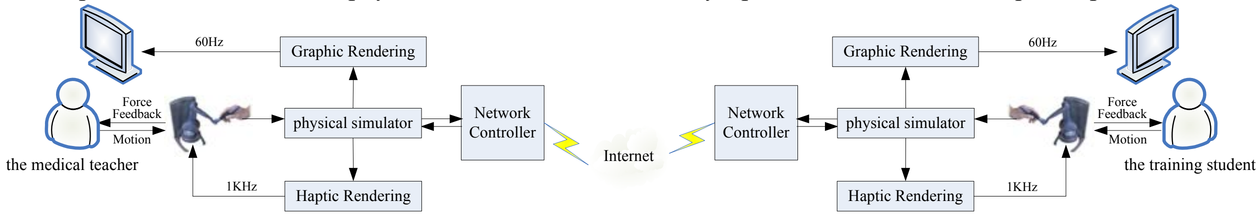

Fig. 2: The system architecture

IV. Haptic Rendering

In performing a lumbar puncture, a spinal needle is inserted between the lumbar vertebrae L3/L4, L4/L5 or L5/S1. The layers of tissue penetrated by the needle as shown in Fig.3 are skin and fatty tissue, followed by the supraspinous ligament, intraspinous ligament, the tough ligamentum flavum, the dura mater and finally the spinal cord [17]. The magnitude of the force can be obtained by the system based on the position of the needle tip. We adopt the methods reported in references [18-22] to compute the magnitude of force applied to the needle. The force applied to the needle consists of three components as shown in Fig.4: the force acting on the needle tip in the axial direction, the friction force acting on the side wall of the needle shaft in the axial direction, and the clamping force acting on the side wall of the needle shaft in the normal direction [23]. The formulation of the total force of the needle is:

$$\vec{f} = \overrightarrow{f_{tip}} + \overrightarrow{f_{friction}} + \overrightarrow{f_{clamping}} \qquad (1)$$

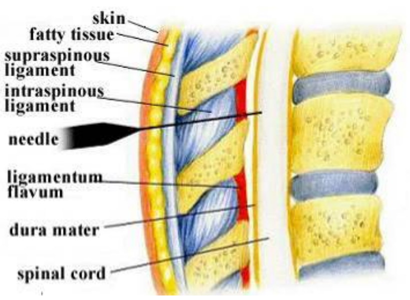

Fig.3: The layers of tissue penetrated by the spinal needle[17]

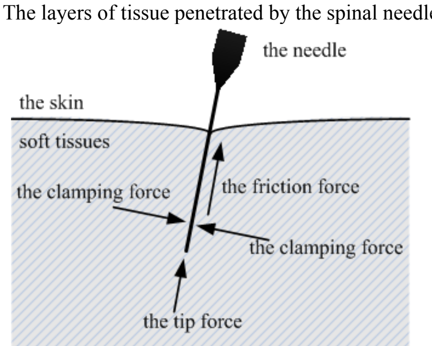

Fig.4: The forces acting on a needle in tissue

A. Physical Simulation for Force $\overrightarrow{f_{tip}}$

The soft tissues can be separated into three categories according to their dominant behavior, namely skin, muscular and ligamental tissue(non-linear viscoelastic solid), connective tissue and fascia(elastic membrane), and fat(viscous solid) [22]. The force $\overrightarrow{f_{tip}}$ 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 and viscosity properties of tissues. Here we use the mass spring model to represent the interaction between the needle tip and viscoelasticity tissues. The force $\overrightarrow{f_{tip}}$ was given in equation (2):

$$\overrightarrow{f_{tip}} = -\left(k\overrightarrow{\Delta x} + \rho\vec{v}\right) \qquad (2)$$

where k and ρ are the tissues' elasticity and viscosity coefficients given by table I, $\overrightarrow{\Delta x}$ is the tissue deformation displacement vectors, $\vec{v}$ is the velocity vector of needle tip.

