Force Modeling for Incision Surgery into Tissue with Haptic Application

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ABSTRACT

This paper presents a novel force modeling for an incision surgery into tissue and its haptic application for a surgeon. During the robot-assisted incision surgery, it is highly urgent to develop the haptic system for realizing sense of touch in the surgical area because surgeons cannot sense sensations. To achieve this goal, the force modeling related to reaction force of biological tissue is proposed in the perspective on energy. The force model describes reaction force focused on the elastic feature of tissue during the incision surgery. Furthermore, the force is realized using calculated information from the model by haptic device using magnetorheological fluid (MRF). The performance of realized force that is controlled by PID controller with open loop control is evaluated.

Keywords: Force model, Magnetorheological fluid, Haptic device, Robot-assisted incision surgery, Reaction force

1. INTRODUCTION

Recently, the trend of surgery has gone over from the laparotomy surgery to the robot-assisted minimally invasive surgery. To reflect this tendency, demands of surgical robot using laparoscope has been incredibly increased. A notable example of commercialized is da Vinci surgical system and ZEUS surgical robotic system, etc [1]. A typical composition of these surgical robot is slave robot which conducts surgical operation under the guidance and master device which commands motion to the slave robot. This surgical robot can precisely follow surgeon's motion under the manipulation of master in real-time to achieve successful surgical operation. During the surgical operation, the surgeon can interacts robot with image from laparoscopic device [2]. However, it is very hard to comprehend inside situation of patient with only visual information during surgery because although, visual information is essential but it is not enough for surgeon to determine decision in critical situation. Also the absence of physical sense leads to foreignness from laparotomy surgery and it makes hard to adapt to robot-assisted surgery in visual only condition. Therefore, generally, excessively long time at least about over 1 month is needed for surgeon to acclimate system. Furthermore, the difference condition between laparotomy surgery and robot-assisted surgery degrades the accuracy of the operation result due to the lack of sense which can lead to situation to cause unnecessary damage to patients. Because of these problems, haptic system for realizing sense of touch has been researched actively in many countries. To resolve these problems, a haptic system to provide the touch of sense information to surgeon should be considered and this subject has a tremendous importance in developing the accurate surgical robot, the surgical simulation, the preoperative planning tool and the autonomous surgery system. Thus, in this paper, a prediction algorithm related to the reaction force of biological tissue is proposed. This predicted force model is formulated by experimental data based on the energy theories. The incision procedure occurs due to the work done by external force. The energy is exchanged or dissipated to other type of energy including elastic potential energy from the deformation of tissue and irreversible energy from the rupture and friction according to the mode of procedure. Also the reaction force from the force model is realized by the haptic device using magnetorheological fluid (MRF in short) with bi-directional clutch (BDC) mechanism [3]. Then force control results are evaluated with data from actual experiment and model.

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2. MATHEMATICAL MODEL

In the majority of cases, a scalpel maintains constant angle and depth to the surface of tissue during the incision process. Also its incision direction is same to direction of the blade edge. To reflect this conditions and draw ideal calculation results, a mathematical model can be represented by following equation.

$$F_{scalpel} = F_{stiffness} + F_{rupture} + F_{cutting} + F_{friction} \tag{1}$$

where $F_{scalpel}$ is the resultant force on the scalpel, $F_{stiffness}$ is the force by stiffness of tissue, $F_{rupture}$ is the force by rupture of tissue, $F_{cutting}$ is the force by cutting after tissue separated and $F_{friction}$ is the force by friction between scalpel and tissue.

In the energy perspective, the incision process occurs due to the work done by external force. Therefore, in the case of quasi-static condition, the work done by external force can be expressed as follows.

$$\Delta W_e = \Delta U + \Delta W_r + \Delta W_f \tag{2}$$

where ΔW_e is the change of energy from external force, ΔU is the change of elastic potential energy stored in tissue, ΔW_r is the change of irreversible energy from rupture of tissue and ΔW_f is the change of irreversible energy from friction between scalpel and tissue. In this sense, the reaction force is just combination of several forces from the work done by external force in equation (1). Therefore, each force has different value along with the process mode.

