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Parameter Setting Method considering Variation of Organ Stiffness for the Control Method to Prevent Overload at Fragile Tissue

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Abstract— **We describe a control method, for a surgical robot, which prevents the overload at fragile tissues. In particular, we focused on the control parameter setting method to ensure the robustness of the performance relative to the variation of the organ stiffness parameter. Firstly, we present Position/ Limited Stress control to achieving both precise positioning and prevention of overload. FEM based organ model was used to estimate the stress in this control method. Secondly, we describe the control parameter setting method. The control parameter was set to realize sufficient performance within the range of stiffness variation. Finally, we carried out a numerical simulation and an in vitro experiment. The simulation result suggests that our control method and parameter setting method helps prevent stress overload, not depending on the stiffness of organ model. The in vitro experimental result suggests that our method helps prevent stress overload of the in vitro-liver, the stiffness parameter of which is unknown.**

I. Introduction

In recent years, research and the development of technology, such as surgical robots and navigation systems, has been carried out. Since surgical robots achieve more minimally invasive and precise surgery than conventional surgical equivalents, they can enhance patients' early recovery. Expectations of surgery performed by minimally invasive surgical robots have increased, and research and development into surgical robot systems has advanced in many fields [1].

A. Motivation

Organs have many blood vessels and nerves which are especially fragile to overloads and must never be damaged. Then, it is necessary to conduct surgical tasks while preventing the stressed state from reaching dangerous levels. To carry out such safe surgery, the stress state of the organ must be observed. A physical organ model is necessary to estimate such information because it is difficult to measure the stress state by any sensor. To achieve this concept, our group reported the stress evaluation of the brain using a 2D-Finite Element Method (FEM) organ model [2]. In that paper, a stress evaluation only was carried out for surgical navigation. Our current work target a control method for minimizing damage to tissue via robotic manipulation. To do so, we propose an organ model-based stress estimator and a control method based on the stress [3].

B. Related Work

The considerable amount of previous work on force information for the surgical robot represents force feedback for the surgeon [4]-[7]. For example, Mitsuishi, et al. develop a method of force feedback augmentation to improve the force perception [4]. Arata, et al. develop the minimally-invasive surgical system, which had performed remote surgery experiments with augmented force feedback capability [5]. Wang et al. develop the robotic system with force feedback for micro surgery [6].

Conventional research into the modeling of living bodies mainly concerns deformation analysis using a FEM [7]-[11]. This research mainly targets surgical planning and training. For example, Alterovitz et al. research the simulation of needle insertion for prostate brach therapy [10]. Meanwhile, DiMaio et al. illustrate a system for measuring the extent of planar tissue phantom deformation during needle insertion, through a linear elastic material model [11].

C. Objectives

We target the development of a control method based on "stress" feedback to the surgical robot in order to prevent overload at fragile tissue. We already reported the basic concept of the control method based on variable impedance control and the FEM organ model based stress estimator [3]. The stress at fragile tissues was estimated by a simulation using an organ model and the stiffness parameter of the robot was subsequently changed corresponding to the estimated stress. In that paper, we modeled an organ based on linear FEM, while organ has more complex properties in general. In addition, the control parameter was set manually while

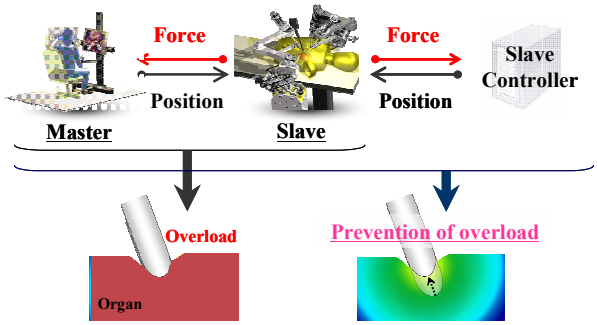

Fig.1 The concept of the control method to prevent the overload

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the controller parameter is particularly vital for facilitating stable movement and the performance. Subsequently, the following are considered in this paper:

1) Evaluation of in vitro situation: In general, organ tissue has complex properties such as nonlinearity [12], meaning the displacement of a surgical tool and the stress on an organ have a nonlinear relationship. In this paper, we evaluated the control method via both the numerical simulation using a nonlinear and viscoelastic organ model and an in vitro experiment using a hog liver.

