Pergamon

Mechatronics Vol. 6, No. 4, pp. 423–436, 1996

0957-4158/96 $15.00+0.00

PII:S0957-4158 (96) 00004-9

A TELEMANIPULATOR SYSTEM AS AN ASSISTANT AND TRAINING TOOL FOR PENETRATING SOFT TISSUE

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Abstract—The requirements are described of a telemanipulator system for assisting in the penetration of soft tissue for medical tasks. A simulation model of events is required to control the procedure. The same model can also be used by the telemanipulator for training purposes. The underlying theory and control of a telemanipulator demonstrator is described, together with a discussion of system requirements. A number of test results are discussed which illustrate the capability of this mechatronics device for use both as a surgeon assistant and as a training aid. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

Soft tissue surgery is a complex procedure requiring precise control of position and force. As an aid to minimally invasive surgery, laparoscopic techniques are often used. The use of a telemanipulator master slave system has been advocated to help automate procedures and to assist the surgeon in the complex control required. However, many local activities must also be automatically carried out by the slave in response to local sensing.

The penetration of soft tissue is required in many medical procedures that require a cutting or piercing action. These can range from slicing and cutting tissue such as muscle and fat, through inserting a hypodermic needle, to opening an initial track for the insertion of tools in the removal of kidney stones. The difficulty with soft tissue is that it deforms and changes shape, both when subjected to a force and when cut through. If a needle is inserted into the skin, it will first deform the tissue. When sufficient force is built up it will penetrate the tissue membrane with enough excess force for the tissue to flow over the needle even though the needle may be stationary. If a specific depth of penetration is required, the needle must be partially withdrawn just after penetration in order to relieve the excess compressive forces induced by the needle. The conventional procedure for judging the progress of the needle, often depends on the length of the needle remaining outside the tissue, some tactile sensing and the operator's knowledge of the process. When using a conventional telemanipulator system in surgery, the tactile sense is usually poor and a surgeon has difficulty in determining the true situation. If this is to be carried out by a telemanipulator, then this procedure will need to have sensing at the slave system as well as a local action by the slave. If compensating action is left to the surgeon, who is observing the state using visual feedback and controlling via the telemanipulator master, then the depth control will be inadequate. Therefore it would be of benefit to provide a tool to assist the operator in deciding the progress of the needle at critical stages, such as when breaking through each layer. A telemaniputor system was designed to detect the breaking through of tissues automatically and provide the operator with a reference signal at the master arm when a breaking through signal was detected. Simultaneously the progress of the slave arm was stopped and immediately withdrawn a short distance using explicit force control. This technique at the slave arm is necessary to avoid the forces, which are used to penetrate the membrane, giving an uncontrollable depth of cut. The operator can then use the master to further advance the cut. For the slave system to take appropriate action, its controller must contain a model of the procedure against which it can compare sensed values.

An additional benefit resulting from the use of a model of the penetrating procedure in the telemanipulator controller is that the telemanipulator can also be used as a simulation system to assist in training surgeons in the penetration of soft tissue. This paper describes a mechatronic system and test results which demonstrate these tasks.

2. PREVIOUS WORK ON TELEMANIPULATOR AND SOFT TISSUE

In recent decades, video-enhanced telescopes (laparoscopes) have been used for minimally invasive (or "keyhole") surgery. Keyhole surgery has the benefit of smaller incisions, less pain and faster post operative recovery. However, it is regarded as more difficult than open surgery. Bozzini [1] was the first to try to use a vision system in the body in 1805. He developed the "Licht Leiter" to visualize the urethra for stones. Jacobeus [2] used the term laparoscopy when he examined the abdomen in 69 patients in 1912. Laparoscopic instruments such as endoloop applicators, hook scissors, tissue morcellators and a laparoscopy training device were developed by Professor Kurt Semm and his team in Germany during the 1960s, thus providing the basis for modern laparoscopy [3]. The first laparoscopic appendectomy was carried out by Semm in 1983. Mouret then performed the first laparoscopic cholecystectomy in 1987. Since then laparoscopic surgery has received considerable attention.

Modern laparoscopy requires the surgeon to use long handled equipment and to watch video displays which have an incorrect or non-intuitive orientation for both eye and hand, with consequential loss of both the tactile feeling and depth of vision perception. In order to improve this inconvenient and tiring way of operating, the use of virtual reality has been suggested. Brown *et al.* [4] proposed that virtual reality be used to provide a computer-generated world including tactile feeling to enable remote surgery. Virtual reality can also be used to create a realistic simulator to train surgeons for operations. Eventually, virtual reality in surgery may lead to remote surgery, diagnosis and training across the world. However the technology is not yet mature. Computer-generated graphics are not realistic, the shapes are not accurate, and the tissue elasticity, tactile and force feedback and other anatomy characteristics are generally inadequate.

