Evaluation of Venipuncture Techniques Based on Measurements of Haptic Sense and Finger Motion

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Abstract Accurate and trouble-free blood collection reduces the physical and mental risk of patients. Visualization of expert venipuncture techniques is important when conducting blood collection training. Fine motions such as needle insertion for venipuncture should be evaluated by measuring both finger motion and haptic sense. This paper proposes a method for evaluating the needle insertion process in blood collection. Blood collection technique of expert medical staff was measured and analyzed experimentally. A winged blood collection needle was inserted into a forearm model used for venipuncture training. A motion capture system was used to detect finger motions during needle insertion. Furthermore, haptic measurements were made by applying a thin and flexible sensor at the contact interface of the grip to measure both contact pressure and shear stress. The haptic sensor measured contact pressure at the fingers while holding a winged needle, and detected changes in stress components along the directions of needle insertion and skin compression during the venipuncture process. During needle insertion, characteristic changes in stress profiles were observed along with the process of puncturing the component layers of the forearm model. The blood collection procedure could be visualized using haptic sensing throughout the experiment. The proposed haptic sensing system may be useful in enhancing blood collection technique and developing automation of the process.

Keywords: blood collection, sensor, motion analysis, haptic sensing, stress measurement.

1. Introduction

Implementation of an accurate and trouble-free blood collection regimen reduces physical risk and mental burden on patients and medical staff. Efficient blood collection processes can be established by analyzing expert techniques. The development of medical robots for automating blood collection has progressed in recent years [1]. Detection of the venipuncture force applied is indispensable to achieve automated blood collection, and experiments measuring the puncture force on soft materials and living tissue have been carried out [2, 3]. Additionally, technologies essential for realizing automatic puncture have been developed [4, 5]. Medical staff inexperienced in blood collection can err when deciding on needle insertion location and during the actual insertion of the needle into the blood vessel. Thus, visualization of expert techniques is useful when conducting blood collection training. We have previously developed a blood collection visualization system for measuring haptic force [6]. It is necessary to analyze the tactile sense of expert staff with a high sampling frequency and to synchronize this data with finger motion trajectory.

In this study, the previously described measurement system has been improved to detect rapid finger motion and haptic sense at the fingertip during the venipuncture process. A motion capture system, based on infrared marker tracking, is applied to detect finger motion during the moment of needle insertion. Several types of haptic sensors have been proposed [7, 8]. We developed a thin and flexible sensor that can detect both contact pressure and shear stress [9–11]. Measurements are made when a medical staff member insert the blood collection needle into a forearm model, then motion and tactile data during the venipuncture process are analyzed to evaluate the expert technique.

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2. Measurement systems

2.1 Haptic sensing system

A haptic measurement instrument was constructed using a thin and flexible sensor capable of detecting contact pressure and shear stress [9–11]. The electrode pattern of the sensor is shown in Fig. 1. The electrode was a 9 μm thick copper film laminated on a 12 μm thick polyimide film. The electrodes were patterned using a wet etching process. The size of one measurement unit was 3.2 × 3.2 mm (Fig. 1), and was designed to be smaller than that used in previous study [6]. There were two shear stress measuring parts with an area of 1.6 × 0.4 mm each, and one contact pressure measuring part with an area of 0.8 × 0.8 mm. A polythiophene-based electric conductive polymer (EL-P5015, Orgacon AGFA-Materials) was used as the stress sensitive element of the sensor. A property of the sensor is that its electrical resistivity varies linearly with the shear stress applied [6, 10, 11]. This sensor is thin and flexible, and can thus be used to perform measurements at the interface between the human body and any contacting substance.

2.2 Motion capture system

Motions made during the blood collection process were measured by a motion capture system (OptiTrack, NaturalPoint). The system uses infrared rays from reflection markers attached to various body segments. Infrared light sources are located beside the cameras in the system. A video image of a moving marker is detected by multiple cameras. Three reflection markers were used to recognize finger motions during the process of needle insertion. The diameter of a reflection marker was 4 mm, and these markers were attached on an acrylic board. The distances between each reflective marker was 28 mm on the long side and 20 mm on the short side in an isosceles right triangle. Six cameras were arranged to capture all motions in the experimental space.

2.3 Synchronization of haptic sensing and motion analysis

Figure 2(a) shows the experimental setup. The stress sensor and motion markers were fixed on a fingerstall using double-sided sticky tape. The fingerstall with the sensor and markers is shown in Fig. 2(b). The motion capture system generated output signals during the measurement, and these signals were used to synchronize with haptic sensing. In addition, an LED light turned on at the time of measurement was used to synchronize these signals with another video capture.

