

# Combined Collision Avoidance and Prevention of Soft Tissue Damage Control Method for Surgical Robots

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**Abstract**—Surgical robots will have a more and more important role in Minimally Invasive Surgery (MIS), especially in laparoscopic procedures. They can overcome some of the problems of laparoscopic surgery and improve surgeon's performance. However, they also introduce new challenges and problems. Perhaps the biggest problem is lack of feedback to surgeons. This lack of feedback can cause serious problems such as tissue damage, or touching vulnerable organs. To avoid such situations, prevention of tissue damage or collision avoidance methods have been proposed. There is however a lack of methods that combine them in a simple control algorithm. In this paper we propose a novel control method for MIS master-slave surgical robot that combines collision avoidance and prevention of tissue damage. We have validated our method with a real robot in in-vitro experiments. Experimental results suggest that our method improves surgeon's performance and safety.

## I. INTRODUCTION

MINIMALLY Invasive Surgery (MIS) has several advantages over open surgery, the most important are: shorter recovery time and less cosmetic impact and trauma for the patient. Not surprisingly, laparoscopic procedures are becoming more and more common whenever possible.

However, laparoscopic procedures also carry certain disadvantages which make them difficult for the surgeon. Major difficulties that surgeons find are fulcrum effect and loss of tactile feedback. Robots can solve the problem of fulcrum effect as well as improve precision on the movements of the surgeon.

Therefore, minimally invasive robotic surgery will play a more important role on the future of surgery [1]. The clearest example can be seen on the Da Vinci system [2]. Although robotic surgery is an improvement compared to manual laparoscopic surgery, it also has several problems, being the principal a lack of feedback to the surgeon for his actions inside the body of a patient.

Human tissue is soft and easily damageable; without a proper feedback about patient's body, it is difficult for the

doctor to determine if his or her actions can cause any damage to the tissue it is being manipulated. Furthermore, it has been reported that lack of feedback and time delay on master-slave systems can cause a big number of collisions [3]. Both problems have been addressed before in a separated way: collision avoidance or safety in surgical robotics, but as far as we know, there is no combined method that implements a solution to both problems.

Collision avoidance in master-slave systems for industrial robotics is a well-known problem [4] [5], however, in case of surgical robotics there is still little research done. Jakopec *et al.* [6] proposed a safety system for arthroscopic surgery. In this case, the surgeon moves the end effector of the robot manually, avoidance of tissue damage outside a predefined area is achieved by increasing the stiffness of the robot. This method is not directly applicable to master-slave surgery. Increase of impedance can be an effective way on the haptic control of the master side to warn the user, but still the slave side has to be controlled and stopped before a collision happens.

A novel method for collision avoidance based on artificial potential fields for master-slave surgical system was proposed by Inoue *et al.* [7]. In their proposed method, the speed of the slave is under the effect of artificial potential fields that reduces the velocity of the slave robot when it approaches a restricted area.

However, a possible problem using potential fields to control the speed is that because only the distance to the forbidden area is taken into account, low speeds will be reduced in the same amount as higher speeds, making the slave robot manipulator to stop at a greater distance from the border or the restricted area than if it was moving at higher speeds (Figure 1).

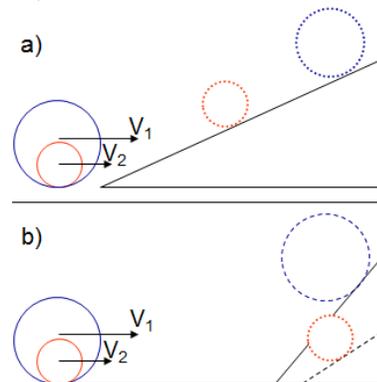


Fig. 1. a) Artificial potential fields apply same deceleration regardless initial speed. Lower speeds will stop earlier than higher speeds. b) With a dynamic

Manuscript received January, 2012. This work was supported by the MEXT Global Center of Excellence Program “Global Robot Academia” Waseda University, Tokyo, Japan.

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approach only deceleration is applied when required to stop always at the same place.

Similarly, research on prevention of soft tissue damage has been reported [8]. Nevertheless, all these solutions solve one of the problems, either collision avoidance or prevention of tissue damage, but as far as we are concern, there is no system combining both in a single control algorithm.