This paper concentrates on the tactile and force aspect of a telemanipulator for virtual reality and laparoscopic surgery. During the past few decades, robotics has been applied in industry because of its repeatability, accuracy and the ability to carry out tasks automatically. For those tasks which could not be adequately programmed in advance, a telemanipulator of master and slave form was adopted in which a human operator could interface to control the master when required. The first modern telemanipulator was developed by Goertz in 1945. Since then it has been extensively applied in fields such as space investigation, undersea exploitation, nuclear industry, medical therapy, terrestrial mining and construction [5]. The medical applications of telemanipulators include their development for use in surgery. Green *et al.* [6, 7] have developed a system of telepresence surgery to demonstrate the feasibility. The master and slave units were connected via a short cable to perform surgical actions such as grasping and cutting. Rovetta *et al.* [8] also tested a tele-surgery system which was linked through satellites from the United States to Italy to carry out basic tasks such as injecting a piece of pig, etc. However, neither has been able to demonstrate a complete sensation of telepresence. Because the sensor signals are so unnatural and incomplete, the operator has difficulty in precise, fast control in critical cases such as avoiding cutting through blood vessels or vital organs. It is therefore necessary to design a system to assist the operator in integrating and interpreting the feedback signals for the specific task of working at a remote site [9]. It is also essential to especially provide a slave system which will react to critical situations that occur too fast to be interpreted by the surgeon. Brett *et al.* [10] have demonstrated the benefit of an automatic tool for a stapedotomy to help in detection of breaking through the tissue and automatic withdrawal of the cutter.

The extension of the concept to a telemanipulator system for the penetration of soft tissues has been developed in this paper and it also has the ability to assist and enhance the real time interpretation of tissue penetration for the surgeon. An identification scheme at the slave site is capable of automatically detecting the penetration of various layers of tissues. A force control scheme can also allow the slave system to automatically withdraw the needle to control the depth of penetration. The force controller at the operator site can simultaneously provide a magnified signal to inform the operator of the situation at the slave arm, so that the operator can take further action such as resuming penetration. The system can thus assist the surgeon to react to rapidly changing situations when he could not otherwise respond in time. This increases the safety and reduces the possibility of danger during the operation. In addition, the system can also provide a simulator for training purposes. Data from the penetrating process can be recorded and used to generate a penetration model containing force characteristics, such as the force drop when breaking through tissue. This data can then be implemented at the master arm to simulate the penetration process.

3. THE TELEMANIPULATOR SYSTEM

A demonstrator of the telemanipulation system has been implemented using a one DOF master and slave system. A block diagram of the apparatus is shown in Fig. 1.

The operator can manipulate the master arm by hand, so that the motion command

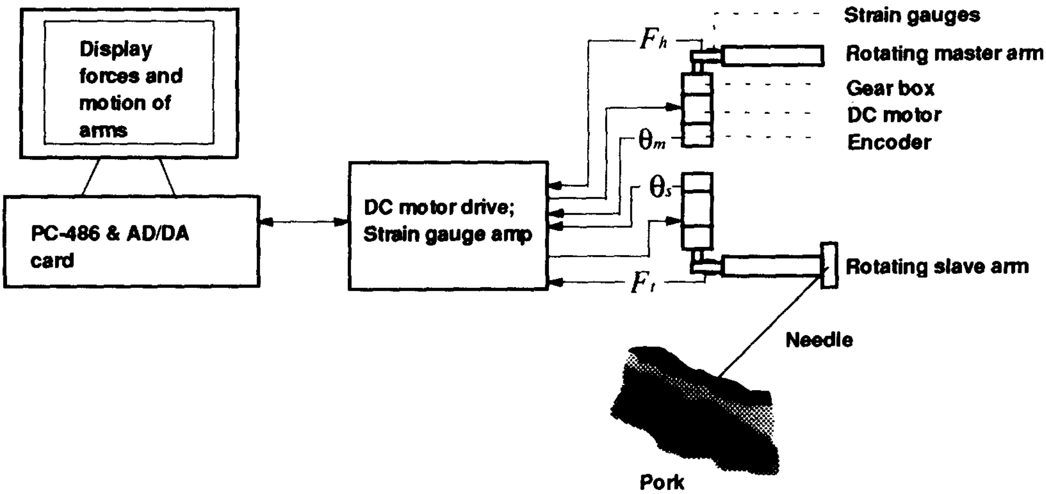


Fig. 1. A telemanipulator system for penetrating soft tissue.

