Needle Insertion Simulator with Haptic Feedback

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Abstract. We introduce a novel injection simulator with haptic feedback which provides realistic physical experience to the medical user. Needle insertion requires very dexterous hands-on skills and fast and appropriate response to avoid dangerous situations for patients. In order to train the injection operation, the proposed injection simulator has been designed to generate delicate force feedback to simulate the needle penetration into various tissues such as skin, muscle, and blood vessels. We have developed and evaluated the proposed simulator with medical doctors and realized that the system offers very realistic haptic feedback with dynamic visual feedback.

Keywords: Needle insertion, Medical simulation, Haptic feedback.

1 Introduction

Medical training has become a hot issue due to the evolution of medical technology and an increase of interest in health and improving the quality of life.

Injection is one of the most basic skills used in medical care. Injection training, however, was difficult to learn due a lack of experimental objects to practice on. The objects for experimentation were animals, corpses, or patients. For experimentation using animals, animal anatomy was different from that of people and there were ethical problems. When using the corpses, there was problem which was the physiological response has not gotten enough. And in experimentation with patients, the safety of the patients was not guaranteed.

Various, advanced injection simulators have been developed recently to solve these problems. Immersion Corp developed Virtual I.V [1] which is an intravenous simulator. Virtual I.V provides haptic feedback during intravenous injection process and virtual reality for injection experimentation. But it has two limitations that it cannot provide haptic feedback during removal of the needle and it do not use real catheter. Smith [2] and Zorcolo [3] presented the Catheter Insertion Simulation using a Phantom haptic interface [4], which is also made by Immersion Corporation. Phantom's advantage is that it is easy to use and the cost of the hardware is reasonable. However, Phantom does not offer enough haptic feedback due to a different purpose and design.

The needle insertion simulator we propose provides a practical injection training environment. Unlike previous haptic devices, our needle insertion simulator is

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designed to offer an optimized environment for injection training and high quality haptic feedback without any loss or distortion of haptic feedback because the motor power is not transmitted by gears or belts but directly by motor to rollers.

The overall system of the needle insertion simulator is shown in figure 1.

Fig. 1. The overall system of the needle insertion simulator

2 Hardware Configuration

This section covers the details of the hardware configuration. The simulator's hardware consists of two main parts: one is the controlling part to calculate the values of the haptic feedback and control the motor, the other is the driving part, which contains the motor and inserted hole.

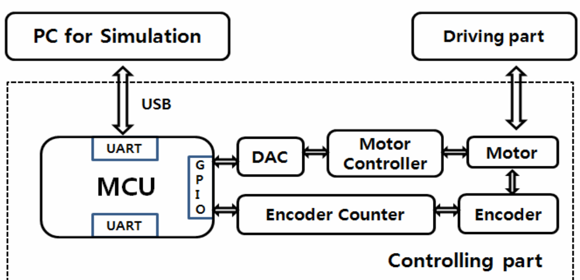

Fig. 2. Framework of the controlling part

2.1 Controlling Part

The block diagram in figure 2 illustrates the overall framework of the controlling part. The main processor of the controlling part is the DSP TMS320F280 manufactured by Texas Instruments, and the Digital to Analog Convertor (DAC) is the DAC0800 obtained from National Semiconductor. We used an RE25 DC motor which works at

24 V/0.6 A and 28.8 mN torque. The MR128 encoder attached to the motor has a 1000 pulse resolution per cycle and this 1000 pulse resolution is increased to four times by the encoder counter's quadrature counting mode, so that it has a total of 4000 resolution per cycle. Also we mounted a 4-Q-DC for the motor controller and SA1 for the tilt sensor which was obtained from DAS Corporation.

The controlling part is explained below. When a needle is inserted into the driving part, the motor rotates as long as the inserted distance. Then the encoder reads the values of the distance and the measured value is delivered to the MCU. Based on the value, the MCU, which calculates the haptic feedback, drives the motor at a 10 KHz frequency. Finally, the haptic feedback is converted to an analog signal by DAC so that the response of the analog signal is faster than the response of the digital signal.