Therefore, we propose a novel control method for master-slave surgical robots, which combines collision avoidance with tissue overload prevention in a simple control algorithm. This control method is based on dynamic window approach to collision avoidance and numerical stress simulation to prevent tissue damage.

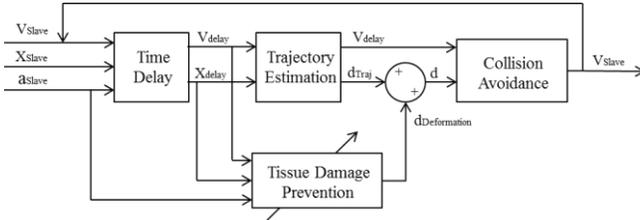


Fig. 2. Control block diagram for collision avoidance and prevention of tissue damage.

## II. COLLISION AVOIDANCE

### A. Dynamic Window approach

The Dynamic Window method for collision avoidance and navigation of autonomous mobile robots was first proposed by Fox *et al.* [9].

With this approach dynamic limitations of robots are considered for motion planning. Because a robot cannot provide infinite accelerations or decelerations, the robot is only allowed to travel at velocities small enough for the robot to be able to brake before colliding with an obstacle. In other words, from all the velocities at which the robot can travel, only those that assure a safe braking before collision with limited deceleration are allowed.

One limitation of the Dynamic Window method is that it doesn't take into account the speed of the obstacles. It considers the obstacles to be static. This is not always true, but in our case we assume that the internal movements of the organs don't change the area where the slave manipulator is allowed to move, such movements can be caused by lungs during respiration or heart beats.

Although assuming no internal organs movement might seem as an unrealistic scenario, we decided to take this approach for two reasons. On one hand, to simplify the experimental setup, which would become more complicated if it was necessary to add object tracking or any kind of technique to calculate the trajectory of a moving object, and on the other hand, because as it will be explained later in this section, the important information for the system is whether there is a collision or not, and at what spatial position it will happen. Therefore, the method used to calculate the location and time of collision is not important for our proposal, but rather the combination of a collision avoidance method with tissue overload prevention.

To select a velocity, the dynamic window method first calculates all safe velocities and adds them to a velocity map. Second, from all velocities in the maps, it selects the velocity that fulfills certain optimization function. This can be for example the velocity that provides the fastest trajectory, minimum path, etc.

As can be seen, this is done autonomously by the robot based on its sensory inputs and location map. In a master-slave configuration this is not the case, since the velocity will be given by the command from the master side. Therefore, it is not possible to use directly the dynamic window approach to a master-slave architecture due to incertitude on future velocities and accelerations.

### B. Dynamic window approach on master-slave system

As it was mentioned before, in case of a master-slave system the velocity or position command is given by the user, but the slave system must be able to stop before it collides with vulnerable tissue or goes into a restricted region. This is not a simple task for the user, who must be familiar with the system and start breaking at a proper time. Thus, an autonomous breaking system for collision avoidance will improve usability and improve safety by reacting to a possible human error.

To achieve this goal, we adapted the dynamic window approach to a master-slave architecture. The system will allow all the velocities inputs coming from the master side as long as there is no risk of collision. In this case, the velocity of the slave robot matches the command from the master side. When there is a risk of collision, the slave becomes fully autonomous and stops before colliding with vulnerable tissue, or entering into a restricted area. This behavior is described by the following equation:

$$\dot{x}_{Slave} = k \cdot \dot{x}_{Master} - \alpha \cdot a_{Max} \cdot T \quad (1)$$

Where  $\dot{x}_{Slave}$  is the velocity of the slave's end effector,  $\dot{x}_{Master}$  the velocity command the master,  $k$  a constant,  $a_{Max}$  the maximum deceleration that the robot can provide,  $T$  the control period, and  $\alpha$  a binary value which is equal to 0 when there is no risk of collision and 1 when the collision avoidance system is activated.

The general kinematic equation of a solid moving along an axis can be written as follow:

$$x(t_k) = x(t_{k-1}) + \int_{t_{k-1}}^{t_k} v(t) \cdot dt \quad (2)$$

$$v(t_k) = v(t_{k-1}) + \int_{t_{k-1}}^{t_k} a(t) \cdot dt \quad (3)$$

Same equations are applicable to the other two axis  $y$  and  $z$  for spatial motion. For simplicity we only show the equation

for one axis. But they can be easily extended to a 3 dimensional movement by combination of the three velocity vectors.