is sent to the slave arm and the slave arm then follows the motion of the master. At the same time, the force which arises at the interaction between the slave arm and the environment is sensed and reproduced on the master arm. Therefore the operator feels as if he is manipulating the remote object using the tactile sensation. The master and slave arms are aluminium in order to provide adequate stiffness with low inertia, and strain gauges are attached to record the forces. The master and slave arm were individually driven by 10 watt Maxon D.C. motors with a two stage planetary gearbox. The D.C. motor drives were operated in torque control mode. Rotational angles were measured through an optical encoder attached to the end of the motor. All signals such as rotational angles, forces, and control torques were processed by PC-486. The signal flow chart of the telemanipulator setup is shown in Fig. 2.

In order to achieve position following at the slave arm and force reflection at the master arm, four primary architectures of master and slave feedback control are used: position–position loop, position–force loop, force–position loop and force–force loop [11]. The force–position loop was adopted here because of its potential to have a high bandwidth of force feedback [11, 12]. The bilateral force control diagram is shown in Fig. 3.

The overall system includes a local PID position controller for the slave arm, a local PID explicit force controller [13] for the master arm and a bilateral controller for linking the master and slave arms. The controller was implemented by a 486 PC. Two sampling rates were used: a high sampling rate of 1000 Hz to calculate the control torque of the motors in order to achieve a higher stiffness, and hence a faster response; 100 Hz, which simulated 10 ms transmission time delay between the master and slave, was used to calculate the desired motion for the slave and the desired force for the master for the bilateral controller. Low-pass filters using a second order Butterworth digital filter with cutoff frequency of 100 Hz were used to filter the measured force signals. Butterworth filters give an effectively flat low band-pass filter and cut off the high frequency noise so that the filtered force signals can be used for

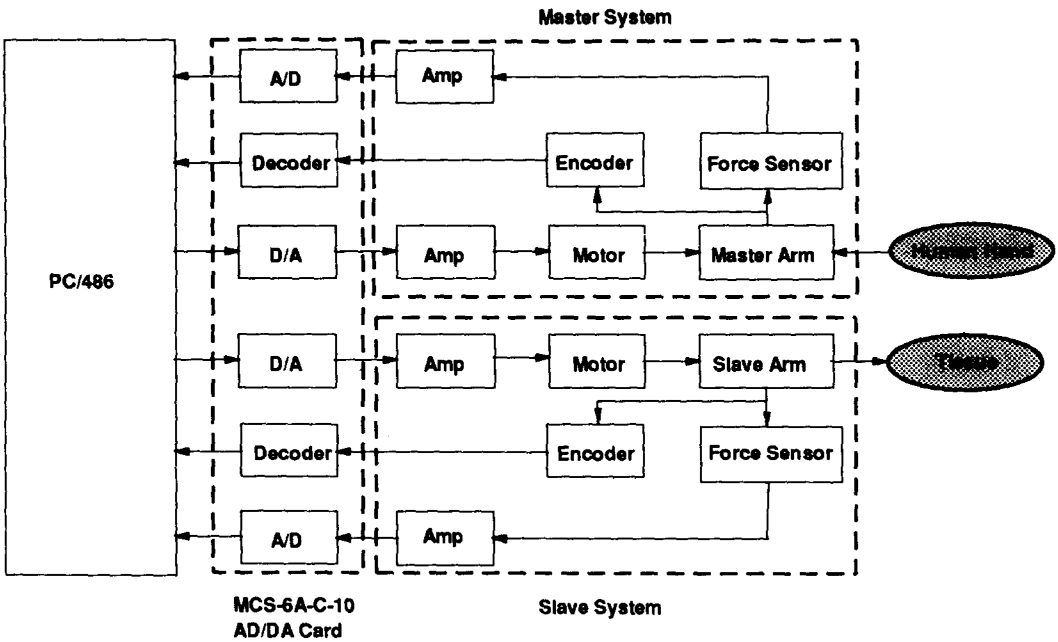


Fig. 2. Block diagram of hardware.