B. Physical Simulation for Force $\overrightarrow{f_{friction}}$

The friction force $\overrightarrow{f_{friction}}$ occurs along the length of the needle inside the tissue, and is due to tissue adhesion and damping [24]. Here we adopt a friction model proposed by Karnopp [25]. The Karnopp friction model includes static and moving friction, depending on the velocity of the needle. If the magnitude of the needle velocity $\vec{v}$ is smaller than the threshold velocity Δv, the needle is considered to have no relative displacement to tissue. The formulation for the static friction is given by the first line of Equation (3). On the other hand, if the magnitude of $\vec{v}$ is greater than the threshold velocity Δv, the relative displacement occurs thus the moving friction is given by the second line of Equation (3).

$$\overrightarrow{f_{friction}} = \begin{cases} -\rho\vec{v}l_1 & v < \Delta v \\ -C\,\mathrm{sgn}(\Delta x)(\vec{v}/|\vec{v}|) - \rho\vec{v}l_1 & v \geq \Delta v \end{cases} \qquad (3)$$

where ρ is the tissues' viscosity coefficient is given by table I, l_1 is the length of the needle penetrated in the

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body tissue. $\vec{v}$ is the needle velocity. Δv is the threshold velocity below which the velocity of $\vec{v}$ is considered to be zero, C is the Coulomb friction coefficient given by table I. $\vec{v}/|\vec{v}|$ is the unit vector of $\vec{v}$. Based on empirical studies in reference [26], the value of Δv is set to 0.014m/s. Δx is the displacement increment of the needle tip. The sgn() function is defined as Equation (4).

$$\mathrm{sgn}(\mu) = \begin{cases} -1 & \mu < 0 \\ 0 & \mu = 0 \\ 1 & \mu > 0 \end{cases} \tag{4}$$

C. Physical Simulation for Force $\overrightarrow{f_{clamping}}$

The clamping force is the resistance force of the tissue compressed out from the needle path. When the needle is inserted into the tissue, the clamping force increases due to the increase of the contact area between the needle and the tissue. So, the total amount of force $\overrightarrow{f_{clamping}}$ increases with the insertion depth of the needle. It is given by equation (5):

$$\overrightarrow{f_{clamping}} = -k\vec{\omega}\left[l_1/\left(l-l_1\right)\right]^2 \tag{5}$$

where k is the tissues' elasticity coefficient given by table I. $\vec{\omega}$ is the angular velocity of the needle. l is the length of the whole needle body. l_1 is the depth of the needle body penetrated into skin.

TABLE I.
PHYSICAL PROPERTIES OF SOFT TISSUES

Tissue	elasticity factor(N/m)	viscosity factor(Ns/m^2)	kinetic friction (N)
skin	327	3.21	0.5
fatty	0	2.98	0.5
supraspinous ligament	561	4.06	0.8
intraspinous ligament	561	4.06	0.8
ligamentum flavum	920	4.21	1.1
dura mater	920	4.21	1.1
spinal cord	0	1.98	0.5
bone	2370	0	0

V. DESIGN OF HAPTIC COLLABORATION PROTOCOL

The Internet uses a packet-switching protocol so each packet selects an independent transmission path, which causes issues such as network latency, packet loss, and out-of-sequence packets. These issues cause problems because force feedback information might not be timely or it might fail to reach remote interactive users, thereby reducing the performance of the remote haptic collaboration system. In the TCP/IP network architecture, the transport layer protocol is based mainly on either the Transmission Control Protocol (TCP) [27] or the User Datagram Protocol (UDP) [28]. TCP provides a reliable and ordered end-to-end unicast connection, which handles packet loss with retransmission as well as packet duplication. UDP is a connectionless unicast or multicast service that provides no guarantee of the packet delivery order. UDP uses fewer system resources than TCP and has a higher transmission speed. However the reliability of TCP is better than UDP. Due to the high real-time nature of remote haptic collaboration systems, we selected UDP as the transport layer protocol.