The force from the deformation of the elastic body like tissue is hard to be calculated its properties in contrast with general isotropic materials. Although there are various numerical analysis approaches to calculate its force [4-5], it is hard to apply to the calculation of reaction force due to the plastic deformation caused by sharp tool like scalpel in incision process at the affected zone [6]. In addition, because real-time data processing is needed for the haptic application, heuristic regression method is most suitable method to minimize computation for the fast calculation. If the scalpel blade is sharp enough and force and stress only act on the contact line, the deformation force can be expressed as follow because work done by external force is completely converted into ΔU .

$$F_{stiffness} = \begin{cases} 0, & z > z_1 \\ l_c f_s(z), & z_1 > z > z_2 \\ 0, & z < z_2 \end{cases} \tag{3}$$

where l_c is the contact line length between scalpel blade and tissue, $f_s(z)$ is the polynomial regression equation and z , z_1 and z_2 are the position of tip of scalpel blade, position of undeformed tissue surface and position of rupture occurred.

The work done by external force is fully stored in the elastic body as elastic potential energy in the elastically load. And it is unloaded again, elastic body recover its shape using the elastic potential energy. However if a crack is occurred during deformation, a portion of potential energy is spent as the irreversible work. In the case of elastic fracture, energy for the crack propagation is proportional to the fracture toughness J following characteristics of material [7]. The irreversible energy from rupture can be express as follow because it is fully spent to make crack in quasi-static condition.

$$W_r = Ja(z) \tag{4}$$

$$a(z) = l_c z \tag{5}$$

where $a(z)$ is the area of crack. It means the creation of crack occurs immediately irrelevant to work done by external force and can be represented as like follow.

$$\Delta U = \Delta W_r = Ja(z) = Jl_c z \tag{6}$$

The work done by external force is not exchanged to elastic energy after crack propagated. Therefore work done by external force is totally dissipated as irreversible energy for rupture and friction as like follow equation.

$$\Delta W_e = \Delta W_r + \Delta W_f \tag{7}$$

The equation (4) can be applied to the cutting mode because it can be considered as continuous propagation of the rupture to blade direction.

In this mode, the work done by external force is not conserved with the elastic energy as like the cutting mode. Thus the equation (7) can be applied in this case. For modeling this friction force, Karnopp friction model [8] can be express as like follow.

$$F_{friction}\left(\dot{z}, F_n\right) = \begin{cases} D_n \operatorname{sgn}(\dot{z}) + k_n \dot{z}, & \dot{z} \le 0 \\ F_n, & \dot{z} = 0 \\ D_p \operatorname{sgn}(\dot{z}) + k_p \dot{z}, & \dot{z} \ge 0 \end{cases} \tag{8}$$

where $\dot{z}$ is the relative velocity between scalpel and tissue, F_n is the sum of nonfrictional force applied to the system(which includes inertial effects and force from elasticity), D_p and D_n are the positive and negative value of the coulomb friction coefficients, and k_p and k_n are the positive and negative value of viscous friction coefficients.

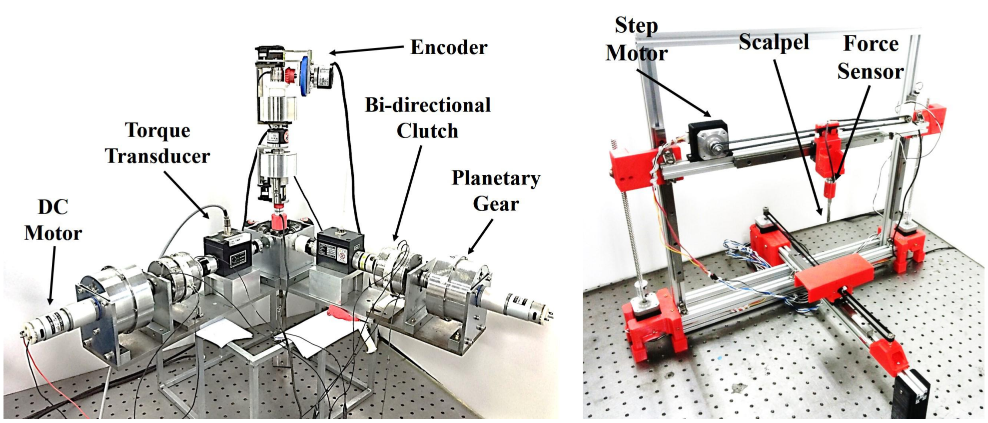
3. HAPTIC DEVICE

To verify the force model, the haptic device using magnetorheological fluid is utilized. The haptic device is comprise of slave robot which conducts the incision process and haptic master which controls slave robot.