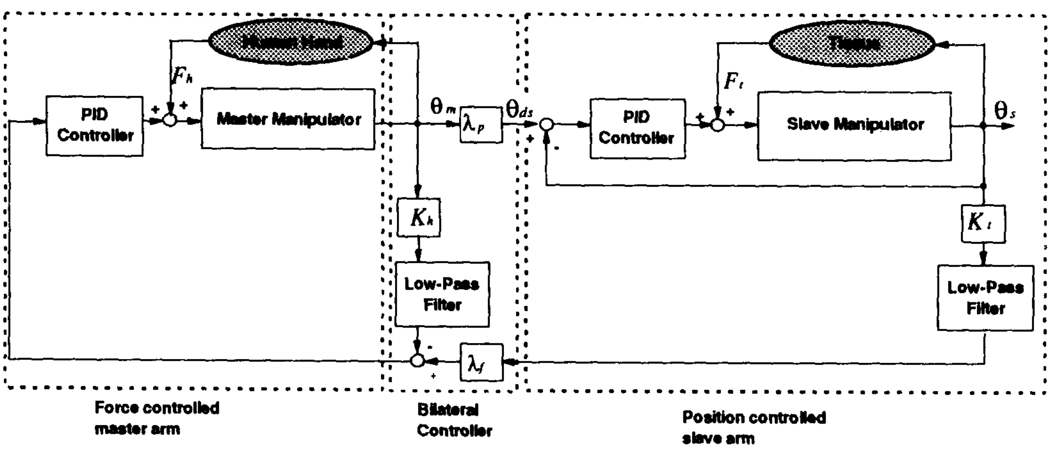


Fig. 3. Block diagram of bilateral force control.

force control. Tests of the telemanipulator system were made to investigate its performance and to assess whether the system could meet the clinical requirements for the manipulation of soft tissue.

The step response and bandwidth results are shown in Fig. 4.

The human response to different actions can vary from the bandwidths of 1–2 Hz (for unexpected signals) to around 10 Hz (for reflex actions) [11]. The bandwidths of the master and slave arm, which were around 20 and 13 Hz respectively (see Fig. 4c and d), show that the response speed of the master and slave system is sufficient for the surgical tasks. Figure 4e and f demonstrate the motion following and force reflection capabilities of the system. The position error was negligible when the resistant force of the tissue was under 1 N and around 0.03 radian when above 2 N. The force reflection to the hand of the operator at the master was an effective feedback of the resistant tissue force at the slave. The system performance is good, being able to track both motion and force, enabling the operator to closely control the manipulation process and to feel the force when attempting to penetrate soft tissue.

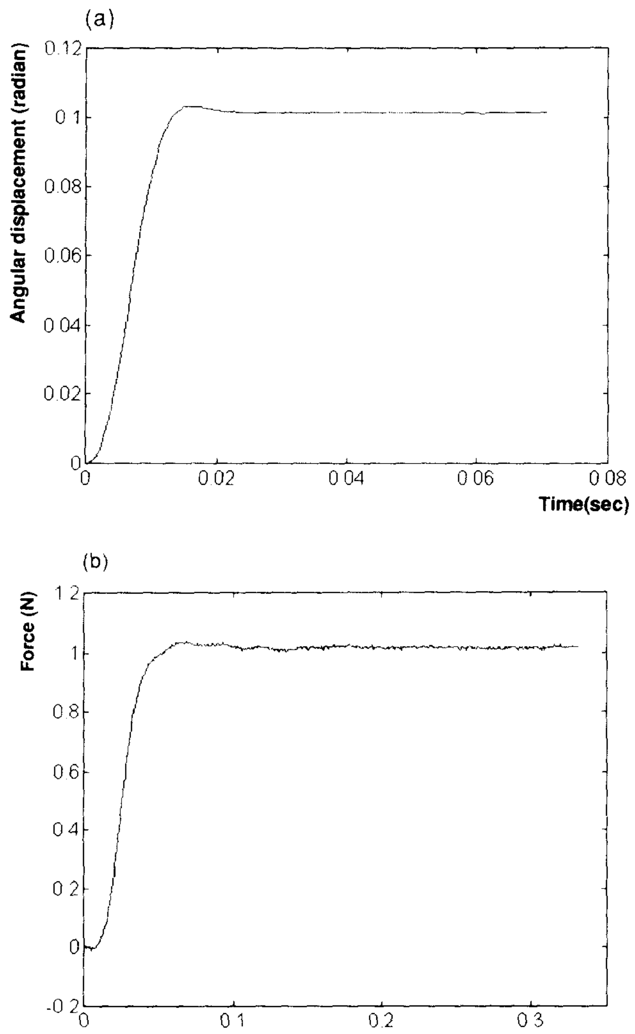


Fig. 4a and b. (a) The step response of the position following of slave to master arm. (b) The step response of force following of master to slave arm.