2) Parameter setting method considering the variation of organs stiffness: The problem to set the control parameter is the individual difference of organ stiffness parameter. The control method changes the virtual stiffness of the robot as the magnitude of the stress at fragile tissues. Then, the control performance is significantly affected by the stiffness parameters of human tissue. However, it is generally difficult to grasp the values of the stiffness parameters of human tissue, because of the individual differences.

In this paper, we developed a parameter setting method for the control method which prevents overload based on these discussions. The basic concept of the parameter setting involves evaluating the robustness of the controller relative to the stiffness parameter variation of the organ. We measured the variation of organ stiffness from the hog liver and conducted parameter setting to realize sufficient performance within the range of stiffness variation.

The rest of this paper is organized as follows: Section II introduces our methods, including that of position/limited stress control and a stress estimator using an organ model; Section III present our control parameter setting method using numerical simulation; Section IV validates our control and parameter setting methods based on an numerical simulation; Section V present the evaluation by an in-vitro experiment; Section VI presents conclusions and plans for future work.

II. METHODS

A. Position/Limited Stress Control Method [3]

Overload may be caused when only a position control is used because the force exerted on the organ is not taken into consideration. Force control, for example impedance control, is conventionally used when the robot comes into contact with the target object. However, the simple uses of these methods result in constant position errors because the surgical robot functionally touches the organ and exerts force. This renders the conventional impedance ineffective because the surgical robot is required for precise positioning.

The control methods for surgical robots require both prevention of overload and position precision. This section A shows a control method realizing both precise positioning and the prevention of overload. We have named the control method "Position/Limited Stress control". The method to estimate the stress at fragile tissue is discussed in following section B.

The idea behind realizing both position precision and prevention of overload is to conduct a change of control method. In surgical situation, position precision is required when the loaded stress is small. Then, we use the position control when the loaded stress is small. Prevention of overload is required when the loaded stress at fragile tissues is large. The stress don't exceed breaking point when stress is controlled to the target stress set to the approximate value. Thus, we use the "stress" control (force control using the stress value) to prevent the overload.

However, simple change of control method causes the unstable state such as oscillation. Thus, we propose transition of control mode from position control to stress control as the stress increases. The control method is separated into two parts, position control part and transition part. The switching of control is decided by the mode change stress σ_c. The mode change stress σ_c is a control parameter which is decided considering the stiffness or breaking strength of target tissue.

The general position control is used in the position control part. The control method in transition part is described as follows in details:

1) Transition method from position control to stress control: The impedance control is the method which decides the virtual impedance of the manipulator. The equation of the impedance control is shown in (1).

$$c\Delta\dot{p} + k\Delta p = -\Delta\sigma$$
$$\Delta p = p_t - p,\ \Delta\sigma = \sigma_t - \sigma \tag{1}$$

where p is the position of the manipulator, σ is the stress at fragile tissue, p_t is the target position of the manipulator ordered by the master manipulator, σ_t is the target stress, and c, k represent the parameters of impedance control.

The impedance parameter k in (1) indicates the virtual stiffness of the manipulator movement. Equation (1) turns to position control when stiffness k is infinite. Moreover, (1) turns to stress control when stiffness k is zero. Therefore, the transition of control method from position control to stress control is made possible by the variable stiffness control.

The approximate setting of the target stress σ_t and impedance parameters c, k from the information (p, σ, p_t) is possible to realize the prevention of overload. The stiffness change algorithm is shown in 2) and target stress generation method is described in 3).

2) Stiffness change algorithm: The stiffness k must decrease and be saturated to zero to transit into stress control, corresponding to the increase in stress. The change of stiffness must also be smooth in order to prevent any unstable state. The example calculation of stiffness k is in (2).

$$k(\sigma) = k_o e^{(\sigma-\sigma_c)/T_k} \quad (\sigma > \sigma_c) \tag{2}$$

where σ_c is the stress at mode change and k_o, T_k is the parameter of the controller.