The haptic master is a device to control slave robot and realize reaction force as shown in figure 1 (a). To guide the position of slave robot, angles of manipulation handle is measured by encoders (Autonics E40H8) which connect to its shaft. Simultaneously, the reaction force is realized by MRF BDC which can transmit the torque generated by a DC motor (D&J IG32GM 04type) into the shaft. The BDC is connected to planetary gear and it can control the torque with magnetorheological fluid changing effective magnetic field using the solenoid coils. The torque tracking using MRF BDC is much superior compared with only DC motor approach in a view point of continuous force control.

The slave robot is a device to conduct incision process and collect reaction force data as shown in figure 1 (b). The slave robot is compose of 3-axis linear robot structure. The scalpel (nopa instruments BLADE#20) of end effector with force sensor (ATI-Nano17) is operated by step motor (Autonics A4k-M245) which is linked to end effector with timing belt in horizontal direction and acme thread in vertical direction.

The haptic master realizes desired reaction force from force model. To achieve this haptic application, PID control with open-loop control which can control in uncertain system condition can be applied. Its block diagram is shown in figure 2.



(a) Haptic master (b) Slave robot

Figure 1. Haptic Device

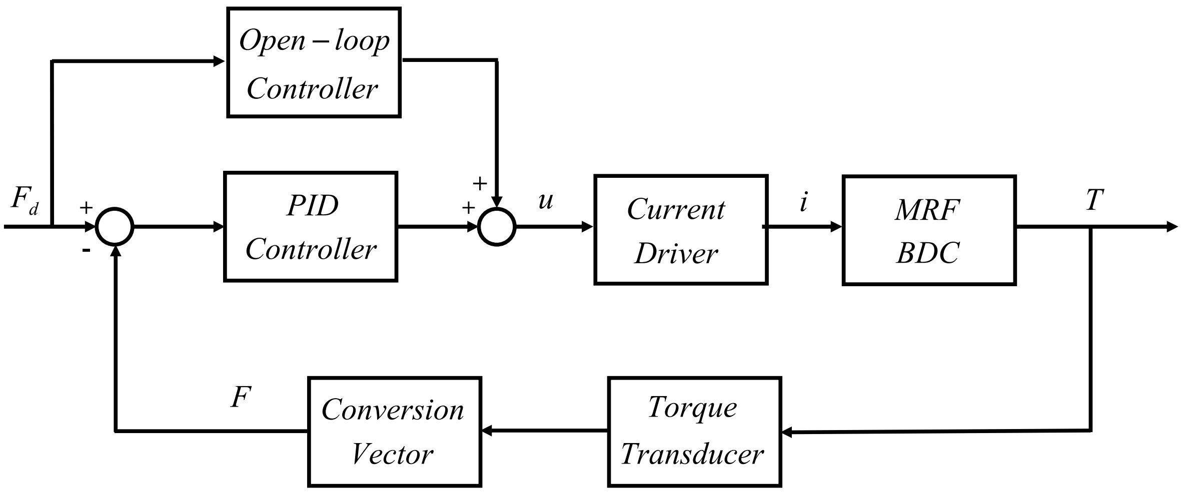


Figure 2. Block diagram of haptic master system

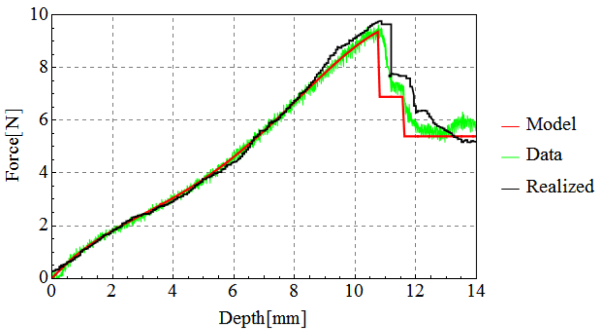
where F_d is the desired reaction force from model, u is the control voltage, i is the input current, T is the output torque and F is the output force. As shown in figure 5, the open-loop controller calculates control voltage based on performance test of haptic master because the desired force is clearly decided by the force model. The rest value of force is controlled by the PID controller which calculates control voltage using difference of F_d and F . This control voltage enters the current driver (NF EC750S) and makes input current for solenoid coils of BDC to make proper magnetic field. Therefore the torque occurs due to viscosity change of MRF by magnetic field. The torque value is sensed by torque transducer (SENSTECH SDS-100K) and it converted as force by conversion vector.