4. PENETRATION OF SOFT TISSUE

An experiment was designed to study the characteristics of inserting a needle through the outer skin, fat and muscle and also to provide a tool to assist this procedure. A biopsy needle was attached to the end of a single rotational motion at the slave arm to act as an end-effector. The outer layer of the needle was fixed to a steel block and the flexible inner needle moved linearly when the slave arm was rotated to push the base of the needle. A piece of pork was placed in front of the needle and fixed during the penetration procedure. The slave manipulator moved at constant angular speed controlled by the computer, so that the biopsy needle penetrated a piece of skinless pork chop at an almost constant speed of 5.7 mm/sec. The force on the needle tip was measured via the strain gauges on the base of the

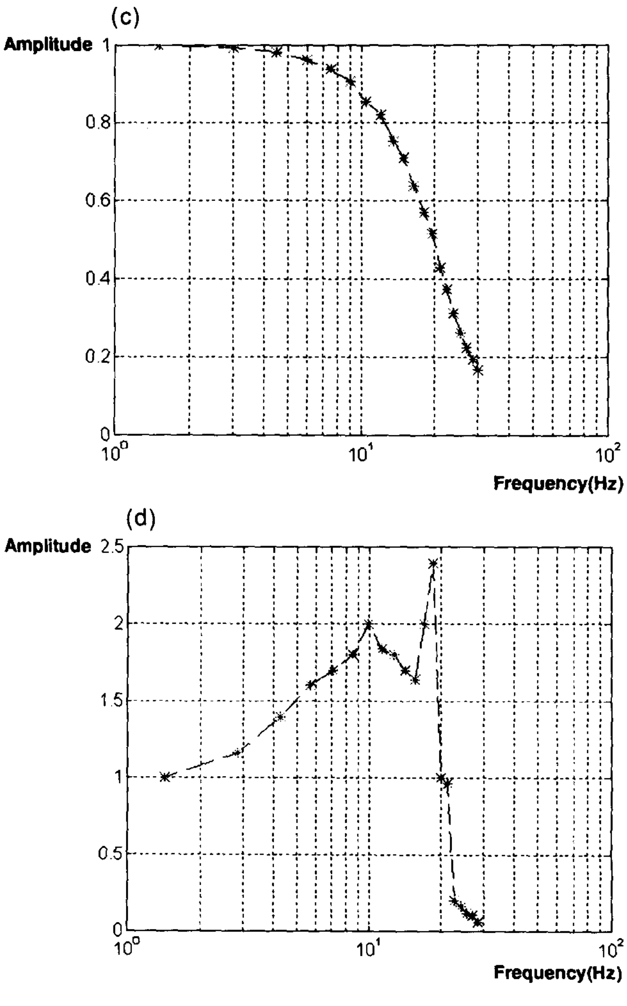
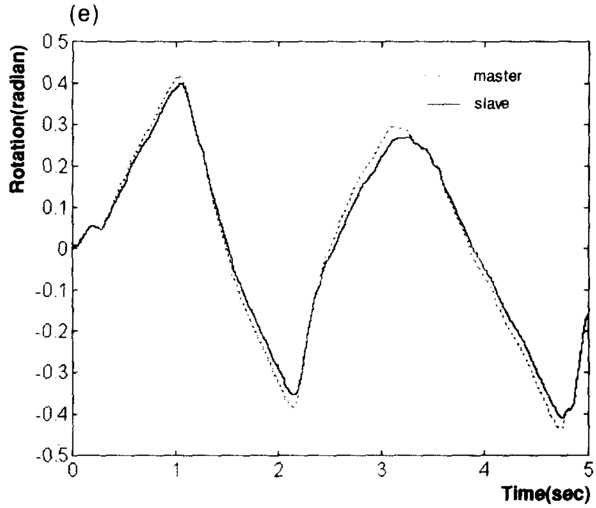


Fig. 4c and d. (c) Frequency response of position following of slave to master arm. (d) Frequency response of the force following of master to slave arm.



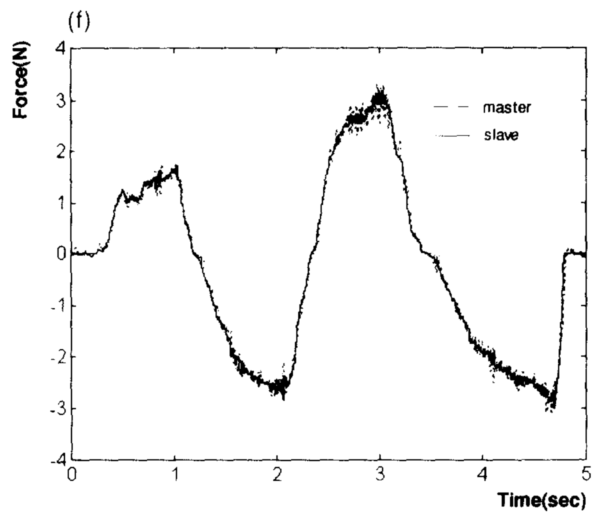


Fig. 4e and f. (e) Motion following of the slave arm to a master input signal. (f) Force following of the master arm to a feedback force signal from the slave arm.

slave arm and the motion of the needle was measured via the encoder of the slave output shaft. The motion and force information were then used to study the characteristics of the penetration behaviour between different layers of tissue. Figure 5 shows the motion and penetration force of the needle.