We can only obtain or change the acceleration of the end effector at discrete times; it remains constant between time intervals. Thus, combining equation (2) and (3) and taking into account discrete times, we can calculate the position of the end effector at  $T_k$  given the initial conditions at  $T_{k-n}$  as follows:

$$x_k = x_{k-n} + \sum_{i=k-n}^k \left( v_i \cdot T + \frac{1}{2} \cdot a_i T^2 \right) \quad (4)$$

It is common for master-slave systems to have a delay between the time when measurements are taken, and the time when the master system receives the measurement data; this delay must be taken into account to estimate the real velocity and position of the end effector at the next control cycle. In all cases it is considered that  $t_{delay}$  is smaller than  $T$ . Including the time delay in the calculation, the estimated position and velocity of the end effector at the next control cycle will be:

$$x_{est} = x_k + v_k \cdot t_{delay} \pm \frac{1}{2} \cdot a_k \cdot t_{delay}^2 \quad (5)$$

$$v_{est} = v_k \pm \frac{1}{2} \cdot a_k \cdot t_{delay} \quad (6)$$

In the worst case, when the robot needs to brake in the shortest time, the deceleration of the end effector will be the maximum deceleration that it is available for all the cycle time  $T_k$  until it stops completely. We are interested only in the situation when, given the position, acceleration and velocity of the robot, it cannot brake before colliding. Therefore, we are interested on finding the time that it will take to the slave robot to reach the restricted area in the worst case.

As explained before, in a master-slave system future velocities and accelerations are unknown, therefore, to calculate the time of collision, if any, the speed  $v_{est}$  is considered constant for the remaining time. Value of new velocities and accelerations will be updated in the next control cycle and collision check will be calculated again. Thus, considering speed and acceleration constant in time, equation (4) becomes in the simple form of a continuously decelerated solid:

$$d_{est} = v_{est} \cdot t_{col} - \frac{1}{2} \cdot a_{max} \cdot t_{col}^2 \quad (7)$$

Where  $d_{est}$  is the estimated distance to the restricted area or tissue,  $v_{est}$  is the estimated velocity at the time  $T_{k+1}$ ,  $a_{max}$  is the maximum deceleration available and  $t_{col}$  time to reach the restricted area, which is the unknown value. Solution to this equation is trivial. There are three possible solutions:

- Two different real roots
- One single double root
- A single conjugated imaginary root

The first case will provide the time that it takes the end effector to reach the forbidden area, the second one indicates the time at which the end effector will reach the forbidden area with velocity zero, and the third one means that the end-effector never reaches the forbidden area.

Therefore, we are only interested on the second and third case. This is, for any given distance and speed, the system checks whether the end effector of the slave robot will reach the restricted area or not, if not, safety stop mode is off and the velocity of the end effector is proportional to master system velocity command. If the conditions given approach a solution to the equation, then the safety stop mode is activated and the robot stopped before reaching the restricted area. Thus, the safety stop mode is activated if the following condition is true:

$$v_k - 2 \cdot a_k \cdot d_{est} \leq 0 \quad (8)$$

However, use of zero as limit value for starting automatic braking doesn't provide good results, partly because in real circumstances there is noise from sensors, position errors, inertia, etc. Therefore, we set a new value  $\epsilon$  that will be the activation value for automatic braking. This parameter is speed dependant and it is set experimentally to a value that gives good accuracy on final stop position.

### C. Trajectory and distance to restricted area estimation

Although in autonomous robots it is possible to compute accurately a future trajectory of the robot, in a master-slave system, future velocity and acceleration commands are unknown, therefore, we can only estimate a trajectory based on the actual velocity and acceleration of the robot.

It is assumed that the acceleration will be the same as at time  $T_k$  for all the remaining time until the end effector reaches the restricted area. If the acceleration changes in the next cycle, the trajectory is updated and checked again whether the end effector will arrive at the restricted area or not.

The trajectory of the end effector given a constant acceleration and initial conditions of velocity and position is a simple problem that can be solve via equation (4). This trajectory is used to estimate the point, if any, where the end effector will collide with the restricted area border, we can estimate then the distance used in (7).

## III. PREVENTION OF TISSUE OVERLOAD

Human tissue is soft and easily deformable. It is also easy to damage. A mechanism that prevents tissue damage is needed.