4. EXPERIMENT RESULTS

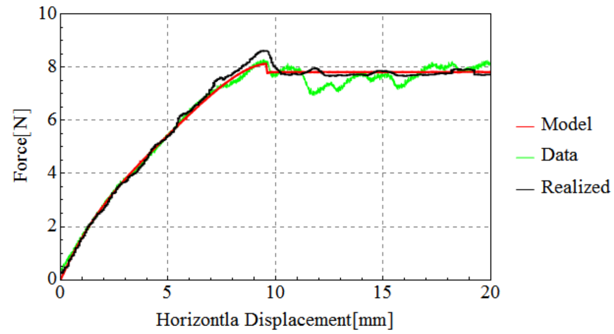
The apparatus for experiments to acquire reaction force is prepared by DAQ board (NI PXIe-1082). The incision process is conducted by regulated setting. The deformation, rupture and cutting modes are measured in 1 mm/s scalpel velocity for quasi-static condition. And the friction mode is measured in $\pm$ 15 mm/s velocity with 0.1 Hz sinusoidal condition. The apparatus for the experiments to verification force modeling is prepared.

Based on the force model, the actual force which occurs due to the MRF BDC is controlled to track the desired force. The proposed force modeling for the incision surgery is evaluated via experiment by using fresh pig flesh with rind. The scalpel heads toward subject vertically and causes crack with reaction force about the depth of scalpel. In the deformation displacement range from 0 to 10.8 mm, the subject shows elastic behavior which can be regressed in a polynomial form. After elastic behavior, rupture occurs with 4 N transition equivalent to the elastic energy dissipation in short time. After the rupture occurs, the scalpel moves horizontally and causes a crack with horizontal reaction force. The subject is elastically deformed to 9.6 mm in polynomial form and crack is propagated with constant cutting force without rupture energy dissipation. Both of vertical and horizontal cases include uneven values due to the inhomogeneous composition of the tissue. The friction force is organized in sinusoidal velocity condition. The asymmetry of result is based on shape of the scalpel which has one side blade. To modify this asymmetry, data which is affected by blade can be rearranged because blade of scalpel direction is headed toward positive direction in the experiment. The average values of static ($\pm$ 1 mm/s) and dynamic ($\pm$ 12~15 mm/s) range are applied to determine coefficients of the equation (8). The value of $D_p, D_n = \pm 0.10595$ and $k_p, k_n = 0.0045$.

The proposed force model based on experimental result is verified by haptic master. The reaction force based on the force model is calculated by variables about position of scalpel. The information about force is acquired by the force transducer and the information about displacement is acquired by the encoder. Using force and displacement value, reaction is realized without real tissue. The PID control algorithm as shown in figure 2 is applied to control reaction force. The control results are shown in figure 3.



(a) Control result of vertical direction



(b) Control result of horizontal direction

Figure 3. Control results of force realization

The control result of vertical direction is plotted in figure 3 (a). The maximum force errors between model and realized force are 0.5421 N in the elastic deformation range and 2.8725 N in rupturing range. The reason for the error in rupturing range is that demagnetization rate of the MRF is relatively slower than magnetization rate. Figure 3 (b) reveals the control results of the horizontal direction control, in which the maximum force errors are 0.5107 N in the elastic deformation range and 0.8624 N in rupturing range.

5. CONCLUSION

In this work, the force modeling and haptic application was evaluated experimentally. First of all, force model based on the energy perspective during the incision process was established using the actual reaction force data. After determining the force model, PID control algorithm was applied to haptic master using MRF BDC mechanism for realizing reaction force. Then experimental results from the real tissue, model and haptic control were compared. From this result, it is found that realized force by control well tracked model and actual force. Thus it can be concluded that the force modeling and haptic application for incision surgery into tissue will be an appropriate method for surgical operation simulation. And also it should be noted that the error corresponding to magnetic properties of the MRF will be improved using a modified model to reflect gradual energy dissipation of real tissue rather than instantaneous dissipation in current model.

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