The Development of a Haptic Robot to Take Blood Samples from the Forearm

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Abstract. This paper presents the results of tests of a robotic mechanism constructed to take blood samples from the forearm. The system was designed to both identify the location of a vein and to insert a needle into the vein, using a single force sensor.
To locate the vein, a probe was pressed against the surface of the forearm in multiple locations across the width of the patient's arm. An algorithm was developed to analyse the force/position profiles obtained during this process to identify the presence of a vein.
An additional feature of the robot design was to insert a needle into the previously located vein, under force control. A control strategy was developed so that the robot would stop automatically and avoid overshoot of the needle.
Results are presented that indicate that the robot can both locate a vein and insert a needle.

1 Introduction

1.1 Palpation

The robot described in this paper finds the veins in a patient's arm by the use of palpation. Clearly, to (partially) automate palpation, a tactile sensor, as part of a haptic device, is required. Other researchers have recognized the usefulness of tactile sensing as a diagnostic tool and have proposed various electro-mechanical systems. Gentle [1] proposed using an array of pressure sensors to screen for breast cancer. Dario [2] proposed a robot driven probe to mimic palpation, intended for the diagnosis of cancer. Wellman and Howe [3,4,5] also investigated palpation, particularly for detecting tumors in breast tissue.

1.2 The Conventional Venepuncture Procedure

The following section briefly describes the conventional venepuncture procedure as described in [6] and [7]. It also identifies the problems faced by the human practitioner which may be overcome by the use of a mechatronic device.

The arm is palpated until a vein is found. The vein should be firm and slightly bouncy, rather like an underinflated balloon. Then the needle is inserted into the

W. Niessen and M. Viergever (Eds.): MICCAI 2001, LNCS 2208, pp. 614–620, 2001.

vessel at between a 30 and 45 degree angle at a speed estimated to be of the order of 20 mm per second. The deepest veins that can be found by a trained medic are generally between 5 mm and 7 mm deep.

The ability to find a suitable vein is is affected by factors such as the amount of subcutaneous fat, the size of the vein, scar tissue present on the arm and the age of the patient (particularly infants and the elderly). The difficulty in finding a suitable vein may lead to multiple needle insertions in an attempt to find a vein. This causes trauma to the patient. Also, when the needle is inserted, it may overshoot the vein and cause painful bruising. A mechatronic device that can find a vein more accurately than a human, and insert a needle without overshooting, would reduce the pain caused to many patients.

2 The Robot

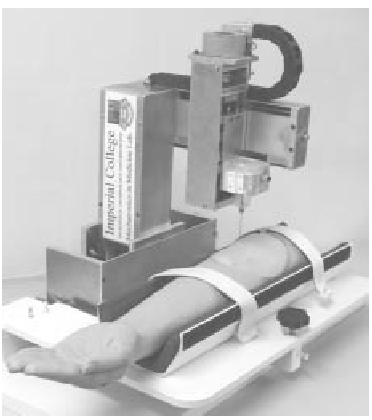

Fig. 1. Overview of the Robot

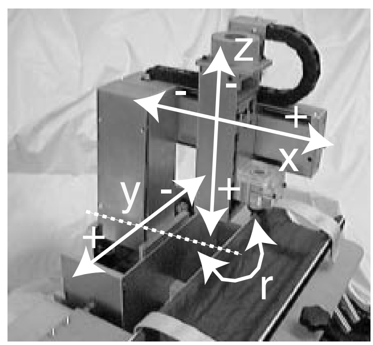

Fig. 2. Axes of the robot, as referred to in this thesis

The robot (see Fig. 1) was designed from specifications drawn up as a result of the feasibility tests described in [8]. It has three powered (linear motion) axes and one unpowered (rotational) axis (see Fig. 2):

The z-axis motor drives a carriage up and down, so that it goes towards and away from the arm that is strapped in under it. This carriage is used to hold either a blunt probe (for finding a vein) or a syringe and needle combination. A single axis piezo-resistive force sensor is mounted on the carriage to measure the force on the probe or needle.

The x-axis motor moves the carriage across the width of the arm. This enables the probe to press in a series of places along the width of the arm.

The r-axis, which is unpowered, enables a human operator to tilt the robot. This is so that, once a vein has been found, the needle can be inserted into the arm at the correct angle.

The y-axis motor moves the whole robot along the length of the arm. This was designed to compensate for the slight difference between where the probe has identified a vein, and where the needle enters the skin, once the robot has been tilted.

The motors used are all inexpensive, standard, stepper types, controlled by the parallel port of a PC, via driver cards. The output from the piezo-resistive force sensor is amplified and then read by a 12-bit analogue-to-digital card in the PC. Switches (read by the parallel port) at the ends of the travel of the x- and z-axes enable home positions to be established for these axes.

Software to control the robot was written in C++ on a PC running Windows 98. There were two major parts of the main control program. The first dealt with the graphical user interface. It checked for user input and plotted the graphs on the screen. The second part dealt with the time critical aspects of the system. This procedure implemented a state machine, which had two phases: one to identify the position of the vein and a second one to insert the needle correctly.