In addition, the tilt sensor offers a slope of the driving part, and this value is transferred to the PC through the USB communication with the encoder value, and used to show the position of the virtual needle.

2.2 Driving Part

The driving part is designed with five conditions to offer an optimized environment for needle insertion simulation.

1. Eliminate loss or distortion of haptic feedback
2. Minimize primitive friction
3. Minimize slipping of the needle
4. Two degrees of freedom
5. Initial insertion slope and variation range of the slope

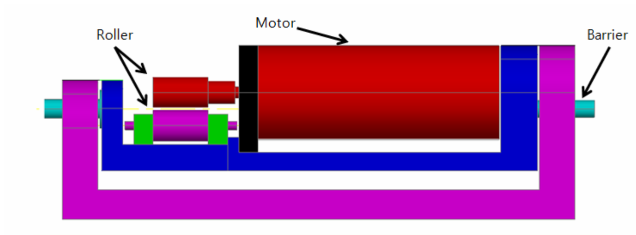

Fig. 3. Design of the driving part

The driving part satisfying the above conditions is shown in figure 3. The most important condition of the needle insertion simulator is that eliminating loss or distortion of haptic feedback. The existing haptic devices are using gears or belts to transmit the motor power. But when using gears, there is back-rash by crack between the gears, and when using belt, there is distortion of haptic feedback because the belt can be stretch. Thus, we designed new mechanism to generate delicate force feedback to simulate the needle penetration into various tissues such as skin, muscle, and blood vessels. Proposed simulator uses friction between two rollers and the needle to transmit haptic feedback. One of the rollers is connected to the motor directly. That is to say, when the needle is inserted to the hole between the rollers, the roller which is connected to the motor generates force feedback. This mechanism using friction does not have any loss or distortion of haptic feedback within maximum static frictional force.

When we insert a needle into the skin, the feeling is weak and delicate. In case of the proposed simulator, therefore, the primitive friction of rollers should be minimized. We used minimum number of bearings due to the direct connection between the motor shaft and roller for minimizing of the primitive friction. Also, the diameter of the roller was determined by an acceptable range of encoder resolution.

The rollers were not only designed to control the space between the two rollers to adjust the friction but they were also coated with urethane to prevent slipping of the needle when it is inserted. But it was hard to eliminate slipping of the needle completely because of such features as thinness and slickness. Therefore, we made a broad and furrowed needle which is shown in figure 4.

During the injection, the needle needs 2 degrees of freedom which are back, forth, up and down. In other word, the rollers should be able to lean in conformity with the needle. For this, the driving part was divided into a fixed external part and a moving internal part.

With a barrier, we could restrict the variation of the slope and adjust the initial insertion slope.

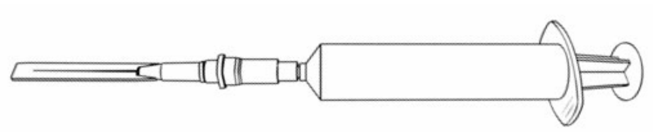

Fig. 4. The broad and furrowed needle

3 Haptic Feedback Profile

We chose intravenous injection toward antecubital basilica vein for needle insertion simulation among several injections. Antecubital basilica vein which is on the forearm is often used for intravenous injection.

In case of intravenous injection simulation, it is important to offer well matched haptic feedback when the needle passes through skin, muscle, and blood vessels. During medical treatment, we assume several conditions such as elasticity of skin, the feeling when the skin is punctured, the feeling when the needle passes through muscle, and the feeling when a blood vessel is punctured.

DiMaio [5] provided a method for quantifying the needle forces and soft tissue deformations that occur during general needle trajectories in multiple dimensions. Okamura [6] studied the force modeling for needle insertion into soft tissue. She measured the axial forces of the needle during insertion into and removal from bovine liver, and modeled force algorithm like tissue stiffness, friction, cutting force, and so on.