In this section we will present a method, which in combination with the collision avoidance mechanism explained in the previous section will avoid collision and tissue damage.

Kobayashi *et al.* [10] developed an algorithm to compute in real-time the stress on soft tissue given the value and direction of the force applied. This relationship is as follows:

$$E(x) = E_0 \cdot \left(1 + A_E \cdot (x - x_{0-E})^2\right) \quad (9)$$

$$\sigma = E(x) \cdot x \quad (10)$$

Where  $E_0$ ,  $A_E$  and  $X_{0-E}$  as constant parameters calculated in a previous FEM simulation and physical properties of tissue, and  $x$  is the position of the end effector of the slave robot. As can be seen, this relationship depends on already known parameters from FEM simulation, which has to be computed in advance, and the position of the end effector of the slave manipulator. To prevent tissue damage, the slave robot must stop before reaching the stress limit of the tissue. This is done in combination with the collision avoidance algorithm explained in the previous section.

There are two possible situations when interacting with tissue: Pulling or pushing. These actions occur under different conditions and we will treat them separately.

#### A. Pushing

When tissue is pushed, or indented, the speed at which is moving can be any value between zero and the maximum speed of the robot. The process to stop the robot before the stress limit of the tissue is reached is as follows:

1. From the current data of velocity and acceleration a future trajectory is calculated.
2. With the estimated trajectory, a collision point with soft tissue and direction of the trajectory are calculated.
3. Appropriate parameters for stress simulation according to estimated trajectory are selected.
4. The maximum distance that the end effector can penetrate into the tissue without causing damage is calculated.
5. This distance is added to the distance between end effector and tissue in order to obtain the total distance in which the robot must stop.
6. Collision avoidance algorithm calculates the maximum speed allowable for actual conditions of position, speed and acceleration.

With (9) and (10) it is possible to estimate the stress on the tissue given the position of the end effector of the slave robot. From a point of time  $t$ , we can estimate also what would be the stress at a time  $t + n \cdot T$ , where  $T$  is the control period and  $n$  any number of cycles, given the speed and acceleration at time  $t$ .

To calculate the maximum distance that the end effector can deform the tissue, we will consider the position, speed and acceleration at a time  $t_0$ . Then, we calculate the speed at which the end effector will contact the tissue at  $t_k$ . Next step is to calculate the new position  $x_{k+1}$  and stress  $s_{k+1}$  by (9) and (10). The previous step is repeated until the value  $s_{k+n}$  reached the stress limit. At that point the iteration is stopped

and the maximum deformation is calculated as  $x_{k+n-1} - x_k$ .

From the previous iterative process, we can see that for higher speeds, because the increment of position at each cycle is bigger than lower speeds, the estimated stress will grow faster. This implies that the deformation allowed will be smaller, forcing the robot to start breaking in advance.

As seen in point 5, the distance that the tissue can be deformed is added to the total distance that the manipulator has to travel until reach the tissue. However, some tissue might be safer if it is not touched or deformed. For example areas which are not involved in the surgical procedure. In this case, the stiffness for the stress simulation will have a value of infinity. As result, the allowed deformation will be zero. Therefore, the robot will stop just before touching these restricted areas.

On the other hand, for tissue that can be deformed, higher speeds will increase quickly the stress on tissue, giving little time to the robot to stop. Because the capacity of a robot to apply decelerations is limited, the only option to stop on time is to start decelerating before contacting the tissue. For small velocities, because it will take several control cycles to reach the stress limit, it is not necessary to start decelerating in advance.

The advantage of this method is that it allows users to touch and interact freely with soft tissue when they are moving the slave robot at low speeds, but the system will decelerate automatically the slave robot until it reaches a safe velocity if it is moving at high speed avoiding tissue damage.

#### B. Pulling

When tissue is pulled the initial velocity is zero. It is not allowed to grasp tissue when the slave robot is moving. As seen before, collision avoidance algorithm checks whether the manipulator will enter into a restricted area or not, however, in this case because the manipulator moves away from the tissue, unless a restricted area is closer than the maximum distance that the tissue can be deformed without damage, the avoidance collision algorithm will be unable to stop the manipulator before tissue is damaged. To avoid this situation, an artificial restricted area is created at the point where the tissue will reach its stress limit. Tissue overload prevention algorithm in a pulling movement is as follows:

1. With the initial values of speed and acceleration, a trajectory is calculated.
2. Given the estimated trajectory appropriate parameters for stress simulation are selected.
3. The maximum deformation that the tissue can be stretched without damage is calculated.
4. The value of the deformation is set as the artificial barrier.
5. Collision avoidance algorithm is called to stop the robot before tissue is damaged.