The results showed that there was an obvious force drop when the needle broke through a tissue layer with a resulting acceleration. In addition, the slope of the force curve changes slightly as the needle penetrates different layers of tissues. The data provide a useful guideline to recognize the moment when breaking through tissue. Therefore a detecting algorithm was developed to detect the breaking through by

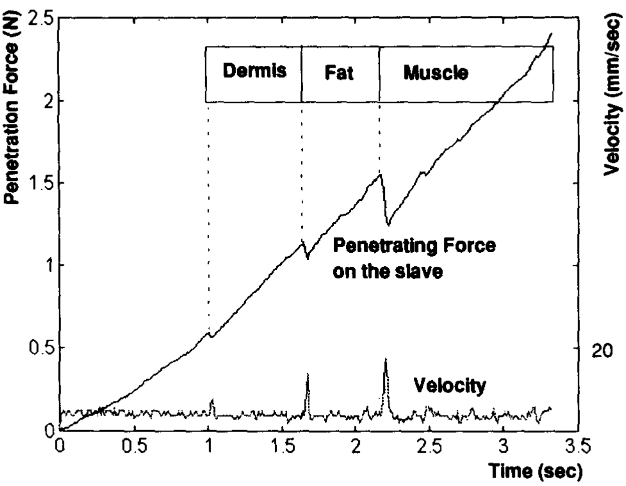


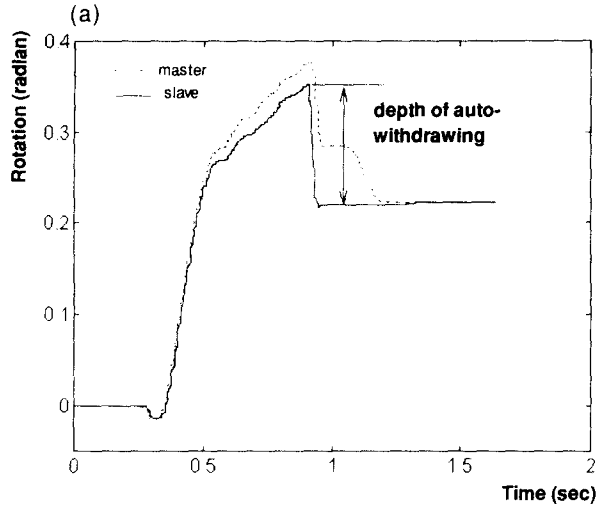
Fig. 5. Needle penetration force of a piece of skinless pork chop at near constant velocity.

using both the force drop and speed characteristics. A force control scheme was then used to partially withdraw the needle automatically from the tissue. Figure 6a and b show the reaction of telemanipulator when the breaking through was detected. The slave arm stopped the penetration motion and immediately withdrew to the position where the penetration force measured zero. The master arm motion reversed to follow the withdrawal of the slave arm and provided an amplified resisting force to the operator. The operator was thus notified of the moment of breaking through the tissue.

5. SIMULATION OF THE PENETRATION OF SOFT TISSUE

Training tools for new practitioners of surgery have recently been in demand. Ethical considerations exclude practitioners from gaining experience by operating on live animal and human subjects. A computer simulation based on an experienced surgeon's knowledge, can offer new practitioners very good training. The practitioner can practice on the simulator repeatedly without recourse to unrealistic soft tissue behaviour in cadavers or to living animals. Practitioners can also compare their results with those of experienced surgeons, thus giving a relative score which can be recorded to document the evolution of a trainee's performance.