A. Communication Process of Protocol

Before sending force feedback data, the remote users must negotiate with each other so the receiving user can prepare their local receiving buffer. Figure 5 shows the communication process. Out-of-sequence packets will cause abrupt movements in applications so, to solve this problem, our solution was to add a sequence number at the front of each packet. At the receiving terminal, the order of the packet is determined based on the sequence number. If the packet sequence number is lower than the previous package that arrived, the packet is discarded. At the receiving terminal, we also designed a controller to preprocess the received data, where the aim was to reduce the errors caused by time delays, packet losses, and out-of-sequence packets. The detailed processing steps are shown in Figure 5.

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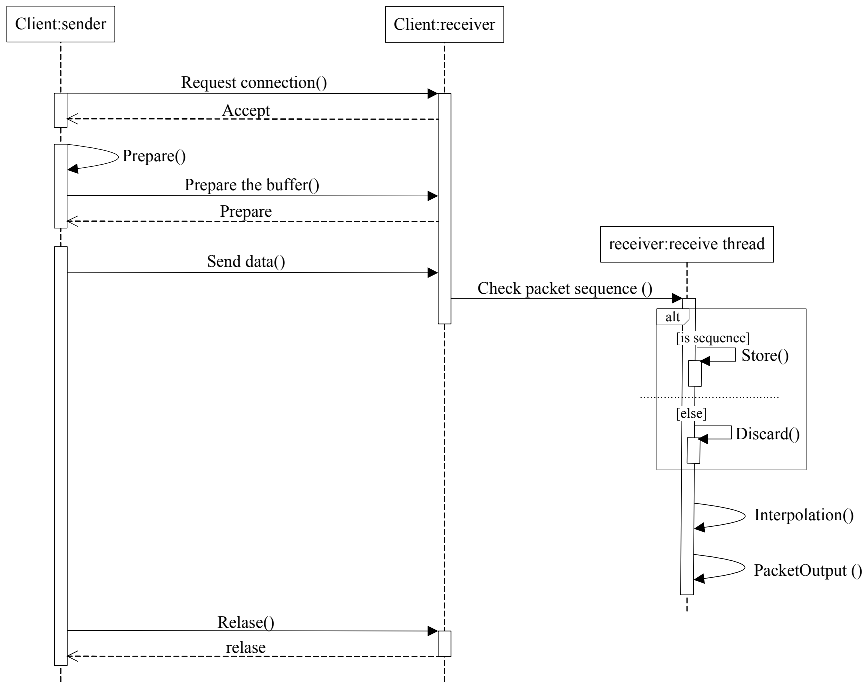

Fig. 5: The communication process

Delay refers to the difference between the time when the packet was sent and the time when it was received, which affects the user's perception of "effective collaboration." Network delays are unavoidable, especially over large distances and the value of the delay has dynamic, random and unpredictable characteristics. For the purpose of outputting force feedback data steadily at a rate of 1000 packets per second, the receiver firstly calculated the time offset δ according to the value of the pre-measured network delay. To ensure the correct interpolation computation and a steady output, a specific amount of data must be stored in the receiving buffer. Thus, the receiver wait for $4*\delta$ time. Finally, a random dynamic delay is converted into a fixed delay to overcome the instability of the system. The detailed processing steps of calculating the time offset δ is shown in Figure 6.

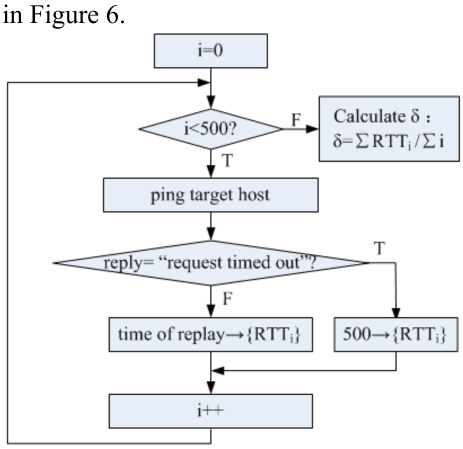

Fig.6: the detailed processing steps of calculating the time offset δ .

B. Pre-processing Interpolation

Packet loss and out-of-sequence packets are also important factors that cause jitter in remote haptic devices such as abrupt movements and abrupt force feedback during applications, which make the system unstable. Previous studies have shown that these effects are sudden and unpredictable, similar to the characteristics of the network delay. Packet losses in a real network environment are affected by the network traffic, the number of nodes, the gateway routing policy, and other factors.