3) Target stress generation: Any change of target stress must be smooth to prevent any unstable state. When the target stress is set to be saturated to a certain load, the stress is limited to the saturated stress, which is named "limited stress". The example calculation of target stress σ_t is in (3).

$$\sigma_t(p_t) = \sigma_c + (\sigma_l - \sigma_c)(1 - e^{(p_t - p_c)/T_f}) \quad (\sigma > \sigma_c) \tag{3}$$

where p_c is the position at mode change, σ_l is the limited stress, and T_f is the parameter of the controller.

Then, the Position/Limited Stress control is calculated by (4) using (1), (2), and (3).

$$c\Delta\dot{p} + k(\sigma)\Delta p = -(\sigma_t(p_t) - \sigma) \quad (4)$$

B. Organ Model-based Stress Estimator

It is very difficult to sense the stress values of each part directly by any sensor. The FEM based organ model is used to estimate stress. The stress estimation and real-time calculation methods are described in this section.

1) Estimation from force information: When solving model, constraints in position or/and force apply to the surface of the model. In a general approach, positional constraints are used because the boundary condition is mainly set as the contact between the surgical tool and the organ. However, the use of constraints in position involves a problem with registration and collision detection. Registration between a pre-planned model and a real organ derive a certain level of error. Collision detection is a complex and well known problem in surgical simulation [7].

The other reason to use the intra-operative force information is robustness for the error of stiffness parameter in organ model. The relationship between the force and the stress are not significantly affected by the stiffness parameter of the organ. Then, an accurate estimation not dependent on the stiffness parameter is expected in the estimation base on the force information.

2) Tissue modeling for stress estimation: It has been reported that there is nonlinear relation between the force loaded on the surgical tool and its displacement as a result of nonlinear properties of organ tissue. It is also well known that since the organ has viscoelastic properties, its deformation is dependent on the velocity of indentation. Then, we have developed the FEM based physical organ model, in previous papers, based on the nonlinear and viscoelastic material properties of the liver [12]. In this research, we also use the modeling method and the following equation is used to represent the viscoelastic and nonlinear material properties.

$$G\frac{d^n\gamma}{dt^n} = \tau \quad (5)$$

$$G(\gamma) = \begin{cases} G_o & (\gamma < \gamma_0) \\ G_0(1 + a_\gamma(\gamma - \gamma_0)^2) & (\gamma > \gamma_0) \end{cases} \quad (6)$$

where t is time, τ is the shear stress, γ is the shear strain and G is the viscoelasticity, n is the order of derivative, G_o is the viscoelastic modulus of the linear part, γ_o is the strain in which the liver begins to show nonlinearity and a_γ is the coefficient for deciding the change of stiffness.

3) Stress for evaluation: To evaluate the tissue stress state, Von-Mises equivalent stress is used. The average stress of the elements at the fragile tissues is used to the data for "Position/Limited Stress control".

4) Technique for real-time estimation: FEM model to simulate the nonlinear response of the organ is accompanied with substantial problems, such as a potentially vast increase in the calculation time required. Therefore, a technique is required to realize real-time stress estimation. As described in 2), we modeled the nonlinear properties of tissues by (6). Subsequently, the force loaded on the surgical tool and the stress at the fragile tissues from a certain pushing location and direction are also described by the following equation:

$$K(x) = K_0(1 + A_K(x - x_{0\text{-}K})^2)$$
$$F = K(x) * x \quad (7)$$

$$E(x) = E_0(1 + A_E(x - x_{0\text{-}E})^2)$$
$$\sigma = E(x) * x \quad (8)$$

Where K_0, A_k and $x_{0\text{-}K}$ are parameters for the force calculation, F is the force loaded on the surgical tool, meaning that loaded on the organ, x is the position of the surgical tool, meaning the pushing displacement, E_0, A_E and $x_{0\text{-}E}$ are parameters for the stress calculation and σ is the stress at the fragile tissues.