Maximum deformation of tissue is calculated with the same iterative method proposed in the previous section. The only difference is the initial step. When the tissue is pulled, there is no need to estimate the speed at which the slave manipulator will reach the tissue.

It must be noted, that since robots don't have infinity accelerations, and tissue can only be deformed for few millimeters, the speed that the robot will reach is small. Because the speed is small, the system will only switch into the safety stop mode moments before reaching the stress limit allowing the user to move freely until then.

#### IV. EXPERIMENT

We have validated the algorithm proposed using a Cartesian robot with three degrees of freedom as can be seen in Fig. 3. The collision avoidance algorithm is only validated in two dimensions, X and Y. The third degree of freedom, vertical position of the end effector, is used for tissue damage prevention validation.

The end effector is equipped with an Autotech BLN micro force sensor. This sensor is able to measure forces and moments in 3 axes. Attached to the end effector there is a plastic cylinder simulating a 5 mm diameter forceps. We use the force sensor to create a force displacement model of liver tissue as explained later.

The maximum speed of the robot is set at 32 mm/s and maximum acceleration and deceleration to 6 mm/s<sup>2</sup>. First, to check the accuracy and select an appropriate automatic braking activation value, the robot was moved to certain points inside a rectangular area of 120 x 110 mm and the final error was measured.

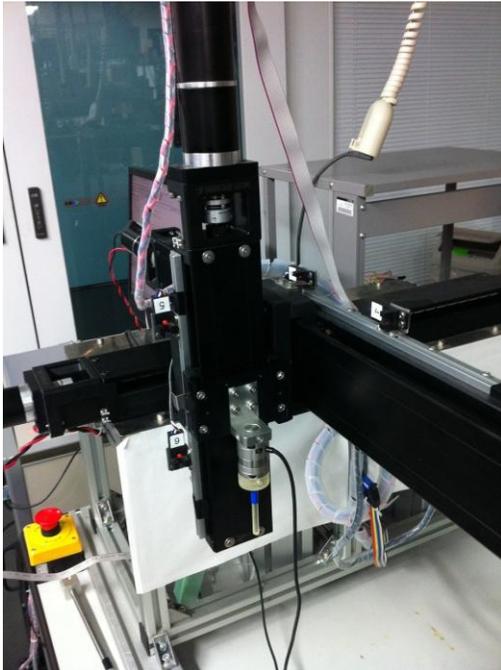


Fig. 3. Cartesian robot used for algorithm validation. At the end effector a part simulating a 5mm diameter forceps is attached (blue ribbon).

##### A. Prevention of Tissue overload

The second experiment consists on a series of pushing movements on porcine liver tissue. A piece of liver from pig of 45x30x25 mm is placed under the end effector and the robot indents the liver with the plastic part simulating a surgical tool. Due to the difficulty to create an experimental

setup where 2 or 3 dimensional tension vectors can be created with a 3 degrees of freedom Cartesian robot, we only validated the proposed method in one dimension. As explained in section II, spatial motions can be created as a combination of the motion along three independent axes, as it is the case with our system. However, validation is required on more complex systems, such as 6 degrees of freedom manipulators, more complicated movements or coupled velocities.

Maximum deformation of the liver tissue, position of the end effector and force are measured. A total of 10 indentations are done.

In section III it was presented a method to compute in real-time the stress on soft tissue knowing the position of the end effector and certain constants [10]. In the same paper is presented the following relationship between force and displacement:

$$K(x) = K_0 \cdot \left(1 + A_k \cdot (x - x_{0-k})^2\right) \quad (11)$$

$$F = K(x) \cdot x \quad (12)$$

Where  $K_0$ ,  $A_k$  and  $x_{0-k}$  are constants from tissue mechanical properties from a FEM simulation done in advance, and  $x$  the position of the end effector of the slave robot. However, because we can only measure force during the test and for simplicity, we will model (12) directly. To obtain the constants above, we indented the liver tissue a total distance of 10 mm at different speeds and measured the reaction force. From the force displacement curve we can estimate the values of all the constants. This model is introduced into the tissue damage prevention calculation to estimate the allowable deformation without causing damage to the tissue as explained in III. For our test we set the maximum force that the robot can apply to 2 N. This value is simply chosen to obtain a deformation between 4 to 5 mm according to the data obtained from the liver tissue.