3. Experimental procedure

A forearm model for blood collection training (BJT-01S, REGINA) was used. In the forearm model, a network of soft tube simulating a blood vessel was embedded in the model and a pump was used to circulate pseudo blood in the tube. Measurement of tactile sense and capture of motion by detecting fingertip movements during needle insertion into the forearm model were conducted.

Because simulated blood was circulated in the blood vessels within the model, the simulated blood flew into the blood collection needle (and into the vacuum tube connected to it) when an insertion was performed accurately. A wing-shaped needle (22G, Nipro) was used as the blood collection needle. The insertion procedures were conducted by three medical staff members, and several trials were conducted. All staff members worked...
in Hirosaki University Hospital and had over 15 years of experience collecting blood. The experiments were conducted under the supervision of a medical doctor. The recording time of the tactile measurement system was limited to 8 s at a sampling rate of 100 Hz. This duration was sufficient for monitoring the entire venipuncture process. The sampling rate was improved from previous study [6].

4. Results

Table 1 summarizes the average times for needle insertion performed by 3 subjects. An example of haptic and needle position measurement data is shown in Fig. 3. Three measurements; shear stress measured in the directions of needle insertion and that in the direction of compression, as well as downward displacement are plotted on the Y axis. Shear stress was measured along with needle position simultaneously. The puncture was completed in approximately 1.8 s.

The results of haptic measurements in the insertion and compressing directions are shown in Fig. 4(a) and (b), respectively. Blood collection was successful in subjects 1 and 2, and failed in subject 3. Penetrations of the epidermis, skin, and blood vessel wall potentially resulted in three peaks in the insertion stress curve. These penetrations may have resulted in reduction of insertion stress and irregular changes in needle movement, as shown by arrows in Figs. 3 and 4(a). The shear stress curves in the direction of skin compression are shown in Fig. 4(b). The differences in stress measured depended how blood collection was carried out, along with individual differences.

Stress in the compression direction evidently decreased after the second peak of stress in the insertion direction in subject 2. Negative shear stress indicates the pulling direction of the skin. Figure 5 shows an example of fingertip trajectory and blood collection needle angle when blood is successfully drawn.

Table 1  Average insertion time for blood collection.

| Subject | Experience [year] | Average insertion time [s] |
|---------|-------------------|---------------------------|
| S1      | 20                | 2.3                       |
| S2      | 32                | 1.9                       |
| S3      | 15                | 2.0                       |

Fig. 3  Example of changes in shear stress measurements along the directions of insertion and compression at the fingertip, and needle motion over time.

Fig. 4  Changes in stress in (a) insertion and (b) compression directions during venipuncture process.

Fig. 5  Trajectory of fingertip and change in angle of blood collection needle in subject 1.
Second order differential processing of shear stress in the insertion direction was conducted with respect to time for characteristics extraction. The results for all subjects are shown in Fig. 6. In Figs. 6(a) and (b), the three peaks were recognized as negative values. However, the values varied widely, and no clear peaks were found in the failure case, as shown in Fig. 6(c). Data processing based on high speed sampling was useful for identifying insertion behavior in the venipuncture process.

5. Discussion

A measurement system of haptic sense and motion capture of the fingers during the needle insertion process was developed in this study. Fine measurements of not only finger motion but also haptic sense experienced by medical staff during the venipuncture process were conducted using this system. Differential analysis of insertion stress measurement data shows the potential of capturing the moments of penetration of various tissues. It is expected that certain points in a stress profile conforming to given characteristics may exist in a successful blood collection attempt. The peaks were considered to appear during penetration of the epidermis, skin, and blood vessel wall of the forearm model. The venipuncture process requires the needle to enter the skin layer and puncture the blood vessel, and then moving the fingertip along the blood vessel. Detecting the series of motions during blood collection requires skill, and haptic senses are therefore important for guiding and controlling finger motion in venipuncture. The timing of changing the needle angle along the blood vessel was detected in the motions made by the medical staff. Angular control of the needle is important for successfully conducting insertion. In light of this, it is possible to confirm whether the blood collection needle is inserted correctly into the blood vessel using haptic sensing analysis. Sensor performances including sensitivity, quantitative capability, and stability are important issues for precise analysis of expert motions and future development of automation technique.

6. Conclusion

A measurement system for analyzing venipuncture procedure was developed in this study. The system consists of tactile sensors and a motion capture system. Furthermore, the venipuncture technique and process of medical staff members were evaluated by applying this system to a forearm model. The blood collection procedure was successfully visualized. The novel system is anticipated to contribute to training of blood collection techniques and developing automation of the process.

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Conflict of interest

The authors declare no conflict of interest relationship with any companies or commercial organizations based on the definition of Japanese Society of Medical and Biological Engineering.

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