In the previous design, the out-of-sequence packets were discarded by the receiving terminal. Thus, the method for dealing with out-of-sequence packets is the same as that used for packet loss. The processes that cause the two problems are merged together. In this study, we use a method to interpolate the missing data. Thus, we use the quadratic spline interpolation for calculations to reduce the computational considerations. Unlike other interpolation functions, the calculation used for spline interpolation is function $f_i(x)$, which only connects two adjacent data points. x_i and x_{i+1}. The two adjacent functions $f_i(x)$ share a data point. Thus, the fluctuations in the spline function calculated using this method are lower than those with other methods. The specific calculation procedure is as follows.

Definition: any quadratic spline interpolation function $f_i(x)$ can be represented as

$$f_i(x) = a_i + b_i x + c_i x^2 \tag{6}$$

where $f_i(x)$ is the i-th time interval of the time sequence, $0 \le i \le 2$ and $x_i \le x \le x_{i+1}$. Assuming that (x, y) is the interpolation that needs to be calculated, the four adjacent data points are: $A(x_i, y_i)$, $B(x_{i+1}, y_{i+1})$, $C(x_{i+2}, y_{i+2})$, $D(x_{i+3}, y_{i+3})$, where *x* needs to satisfy the condition: $x_{i+1} \le x \le x_{i+2}$.

First, function $f_i(x)$ is obtained by calculating the

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parameter (a_i, b_i, c_i). (a_i, b_i, c_i) is calculated using nine linear equations.

If four data points, A, B, C, and D, comprise the three time intervals, we obtain the following.

$$y_{i+1} = a_0 + b_0 x_{i+1} + c_0 x_{i+1}^2 \qquad (7)$$

$$y_{i+1} = a_1 + b_1 x_{i+1} + c_1 x_{i+1}^2 \qquad (8)$$

$$y_{i+2} = a_1 + b_1 x_{i+2} + c_1 x_{i+2}^2 \qquad (9)$$

$$y_{i+2} = a_2 + b_2 x_{i+2} + c_2 x_{i+2}^2 \qquad (10)$$

The functions $f_0(x)$ and $f_2(x)$, respectively, pass through the points A and D, so we obtain the following.

$$y_i = a_0 + b_0 x_i + c_0 x_i^2 \qquad (11)$$

$$y_{i+3} = a_2 + b_2 x_{i+3} + c_2 x_{i+3}^2 \qquad (12)$$

The first-order derivative of $f_i(x)$ at points B and C must be equal, so we obtain the following.

$$b_0 + 2c_0 x_{i+1} = b_1 + 2c_1 x_{i+1} \qquad (13)$$

$$b_1 + 2c_1 x_{i+2} = b_2 + 2c_2 x_{i+2} \qquad (14)$$

The second-order derivative of $f_0(x)$ must be equal to 0, so we obtain the following.

$$c_0 = 0 \qquad (15)$$

After calculating the nine linear equations using equations (7) – (15), we obtain the results as (a_0, b_0, c_0), (a_1, b_1, c_1), (a_2, b_2, c_2). Because $x_{i+1} \le x \le x_{i+2}$, point (x, y) is on the curve $f_1(x)$ so (x, y) is obtained as follows.

$$y = a_1 + b_1 x + c_1 x^2 \qquad (16)$$

Finally, the interpolation (x, y) can be calculated using equation (16).

VI. Experiments and Results

Figure 1 shows the system in use of one terminal. Two operators cooperate with each other to complete a procedure of lumber puncture on virtual body using their personal computers via the PHANTOM Desktop device. The network was a 100 Mbps Fast Ethernet, which accessed the Internet via CERNET. Winsock was used to connect to the remote computers.

A. Performance of Haptic Feedback

In order to verify the effectiveness and the performance of the system, Figure 7 and Figure 8 show the needle forces received by the remote user. Figure 7 shows the type of tissues traversed during a virtual needle insertion. The two prominent peaks correspond to the passage through the skin and the Ligamentum Flavum. The second prominent peak is "loss of resistance", which agrees well with real operation, when the needle penetrates the Ligamentum Flavum, a significant drop in resistance is encountered. If the student punctured wrong place caused the virtual needle hitting the bone, the force is shown as Figure 8. So it is clear that the physical simulation described in section 4 can successfully simulate the LP procedure.