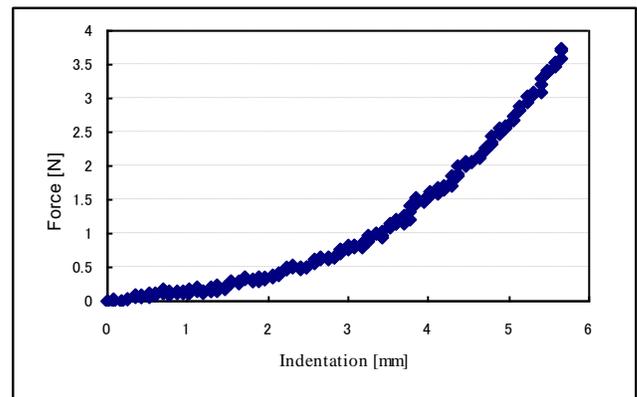


Fig. 4. Example of force-displacement curve for indentation of pig liver. A curve according to (11) and (12) is fitted for different speeds and used to estimate the maximum deformation of the tissue without suffering damage.

##### B. Discussion

Automatic braking and indentation tests indicate that our algorithm perform well in both situations. In none of the

movements of the robot crossed the boundary of the restricted area. Also, it was able to stop before reaching the force limit set as safe.

It has to be noted that the accuracy of the final position or the error of the end effector with respect to position in which it should stop (Figure 5), varies with the speed. It is believed that this lack of accuracy is due mainly to the activation parameter used in (8). A better chosen value of this parameter will reduce the position error robot to stop in the given location.

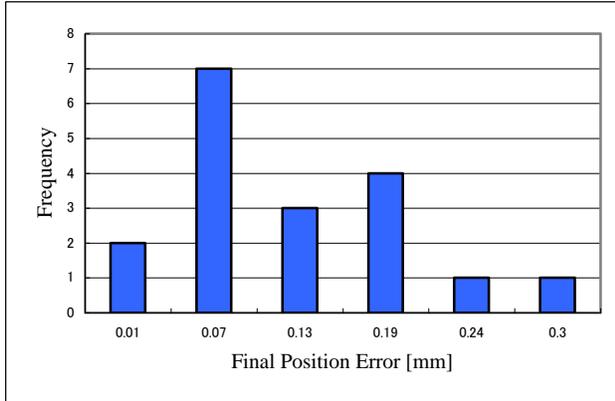


Fig. 5. Final position error of the end effector is affected by the selection of the activation parameter which is speed dependent. Same value can cause a bigger position error at different speeds.

## V. CONCLUSION

In this paper, we introduced a novel simple method that combines collision avoidance with prevention of tissue overload in master-slave surgical robotic systems. Experimental results suggest that this algorithm improves performance of operator. According to the experimental results, we can also conclude that it increases safety on surgical procedures by not allowing tissue to be damaged.

Future work includes automatic selection of activation parameter to improve accuracy, as well as implementation of the algorithm in real master-slave surgical robot and *in-vivo* experiments for user performance evaluation.

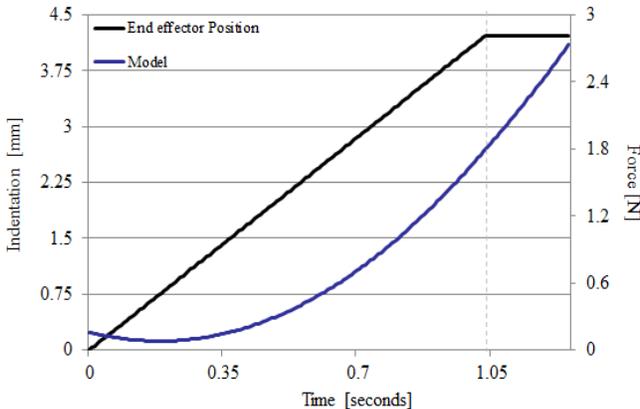


Fig. 6. Indentation of pig liver, black line, and plot of force displacement model of liver tissue. The limit to stop is set at 2 N. In all cases the robot stopped before reaching the force limit.

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