When we grasp both the parameters for the force calculation (K_0, A_k and $x_{0\text{-}K}$) and those for the stress calculation (E_0, A_E and $x_{0\text{-}E}$), the stress at fragile tissue σ can be calculated based on the force F by only solving the simultaneous equation of (7) and (8). Then, we prepare these parameters before the operation. Both these parameters are calculated by simulation using an organ model in each pushing location and direction, with the relevant data recorded in a database. The stress at fragile tissues is calculated based on the force information during the operation using the parameters from the database. The process used to estimate stress at fragile tissues is as follows:

a) Off-line calculation:

1. The FEM based organ model is developed and the section of fragile tissue is selected.
2. The pushing location on the organ surface is set.
3. The pushing direction is set.
4. The simulation that assumes the manipulator pushing the organ is carried out. The reaction force and the stress at fragile tissue are calculated.
5. The parameters for the force calculation (K_0, A_k and $x_{0\text{-}K}$) and those for the stress calculation (E_0, A_E and $x_{0\text{-}E}$) are identified by the nonlinear least squares method. The parameters are recorded in the database.
6. Steps 3-6 are repeatedly conducted, changing the pushing location and direction.

b) On-line calculation:

1. The operator sets the pushing location and direction.
2. The parameters are read from the database.
3. The stress at the fragile tissue σ is calculated by solving the simultaneous equations of (7) and (8); based on the measured force information.

III. PARAMETER SETTING

The robustness of the controller to cope with the variation in human stiffness properties is crucial because the stiffness of the target organ significantly affects the performance of the control method. In particular, we focus on the parameter of controller T_k in (2) as the optimized parameter in this paper. T_k is the parameter which decides the transition degree of the manipulator stiffness. The approximate setting this parameter is vital to realize stable movement. The other parameter is manually set in this paper and the optimization of other parameters will be carried out in future work.

In this section, we propose the parameter setting method based on evaluating the robustness of the controller relative to the parameter variation of the organ.

A. Variation measurement of the stiffness parameter

The process to measure the nonlinear stiffness parameter described in previous work [12] was repeatedly carried out on 50 hog liver samples. Figure 2 shows the viscoelasticity G in (6) vs. the strain γ diagram of the 50 sample livers. A histogram of the data was also created to visualize the distribution status of G_o and a_γ. A histogram hierarchy was calculated from a total of 50 data via the Sturges' formula to be determined in 7. The histogram of G_o and a_γ is shown in Fig. 3. Key parameter values, such as the mode, maximum and minimum values of each parameter, are shown in Table 1.

B. Optimization process

This section shows the control parameter optimization in specific pushing locations and directions. Consideration about the boundary condition such as pushing location and direction will be discussed in the following section C.

This is an iterative method that uses the simulation results in each iteration to improve the evaluation value. The following sentence shows the process to find the optimized control parameter T_k.

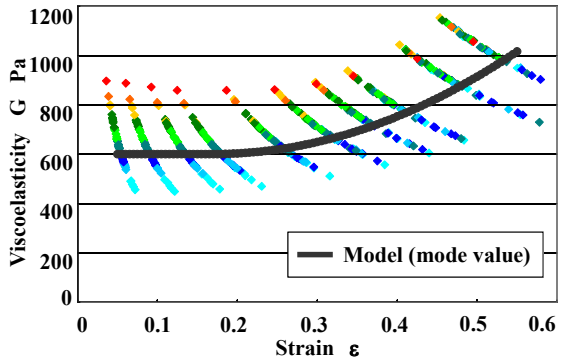

Fig.2. Variation of nonlinear properties: the color of the plot means data from a certain hog liver.

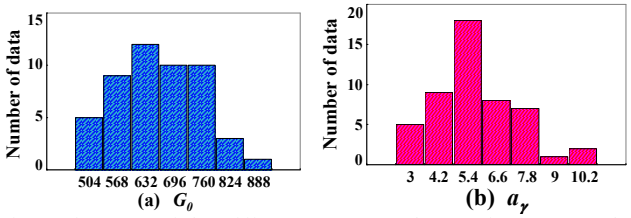

Fig.3. Histogram of the stiffness parameter: The Y axis represents the number of samples existing in the interval.