A simulator using a telemanipulator system was developed to imitate tactile feel during tissue penetration. It was intended to give experience of a resisting force as it happened in the penetration procedure, and was especially aimed at the drop in force levels when breaking through tissue. A linear model of penetrating soft tissue was developed experimentally rather than analytically. The Kelvin–Voigt model of a spring and dashpot in parallel was used to represent a single layer of tissue (rather than the Maxwell model of spring and dashpot in series), because visco-elastic soft



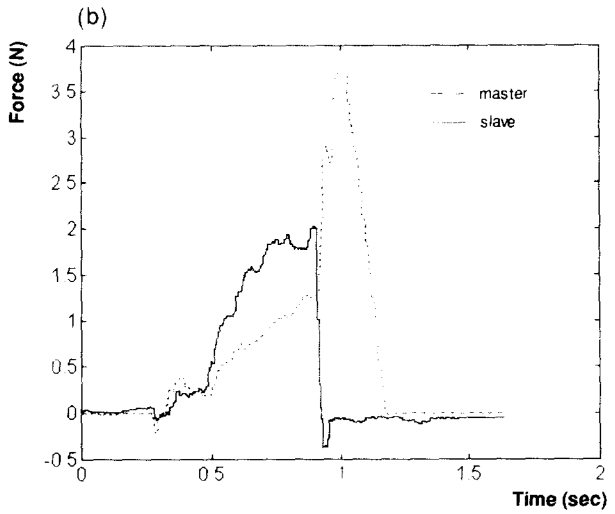


Fig. 6. (a) Displacement record of penetrating soft tissue. (b) Force record of penetration.

tissue is considered to be more solid than liquid material. The more accurate Burger model with parallel and series springs and dashpots, which include both the solid and liquid properties, was not used here because it is too complex for determining the parameters [14]. A number of force, displacement and velocity values were measured by penetrating a number of pieces of pork and by using different positions on the same piece of pork. The data showed a great deal of variation in the breakthrough position, the value of force drop and the slope of the penetrating force curve. However, in general, the slope increases with increasing depth of penetration, which suggests that a number of different tissue layers can be represented by a series connection of the parallel spring and dashpot. The further general observation of the measured data was that the force dropped at the moment of penetration. A nonlinear element of a switch (to switch off the earlier tissue spring and dashpot after penetrating a layer) was used here to simulate the discontinuity at the breakthrough points. Based on the above observations, a force control strategy was introduced using a piecewise linear model of each parallel spring and dashpot combination to approximate the combined pressing and penetration process. This contrasts with the nonlinear model used by Brett *et al.* [15]. The force controlled simulation based on the piecewise linear model, more accurately reflects the experimental relationship of force, displacement and velocity than that of the velocity controlled simulator in [15]. Our model can be written as

$$F_t = K_t(x)X_t(x) + C_t(x)\dot{X}_t(x), \tag{1}$$

where F_t is the resistance force at the needle tip, x is the position of the needle, X_t is the deformation of the tissue, K_t is the recovery spring constant of the tissue, C_t is the viscous resistant constant of the tissue,

$$X_t = x - u(x - \sigma_1)L_1 - u(x - \sigma_2)L_2 - u(x - \sigma_3)L_3 - \dots \tag{2}$$

$$\frac{1}{K_t} = u(\sigma_1 - x)\frac{1}{K_1} + u(\sigma_2 - x)\frac{1}{K_2} + u(\sigma_3 - x)\frac{1}{K_3} + \dots \tag{3}$$

$$\frac{1}{C_t} = u(\sigma_1 - x)\frac{1}{C_1} + u(\sigma_2 - x)\frac{1}{C_2} + u(\sigma_3 - x)\frac{1}{C_3} + \dots, \tag{4}$$

where σ_i is the break through point and L_i the thickness of each layer of tissue.

The discontinuity of breaking through the tissue was represented by the unit step function $u(x - \sigma_i)$ (at break through points $x = \sigma_i$). The break through point σ_i was lumped in the model although it depends on many factors, such as the radius of the needle tip, the feeding velocity and the tissue characteristics [10]. All parameters were identified based on the measurements taken whilst penetrating tissue. By locating the force drop point and fitting the curve with a least square method, these parameters for a set of measured data of penetration force were chosen as:

$$\text{break through points (mm): } \sigma_1 = 4.860,\ \sigma_2 = 7.854,\ \sigma_3 = 10.358 \tag{5}$$

$$\text{depths of each layer (mm): } L_1 = 2.419,\ L_2 = 0.907,\ L_3 = 2.232 \tag{6}$$

$$\text{recovery spring constants (N/mm): } K_1 = 0.257,\ K_2 = 5.361,\ K_3 = 6.620,\ K_4 = 0.222 \tag{7}$$

viscous resistant constants (N · sec/mm):

$$C_1 = 0.008,\ C_2 = 0.585,\ C_3 = 0.552,\ C_4 = 0.381 \tag{8}$$

and the piecewise linear model was

$$F_t = \begin{cases} 0.114x + 0.008\dot{x} & 0 \leqslant x < 4.860 \\ 0.206(x - 2.419) + 0.163\dot{x} & 4.860 \leqslant x < 7.854 \\ 0.215(x - 2.419 - 0.907) + 0.225\dot{x} & 7.854 \leqslant x < 10.358 \\ 0.222(x - 2.419 - 0.907 - 2.232) + 0.381\dot{x} & x \geqslant 10.358. \end{cases} \tag{9}$$