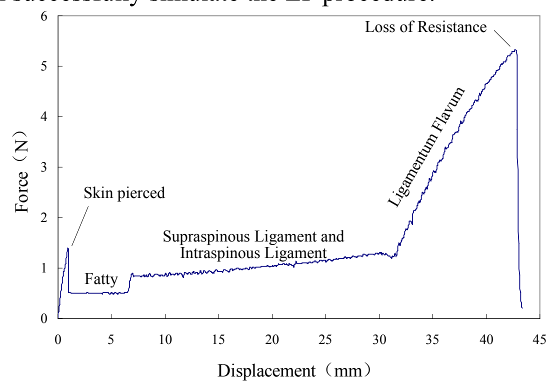


Fig.7: the received needle forces during insertion

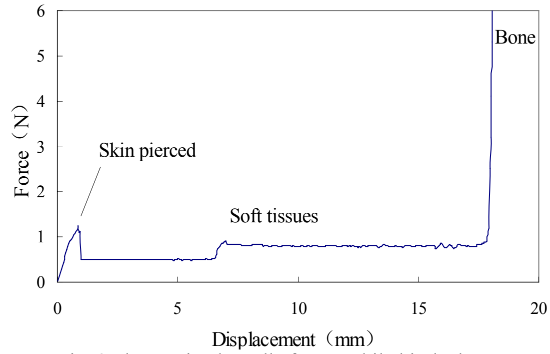
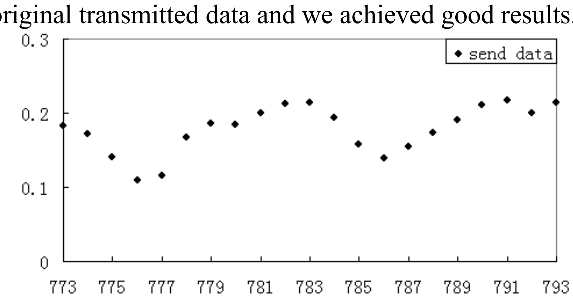


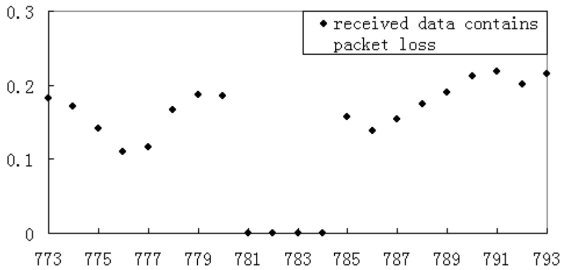
Fig. 8: the received needle forces while hit the bone

B. Effect of Interpolation

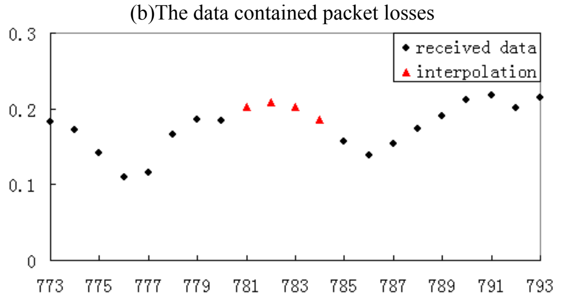
To demonstrate the effect of the interpolation calculation, we amplified part of the discrete time force feedback data (773–793 ms). Figure 9(a) shows the complete and accurate data from the sender. Figure 9(b) shows that the data received by the remote user contained packet losses. Figure 9 (c) shows the output effect after interpolation using the method in Section 3.2.2. Figure 9 (d) shows the output effect calculated based on the mean value interpolation method and it is easy to see from the figures that the error calculated using our method was lower than that with the traditional mean value method. The results with our method were consistent with the original transmitted data and we achieved good results.