Table 1 Value of each parameter

	G_o Pa	A_γ
Average	637	5.2
Minimum value	456	1.9
Maximum value	875	9.7
Mode value	600	4.8
Standard derivation	96	1.7

1. The pushing location and direction, the ordered movement of the manipulator.
2. The initial control parameter are selected.
3. The stiffness parameter of the organ is set.
4. A simulation to estimate the stress value at fragile tissues is carried out.
5. The evaluation value of the result on step 4 is calculated. The integrated value of the stress exceeding the limit stress is used as the evaluation value as shown in (9). Figure 4 displays an example of the evaluation value calculation:

$$e = \sqrt{\frac{\sum_{j=1}^{n} \Delta\sigma_j^2}{n}} \qquad \Delta\sigma = \begin{cases} \sigma - \sigma_l & (\sigma > \sigma_l) \\ 0 & (\sigma < \sigma_l) \end{cases} \tag{9}$$

where e is the evaluation value, n is the data number of integration, σ_l is the limited stress, and σ is the stress loaded on the target fragile tissue.

6. Steps 3-6 are repeatedly carried out, changing the organ stiffness parameter in step 3. The evaluation value considering the organ stiffness variation E is calculated by the following equation (10):

$$E = \frac{\sum_{i=1}^{N} e_i}{N} \tag{10}$$

where N is the data number of organ stiffness.

7. The algorithm returns to step 2 after setting a new control parameter $T_{k:i+1}$ and we search the control parameter to minimize the evaluation value considering the organ stiffness variation E.

C. Pushing location and direction

The values of fragile tissues stress are largely dependent on the boundary condition such as pushing location and direction. Then, we change the control parameter T_k corresponding to the pushing location and direction. First, the reaction force from the organ and the stress value at fragile tissues are estimated as described in section II B. The control parameter T_k is optimized at each pushing location and direction via the optimization method described in III. The process is as follows:

1) Off-line calculation:

1. The FEM based organ model is developed and the section of fragile tissue is selected.

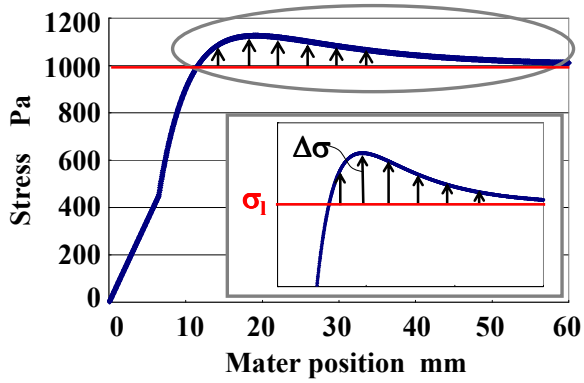

Fig.4. Definition of the evaluation value e

2. The pushing location on the organ surface is set.
3. The pushing direction is set.
4. The optimized control parameter T_k is searched for using the optimization method described in B. The optimized control parameters are recorded in the database.
5. Steps 2-4 are conducted repeatedly, changing the pushing location and direction.

2) On-line calculation:

1. The operator sets the pushing location and direction.
2. The control parameter is read from the database, based on the pushing location and direction set by the manipulator. The manipulator is controlled via the read control parameter.

IV. Numerical Simulation

In this section, a numerical simulation concerning Position/Limited Stress control and its parameter setting methods was carried out. We evaluate whether the optimized control parameter realizes accurate performance in each simulation using an organ model incorporating various stiffness parameters.

A. Method of optimization process

1) Organ model: The shape of the liver model was a 60 x 60 mm rectangle and its thickness was 20 mm. As boundary conditions, the dorsal side of the model was set as the fixed end. The model shape and boundary conditions are shown in Fig.5.

2) Setting fragile tissues in the organ model: The fragile tissue was assumed to be the section enclosed by a purple rectangle in Fig.5.

3) Setting the ordered movement: The pushing location was set to be the organ center (at X: 0 mm, Y: 0 mm in Fig.5). The Y coordinate of the ordered position increases linearly at 1.0 mm/s.

4) Setting the initial control parameter: The initial control parameter T_k was set to be 10. The limit stress σ_l was set to be1000 Pa. The stiffness parameter of the manipulator k_o in (2) was set to be 15000, c in (1) was set to be 3000. T_f in (3) was set to be 10.