We defined haptic feedback as three stages for intravenous injection simulation.

1. Elasticity of skin
2. Friction in muscle layer
3. Elasticity of blood vessel

Because of the elasticity, the skin and the blood vessel have reaction against the needle insertion. But if the injection force exceeds the critical point, the needle penetrates them. Its effect is illustrated by the “Jog effect” equation 1. The effect of the penetration could be expressed by the difference between two effects as shown in figure 5.

$$f_T(T) = (T - n)^2 / a + b \tag{1}$$

After penetration, there is friction in muscle layer. We used Friction Cone Model [7] to describe this effect. The friction is calculated by equation 2. Where P_{curr_f} is the current position, P_{now} is the angular position, P_{pre} is the previous position, S_{f1} and S_{f2} are the scaling factors, P_{diff} is the difference of position, L_f is the friction level, and T_f is the friction torque.

$$\begin{aligned}
&L_f = \exp(P_{now}(n)/S_{f1}) \\
&P_{curr_f}(n) = P_{prev}(n-1) + (P_{now}(n) - P_{pre}(n-1)) \times S_{f2} \\
&P_{diff}(n) = (P_{now}(n) - P_{curr_f}(n)) \times L_f \\
&P_{prev}(n) = P_{curr_f}(n) \\
&\text{if} \quad P_{diff}(n) > T_{f_max} \quad \text{then} \quad T_f(n) = T_{f_max} \\
&\text{else if} \quad P_{diff}(n) < T_{f_min} \quad \text{then} \quad T_f(n) = T_{f_min} \\
&\text{else} \quad T_f(n) = P_{diff}(n)
\end{aligned} \tag{2}$$

The elasticity of blood vessels is also described by the “Jog effect” in equation 1, but we used a smaller value of ‘a’ because the blood vessel has stronger elasticity than the skin.

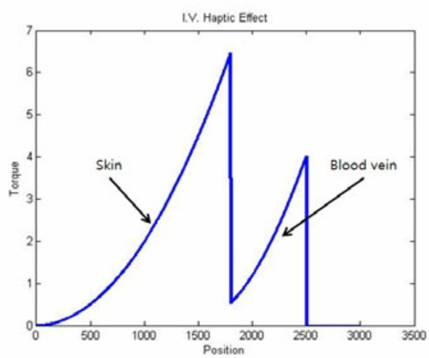

Fig. 5. Profiled haptic feedback for intravenous injection simulation

4 Results

This section covers an interview with an expert about the proposed needle insertion simulator.

We had an interview with an expert, who is an Associate Professor at the school of dentistry of Seoul National University, to evaluate the practical environment that the needle insertion simulator offers. The interview proceeded for two hours with an evaluation and a consultation after enough testing of the simulator. According to the expert, the proposed simulator offered more advanced haptic feedback than other haptic simulators. Especially, it has advantages in illustrating the elasticity of skin, blood vessels, and feeling about the puncture. On the other hand, she advised that the distances between the skin, muscle, and blood vessels were a little bit different, and suggested a haptic needle insertion simulator combined with a model arm to improve reality.

5 Conclusions

Recently, the medical experimentation which is one of the important courses for training medical workers has become a hot issue. There were two major problems in medical experimentation, about objects and subjects. The medical simulators with haptic feedback and virtual reality have been developed recently for solving these problems.

We proposed a needle insertion simulator among various medical experimentations. Unlike previous haptic devices, the proposed simulator provides a more realistic experimentation environment because it was designed for needle insertion simulation. Also, it offers high quality haptic feedback like real feeling of the injection according to an expert. In the future, we intend to develop haptic feedback and injection experimentation contents for different ages and various parts of the human body as well as 3D virtual reality to improve the needle insertion simulator.

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