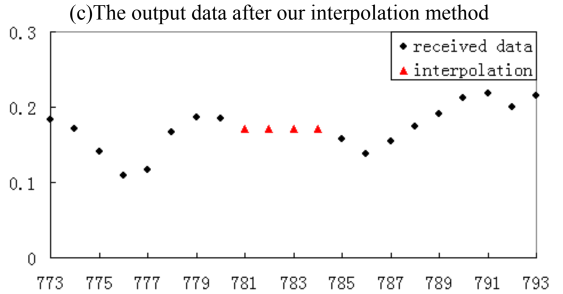
(a)The complete and accurate data



(b)The data contained packet losses



(c)The output data after our interpolation method



(d)The output data after the mean value interpolation method

Fig. 9 The data amplified from part of the discrete time force feedback data (773–793 ms).

C. User Experience

We invited 20 experienced physicians to assist our experiment, i.e., 10 physicians from Nantong University acting as teachers and 10 from a university in Beijing acting as students. The 20 physicians were divided into groups to complete the remote haptic collaboration experiment. They performed a total of 20 experiments, i.e., 10 experiments via the same LAN at their school and 10 experiments via the WAN between Beijing and Nantong. They all completed the task successfully. When asked to insert the needle between two spinous processes and puncture through the LF, the subjects were able to successfully perform the procedure and feel the "loss of resistance" when the needle exits the ligament. All users agreed that they could feel the positive response of hand-to-hand teaching and training process via the PHANTOM device.

VII. Conclusion

In this study, we proposed and developed a new method with remote haptic collaboration for the training of lumbar puncture. In order to achieve better performance of remote teaching and training, a physical model to simulate the interaction force between the needle and different tissues was built and the protocol was designed to facilitate the real-time transmission of force feedback data. Based on the processing delay and preprocessing interpolation, we minimized the negative effects of remote haptic perception caused by network communication. After detecting the network parameters, the appropriate time offset value was selected to change a random network delay into a fixed delay. The integrity of the received data was improved so the stability of haptic feedback was enhanced. The experimental results also verified the feeling of "loss of resistance". In future work, we plan to extend this work to build more accurate physical model of haptic rending and model the predicted force feedback, thereby enhance the user experience during remote haptic collaboration.

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References

[1] T.López, F.J.Sánchez, J.C.Garzón, C.Muriel, Spinal anesthesia in pediatric patients[J]. *Minerva anestesiologica*, vol.78, no. 1, pp.78–87, 2012.

[2] T. Dang, T. M. Annaswamy, and M. A. Srinivasan, Development and evaluation of an epidural injection simulator with force feedback for medical training[C], *Proc. Medicine Meets Virtual Reality*, pp.97 -102, 2001.

[3] LanFeng Zhou, Jian Jiang, An Approach To Navigation For Lunar Rover Based On Virtual Reality Technology[J]. *Journal of software*, vol.7, no.3, pp.632-637, 2012.

[4] Yan Zhang, Xun Zhang, Li Lin, Effectiveness Assessment on Urban Planning Analyzed in Virtual Reality Environments[J]. *Journal of software*, vol.8, no.1, pp.78-84, 2013.

[5] Ruidan Su, Kunlin Zhang, Weiwei Yan,et al, Research on Virtual Reality Sound Effects for High-Speed Train Simulation System[J]. *Journal of software*, vol.7, no.8, pp.1919-1922, 2012.

[6] Mandayam A Srinivasan, What is haptics?, Massachusetts Institute of Technology. http://sensable.org/support/phantom ghost/datafiles/what_is_haptics.pdf

[7] P.N.Gorman, T.J.Parker, A.J.Harrison, T.A. Thomas and A.Carr, Simulation of resistance forces acting on surgical needles[C], *Proceedings of Institution of Mechanical Engineers*, pp.335-347, 1997.

[8] J.B. Ra, et al, Spine needle biopsy simulator using visual and force feedback[J], *Comp Aided Surg*, vol. 7, pp 353-363, 2002.

[9] C. Sutherland, K. Hashtrudi-Zaad, P. Abolmaesumi, P. Mousavi, Towards an augmented ultrasound guided spinal needle insertion system[C]. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pp.3459-3462, 2011.