5) Setting stiffness parameters for the organ model: The actual liver was non-uniform tissue, including cirrhosis and cancer. However, as the first step in this study, the organ was presumed to comprise uniform tissue. The stiffness parameters were manually set to fit the force data of preliminary experiment. We used the following five type of organ model to consider the stiffness variation of the organ:

(a) Go: max value in Fig. 3(a), a_γ: max value in Fig. 3(b).
(b) Go: max value in Fig. 3(a), a_γ: min value in Fig. 3(b).
(c) Go: min value in Fig. 3(a), a_γ: max value in Fig. 3(b).
(e) Go: min value in Fig. 3(a), a_γ: min value in Fig. 3(b).
(d) Go:mode value in Fig.3(a), a_γ: mode value in Fig.3(b).

6) Condition: the optimization process described in III B was carried out using the setup of 1)-5).

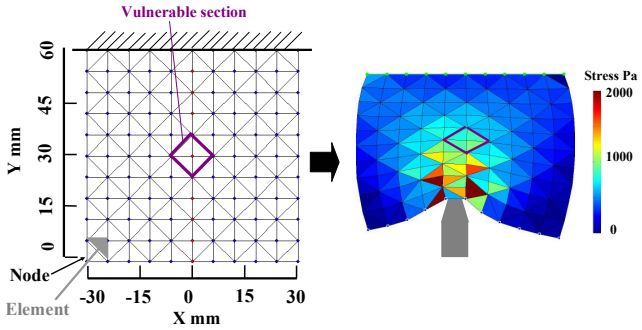

Fig. 5: Boundary condition of the liver model and produced mesh. A 2-D slice of the liver model is defined using mesh triangular elements. The total node number of this model is 121, the total element number is 200, and the model thickness is 20 mm.

B. Results of stress at fragile tissues

Figure 6 shows a result showing the relationship between the pushing displacement and the stress at fragile tissues. This result displays that the displacement when stress exceeding the limit stress varied in each organ model.

C. Results of evaluation value considering the organ stiffness variation E

Figure 7 shows the relationship between the control parameter T_k and evaluation value E in (10). The result shows the evaluation value considering the organ stiffness variation E had an extremal value when the control parameter T_k was about 60. Figure 8 shows a sample of the stress data in the simulation using the organ model *(e)* when the control parameter T_k was set at 20, 60 and 100 respectively. The stress didn't exceed the limit stress (1000 Pa) when T_k was set to 60 in Fig.8. The stress data when T_k was set at 20 overshoots the limit stress. The stress data when T_k was set to 100 has exceeded the stress value during the steady state. That causes the significant evaluation value considering the organ stiffness variation E when T_k was set to 20 and 100 respectively.

D. Results of evaluation value e

Figure 9 shows the relationship between the control parameter T_k and the evaluation value e in the simulation using each organ model *(a)-(e)*. The value of the evaluation value e varied depending on each organ model. This result suggests the necessity to consider the variation of organ stiffness parameter in a control parameter setting.

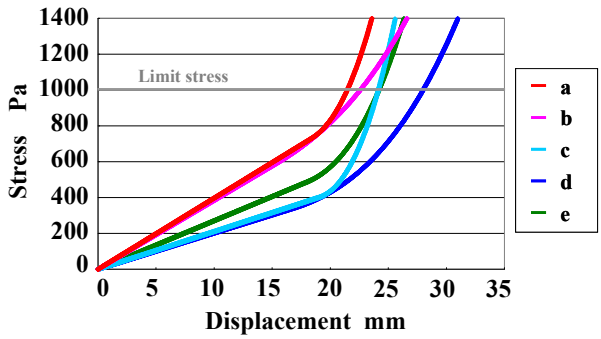

Fig.6. The stress at fragile tissues vs. the pushing displacement

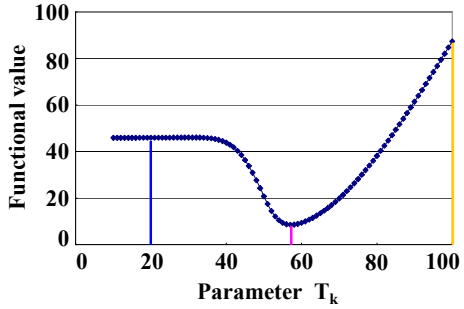

Fig. 7: The control parameter T_k vs. the evaluation value considering the parameter variation of organ stiffness E