Safety issues were of high importance. The robot was designed so that the needle insertion motion was physically constrained so as not to push the needle beyond a maximum depth of 20 mm. Also, all the axes could be operated by hand in the event of a power failure. Various software devices were implemented to check the behaviour of the robot and to default to a safe condition in the event of an error.

2.1 Software for Automatic Vein Identification

The z-axis was controlled so that the blunt probe pressed down against the surface of the arm. The z-position was noted when two force thresholds were reached - one at 1.77 N and one at 3.82 N. The force threshold values were selected in the following way: 1.77 N was chosen to be sufficiently high as to be in the linear region of the force/position graph (i.e. above the curved portion of the graph that is typical of visco-elastic response). 3.82 N was chosen because it was the maximum force that felt comfortable to a patient when the probe was pressed against the surface of the skin. The thresholds were chosen empirically; further research is required to determine how to select threshold values for different patient types.

This probing process was repeated at multiple locations across the width of the arm. The z-position at the first threshold was taken to be a measure of the elasticity of the tissue beneath the probe and this was the criterion used to choose the location of the vein.

2.2 Software for Automatic Needle Insertion

The initial task was to position the needle above a vein, so that when the needle insertion motor was activated, the needle would enter the vein at the correct angle. The x-axis position was decremented until the x-position of the vein (as determined by the software described in the section above) was reached. The program then prompted the operator of the robot to manually loosen the locking screw and tilt the robot to its maximum position, away from the patient. This resulted in the needle insertion path being at an angle of 30° to the patient's arm, the angle recommended for conventional venepuncture. The operator was also prompted to change the probe for a needle. When this was complete, he/she clicked a button to allow the robot to continue.

The most critical software module was one to detect the moment of breakthrough of an elastic membrane. This could then be used to detect breakthrough of both the skin and the vein wall. The key force/position characteristics of penetration of an elastic membrane are a peak, followed by a drop in force level. The software detected these features by storing the current maximum value of the force. If the five following values were less than this maximum, membrane breakthrough was deemed to have occured. Thus, penetration was detected within 10 ms.

The software advanced the z-axis motor so that the needle moved downwards towards the skin surface. The algorithm detected the skin membrane breakthrough and then the vein wall breakthrough, at which point the z-axis motor was halted. The program then prompted the human operator of the robot to take the required blood samples by inserting a vacuum capsule. It did nothing else until the operator clicked on a 'continue' button, at which point the needle was withdrawn.

3 Results

3.1 Vein Identification Tests on a Human

The sample procedure was carried out 14 times on a single human arm (at which point the arm was too sore to continue). A tourniquet was used, as in the conventional venepuncture procedure. The results are shown in Fig. 3. Out of the 14 scans, the system chose position 6 to be the vein 3 times, and position 7, 11 times. The position of the vein was judged (visually) to be at 7. Thus, the system identified the position of the vein correctly 11 out of 14 attempts, a success rate of 78%. However, this figure is deceptive because the arm moved slightly between scans, so occasionally the vein would be shifted closer to position 6. Also, the distance between the samples was relatively large, so the probe did not always press against the centre of the vein. This could be improved by taking samples closer together, but then a scan would take too long, unless the cycle time per scan were improved.

Further tests are planned on a wide variety of patient types.

3.2 Needle Insertion Tests on Biological Specimens

The robot was first tested on a phantom and behaved well, with the needle being inserted into the artificial vein without overshooting. The next experiments had to be carried out on more biologically realistic subjects. Animal testing was impractical because of the difficulty in obtaining ethical permission. Also, the

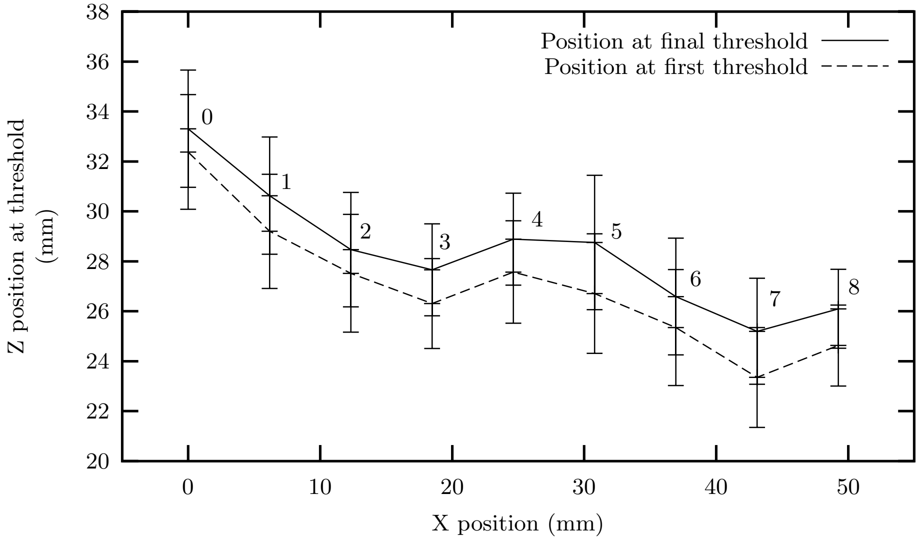

Fig. 3. Graphs obtained pressing on a human arm

force characteristics of animal tissue are different to human tissue, challenging the validity of such tests. Human cadavers were not suitable because of the change in characteristics of soft tissue soon after death, and the effects of the chemicals used to preserve the cadaver. Also, the veins in a cadaver would no longer be filled with blood and so would not behave in a realistic way.