The above equations were derived from measurements of a particular test at near constant velocity. The values of parameters are typical of (but not identical to) those for other pieces of pork soft tissue or for other penetration positions in the same piece of pork. Variations are due to the non-homogeneous texture and other factors, such as the "freshness", temperature and humidity of the soft tissue.

Figure 7 shows a comparison of the model with the measured data. The output of the model can be seen to fit the measured data closely. It indicates that the spring and dashpot model is appropriate to represent the procedure of penetrating soft tissue.

The simulator was then implemented on the master arm, which was controlled through an explicit force control scheme. The results of the simulator when penetrating soft tissue are shown in Fig. 8. The graph shows that the force drop at the break

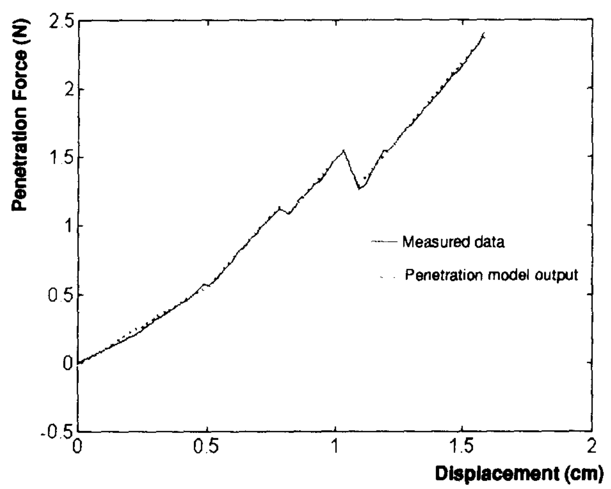


Fig. 7. Penetration model using the least square parameter identification.

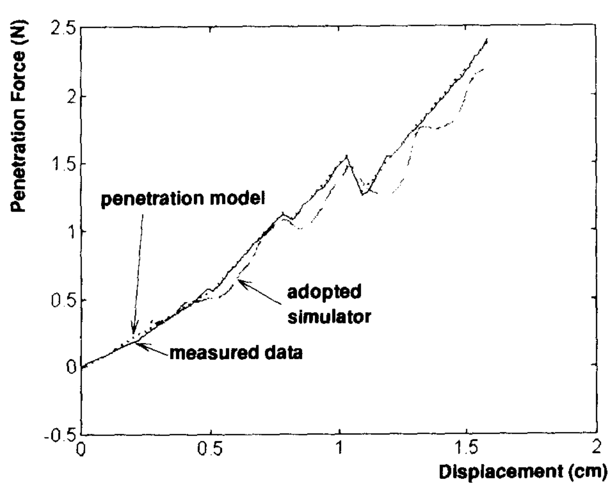


Fig. 8. Implementation of penetration simulator.

through point was capable of giving detection feedback to the operator when passing through a tissue boundary. This simulator gives the operator a very realistic sense of the tissue penetration process.

6. CONCLUSIONS

(1) A telemanipulator system has been developed to aid in force control and its application in the manipulation of soft tissue. The bandwidth (more than 10 Hz) of the system provided an adequate response speed for the task of penetrating soft tissue. In addition the accuracy of motion following of the slave and force reflection to the master gave a good sense of telepresence for the operator.

(2) It has demonstrated the potential to provide an assistant tool for the detection of certain critical tissue penetration situations and the ability to react instantaneously in order to control penetration depth. It was found that the penetration force drop, acceleration of needle movement and change of the slope of penetration force are all useful for detection of break through of tissue. A spring and dashpot model of penetration of soft tissue was used to assist the detection of break through of the tissue. The parameters of the model were decided using a least square method. More penetration tests are needed to identify the values of these parameters, such as recovery constants K_i and viscous resistant coefficients C_i, for specific types of tissue.

(3) It was found that the telemanipulator can also provide a training tool to reproduce the surgical procedure, based on the model of penetration of tissue taken from previously recorded data. The amplified scaling of motion and force level provided by the telemanipulator would also be beneficial for the purpose of training when the penetration force is too poor to be recognized by an inexperienced practitioner.

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