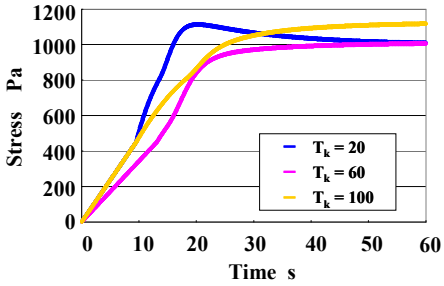

Fig. 8: The sample of time varied data of the stress at fragile tissue. This data was obtained from the simulation using an organ model *(e)*.

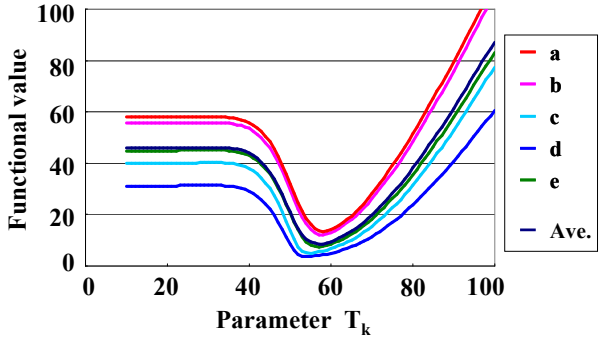

Fig.9 Evaluation values e in the simulation using each organ model *(a)-(e)* : the each line of color shows the evaluation value in case of each organ model

E. Evaluation simulation

1) Setting the ordered movement: The pushing location was set to be the organ center (at X: 0 mm, Y: 0 mm in Fig.5). The Y coordinate of the ordered position increases linearly at 1.0 mm/s, which is of the same order as the optimization process.

2) Control parameter: the control parameter T_k was set to be optimized value (in this case about 60).

3) Simulation condition: This simulation assumed a situation whereby the command from the master manipulator has the potential to exert dangerous stress on fragile tissues. The manipulator was controlled using the position/limited stress control method. Simulations were repeatedly conducted, changing the stiffness parameter of the organ model.

4) Results and Discussions: Figure 10 shows the result of the evaluation simulation. The stress at the fragile tissue did not largely exceed the limit stress in any cases of organ models

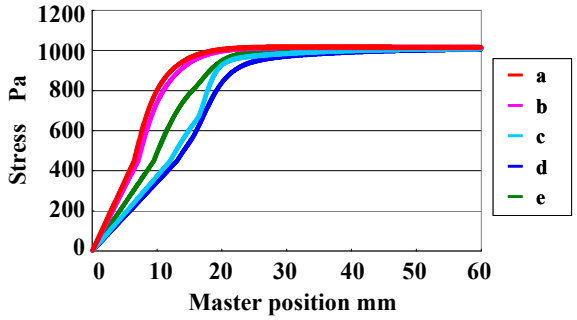

Fig. 10. Result of evaluation simulation. the each line of color shows the stress value at fragile tissue in case of each organ model *(a)- (e)*

(a)-(e). This result suggests that our control method successfully prevents stress overload. The proposed parameter setting method is effective in achieving robustness relative to the variation in the stiffness parameter of the organ.

V. Experiments

In this section, we evaluate whether our control method is effective to realize sufficient performance to the real hog liver, the stiffness parameter of which is unknown.

A. Experimental manipulator

Figure 11 shows the manipulator used in the experiment. The experimental manipulator has four degrees of freedom achieving planner movement. The manipulator used for this experiment consisted of two parts: namely positioning and pushing parts. A positioning part has three serial joints to help position the pushing part with three rotation degree of freedom. The pushing part only realizes the translation movement to push the organ. A six-axis force/torque sensor (NANO 1.2/1, BL AUTOTEC) is attached to the root of the pushing part and the surgical tool is attached to the six-axis force/torque sensor.