The ideal situation would have been to test the device on live human subjects. However, the difficulty (and time) involved in obtaining permission from the appropriate authorities negated this possibility. Instead, tests were carried out on samples of lamb and chicken (obtained from the butchers). Although the behaviour of these tissues is not identical to human tissue, it was decided that these would be sufficient to test the system's efficacy on non-homogeneous material. The tissues did not have blood vessels, so an 'artificial vein' (a silicon rubber tube filled with liquid) was placed under the layer of skin and fat on the lamb and chicken. This artificial vein was taken from a phantom developed to train medical practitioners to take blood. The 'vein' and 'blood' were designed to mimic the physical behaviour of natural tissue in this procedure. Therefore, it was concluded that its response to needle insertion would be close to that experienced in humans patients.

The samples of lamb and chicken were cut with a scalpel in order that the tube could be inserted under the layer of skin and fat so that the top of the 'vein' was flush with the surface of the muscle. The samples were placed in the position where the patient's arm would normally lie, and the needle insertion software was run. During the run, the meat and 'vein' assembly were held firmly to avoid slippage. When the program paused to indicate that the needle was inside a vein, the chicken skin was manually peeled back to enable a visual inspection. The needle entered the vein and did not overshoot. The point of entry of the needle into the vein was marked on both the vein and the needle. When the needle was withdrawn, the distance of this mark from the tip was measured and found to be 5 mm. Thus, the distance the needle tip reached from the outer surface of the vein was (5.sin 30=) 2.5 mm, approximately half the diameter of the vein, the ideal position for taking a blood sample.

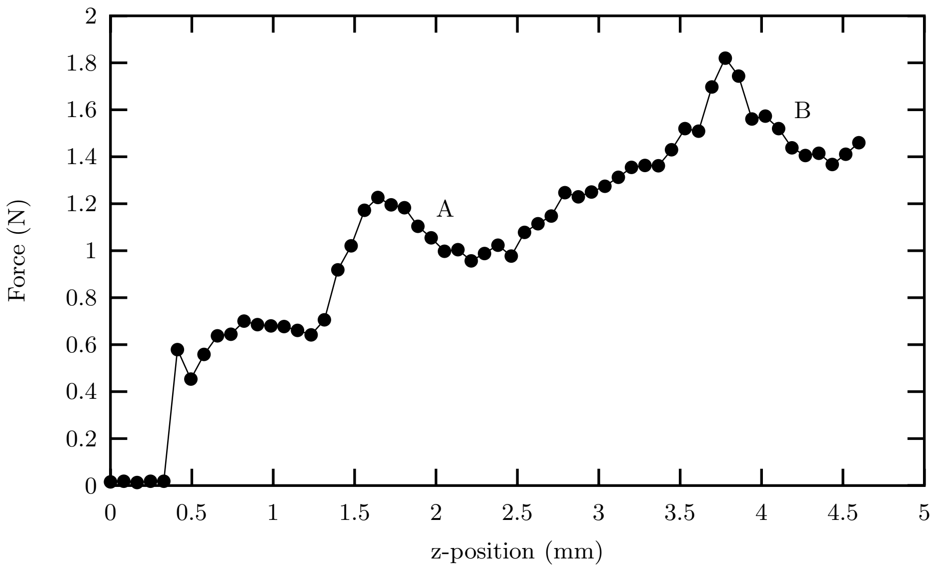

Fig. 4. Graph of force against position as the needle is inserted into chicken flesh. Points *A* and *B* are explained in the text

Fig. 4 shows the force/position profile as the needle was inserted into the chicken flesh. Point *A* on the graph indicates the moment when the program determines that skin breakthrough has occured and point *B* indicates the moment when the program determines that the vein wall has been penetrated.

4 Conclusion

This paper has presented research work on a device to take blood samples from the forearm. However, the approach taken dealt with generic issues such as feature identification using a single force control probe, automatic needle insertion that could be used in other procedures, and control strategies for soft tissue. It also gathered data about the physical characteristic of soft tissue, an area that has received scant attention.

Further tests are planned to be carried out on a wide range of patient types (infants, elderly, obese, etc.) to verify that the approach described in this paper is applicable. These tests would also ascertain the reliability of the device, its accuracy and its limitations (e.g. what is the minimum size of vein that can be found ?).

The blood sampling procedure involves considerable pain and discomfort to many people, and yet no devices are in common use to improve the performance of the nurses and doctors who carry it out. The novel device described in this paper was used to obtain results that show that the robotic device can improve on human performance, by more accurately finding a vein, and inserting a needle into that vein without overshoot. Such a device would be of considerable benefit for patients with veins that are difficult to find, such as those with scar tissue, the elderly, or infants. The robot shows great potential to be developed into a commercial device.

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