[10] M. Farber, J. Heller, F. Hummel, C. Gerloff, and H. Handels, Virtual reality based training of lumbar punctures using a 6 degree of freedom haptic device[J], *Advances in Medical Engineering*, vol. 114, pp. 236-240, 2007.

[11] G. Sankaranarayanan and B. Hannaford, Experimental Comparison of Internet Haptic Collaboration with Time-Delay Compensation Techniques[C], *Proc. IEEE Int.*

Conf. Robot. Autom., pp.206-211, 2008
[12] R Rakhsha, D Constantinescu. Distributed haptic cooperation with passive multirate wave communications[C]. *IEEE Haptics Symposium 2012.* Canada, pp.117-123, 2012
[13] J. Kammerl, I. Vittorias, V. Nitsch, B. Faerber, E. Steinbach, and S. Hirche, Perception-based data reduction for haptic force-feedback signals using adaptive deadbands[J]. *MIT Press Journals, Presence: Teleoperators and Virtual Environments*, vol.19, no.5, pp.450-462, 2010
[14] K.M. Yap, T.H. Lee, A Study to Support Haptic Collaboration with Real Time Force Feedback over Wireless Networks[C]. *2011 First International Conference on Robot, Vision and Signal Processing (RVSP)*. *Kaohsiung*, pp.348-351, 2011
[15] D Lee, K Huang, Peer-to-peer control architecture for multiuser haptics collaboration over undirected delayed packet-switching network[C]. *proc. IEEE International Conference on Robotics & Automation (ICRA)*, pp.1333-1338, 2010
[16] SenSAble Technologies. http://www.sensable.com
[17] http://www.pharmacology2000.com/Central/Local_Anes/epidural_block.gif
[18] S. DiMaio, S. Salcudean, Interactive simulation of needle insertion models[J], *IEEE Transactions on Biomedical Engineering*, vol. 52, no. 7, pp. 1167-1179, 2005.
[19] A. Haddadi and K. Hashtrudi-Zaad, Development of a dynamic model for bevel-tip flexible needle insertion into soft tissues[C], *Proceedings of the International IEEE Engineering in Medicine and Biology Society Coneference*, pp. 7478-7482, 2011.
[20] P. Brett, T. Parker, A. Harrison, T. Thomas, and A. Carr, Simulation of resistance forces acting on surgical needles[J], *Proceedings of the Institute of Mechanical Engineers*, vol. 211, pp. 225-347, 1997.
[21] A. Okamura, C. Simone, and M. O'Leary, Force modeling for needle insertion into soft tissue[C], *IEEE Transactions on Biomedical Engineering*, pp. 1707–1716, 2004.
[22] S. DiMaio and S. Salcudean, Needle insertion modeling and simulation[J], *IEEE Transactions on Robotics and Automation*, vol. 19, no. 5, pp. 864-875, 2003.
[23] H. Kataoka, T. Washio, K. Chinzei, K. Mizuhara, C. Simone, and A. M. Okamura, Measurement of the tip and friction force acting on a needle during penetration[C], *Proc. Medical Image Computing and Computer Aided Intervention*, pp.216-223, 2002
[24] M. D. O'Leary, C. Simone, T. Washio, K. Yoshinaka, and A. M. Okamura, Robotic needle insertion: Effects of friction and needle geometry[C], *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.1774-1780, 2003.
[25] R.A.Romano, C.Garcia, Karnopp friction model identification for a real control valve[C], *Proceedings of the 17th IFAC World Congress*, pp.14906-14911, 2008.
[26] CHEN Zhuo, WANG Hai-sheng,Min You-jiang, et al, Preliminary Study on Force Feedback of Acupuncture in Virtual Reality Based on the Visible Human[J], *Chinese Journal of Medical Instrumentation*, vol.31, no.1, pp.5-9, 2007.
[27] Postel, Jon, Transmission Control Protocol, *RFC 793*, September 1981.
[28] Postel, Jon, User Datagram Protocol, *RFC 768*, August 1980.

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