B. Organ condition

The liver was cut in a rectangular shape (60 x 60mm, thickness approx. 20mm) and was placed on the measurement table. The dorsal aspect of the liver is fixed by the wall. When the liver was fixed, double sided tape was used to place sandpaper on the wall, whereupon the liver and sandpaper were attached to each other with instant glue.

C. Control parameter

The control parameter was set as well as the numerical simulation shown in section IV A 4). The control parameter T_k was set to be optimized value (in this case about 60).

D. Experimental Condition

This experiment assumed a situation whereby the command from the master manipulator has the potential to exert dangerous stress on fragile tissues. The manipulator was ordered to push the liver in the Y direction and then controlled using the position/limited stress control method. The Y position of the ordered target (Master position) increases linearly at 1.0 mm/s.

The experiment was repeatedly carried out, changing the following condition of the pushing location and direction:

(a) X coordinate of the pushing location: 0.0 mm Direction: 90 deg
(b) X coordinate of the pushing location: 15.0 mm Direction: 90 deg
(c) X coordinate of the pushing location: 15.0 mm Direction: 45 deg

E. Results and Discussions

The optimized controller parameter T_k at each experimental condition is as follows: T_k is 60 in case of condition (a), T_k is 55 in case of condition *(b)*, T_k is 50 in case of condition (c). This result suggests that optimized parameter varies depending on the pushing location and direction.

Figure 12 shows the estimated stress at the fragile tissue didn't exceed the limit stress in any case of experimental condition *(a)-(c)*. This result suggests that our control and parameter setting methods help prevent stress overload to the in vitro-liver, the stiffness parameter of which is unknown.

VI. Conclusions and Future Work

We describe a control method, for a surgical robot, which prevents the overload at fragile tissues. In particular, we focused on the control parameter setting method to ensure the robustness of the performance relative to the variation of the organ stiffness parameter. Firstly, we present Position/ Limited Stress control to achieving both precise positioning and prevention of overload. FEM based organ model was used to estimate the stress in this control method. Secondly, we describe the control parameter setting method. The control parameter was set to realize sufficient performance within the range of stiffness variation. Finally, we carried out a numerical simulation and an in vitro experiment.

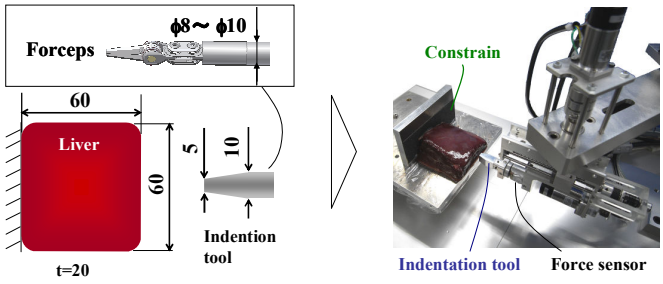

Fig. 11. Experimental setup

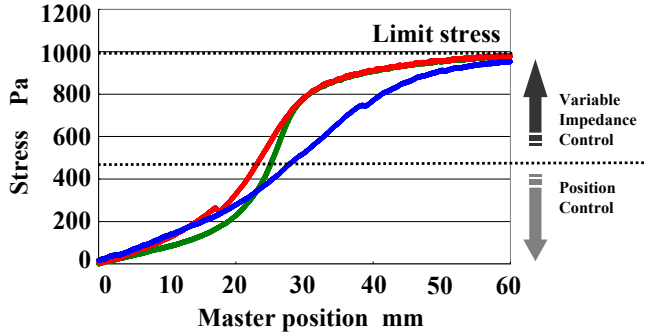

Fig. 12. Experimental result

The simulation result suggests that our control method and parameter setting method helps prevent stress overload, not depending on the stiffness of organ model. The in vitro experimental result suggests that our method helps prevent stress overload of the in vitro-liver, the stiffness parameter of which is unknown.

In future work, further precise organ modeling will be carried out. For example, a 3D organ model will be developed. Moreover, the acquisition of organ geometries will be researched for actual applications and consideration of non-uniformity caused by cancer and cirrhosis will be a future challenge. The optimization of other control parameters, which were not the focus in this paper, will also be carried out. Using these control methods, a surgical robot achieving safe and precise surgery will be developed.

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