The Haptic Scissors: Cutting in Virtual Environments

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Abstract

The "Haptic Scissors" is a device that creates the sensation of cutting in virtual environments. The scissors have two degrees of freedom of motion and force feedback, one for cutting (single blade rotation) and one for translation. An algorithm was developed to simultaneously display translational and cutting forces for a realistic cutting simulation. In previous work, we used filtered data from cutting biological tissues to create "haptic recordings" of the cutting experience. Here, we consider two cutting models: one based on real tissue data and one that is analytical. The model based on real tissue is a segmented linear empirical model of the original data. Experimental results show that users cannot differentiate between these models and the haptic recordings created earlier. The analytical model uses a combination of friction, assumed material properties, and user motion (position and velocity) to determine the displayed cutting forces.

1. Introduction

Current simulations of biological tissues in surgical procedures are mostly, if not completely, visual with regard to cutting. This work is motivated by the need for haptic display not only in "poking" and "pulling" surgical tasks, but also in grasping and cutting. Simulations of tissue cutting will likely be more realistic than cadaver tissues, which have significantly different mechanical properties from living tissues. These simulations will also be more practical than physical phantoms, which cannot be reused. Also, haptic rendering of tissue cutting has the potential to reduce the need to sacrifice animals for surgical training and dissection.

The work in this paper is an extension of our previous work in the development of a single degree-of-freedom haptic scissor [2]. This original haptic scissor used "haptic recordings," look-up tables of position vs. force values from real biological tissue cutting data, to display the forces. However, this system was limited in realism for two major reasons: (1) the scissors did not translate during cutting, and (2) the haptic recordings did not take into account the context of user motion. These two problems limited our previous display to a single closing of the scissor blades.

Cutting has also been explored in other previous work. The data used in this paper was originally gathered by Greenish and Hayward. However, a Fourier analysis did not reveal a clear relationship between force and position, velocity, or other dynamic interaction properties from the data acquired [3,4]. In [7], a haptic simulation was created from data acquired during cutting with a single blade. Resolved-force haptic devices, such as the Phantom from SensAble Technologies (Woburn, MA), have been used to display external cutting forces of a single blade in surgical procedures (e.g., [1,5]). In addition, cutting with scissors has been modeled, without the display of internal cutting forces, in [6,8].

2. The Haptic Scissors

2.1 Design

The current design of the haptic scissors is shown in Figure 1. The scissors have two degrees-of-freedom, one for cutting (rotational) forces, and one for translational forces. The rotational degree-of-freedom has an angular resolution of 0.056° and a maximum torque output of 280 mNm, which corresponds to a force output of 7.58 N at

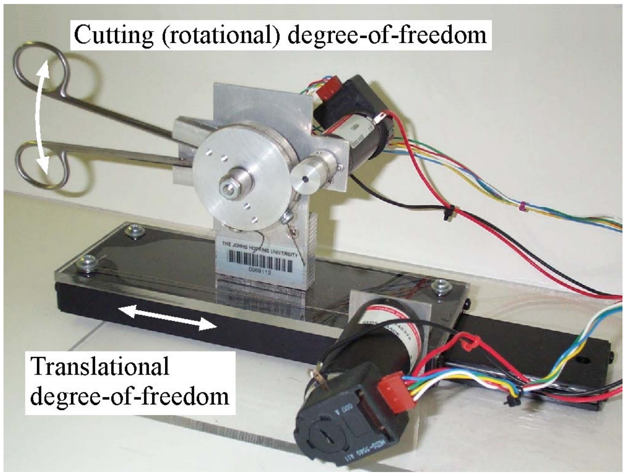

Figure 1. The two-degree-of-freedom haptic scissors.

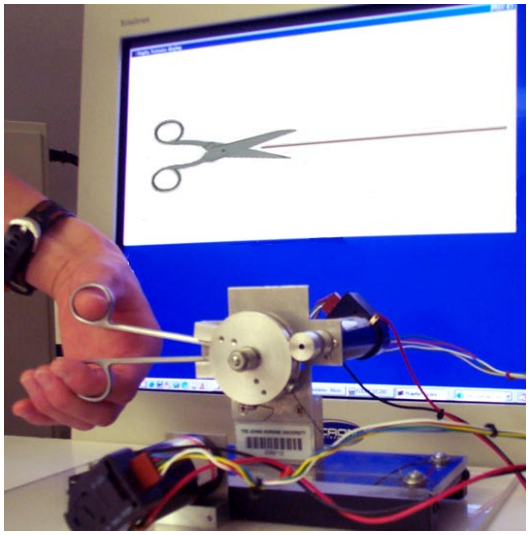

Figure 2. The haptic scissors and graphic display.

the handle. The translational degree-of-freedom has a resolution of 0.0152 mm and maximum force output of 159 N. (However, the cables are likely to slip before the maximum force is reached.)

A Maxon RE 25mm diameter/20-Watt motor (rotational) and a Maxon RE 35mm diameter/90-Watt motor (translational) were used for actuation, both with HP HEDS 5540 encoders for sensing. A PWM amplifier (25A-series, Model 12A8) from Advanced Motion Control was used for each motor. A Servo To Go card (Model 2) was used to read the encoders, and a Measurement Computing card (CIO-DAS 1600/12) was used for voltage/force output. The control computer was a Pentium III 800 MHz running Windows 98, and the development environment was Microsoft Visual C++. The graphic and haptic update rates were 50 Hz and 1000 Hz, respectively. The graphic display used an OpenGL NURBS scissor model, as shown in Figure 2.

2.2 Haptic Rendering of Scissor Translation

Simultaneous rendering of cutting (rotational) and translational forces is necessary for realistic simulation of the cutting process.

The first step is recognition of the direction of motion of the blades: opening or closing. This is determined by the sign of the angular velocity of the scissor blades. Because of noise that would have been seen in differentiating the position obtained from optical encoders, position data was passed through a first-order filter with a corner frequency of 10 rad/sec before differentiation. Even with filtering, however, the system still exhibited ringing or vibration effects at low velocity. This was because the force output was sufficient to move the scissors in the opposite direction, changing the sign of the velocity and consequently the direction of the output force in a cyclical manner. The issue was overcome and the system stabilized by creating a small linear force rampdown band around zero velocity. Within this band, the cutting force was multiplied by a scale factor proportional to the velocity. This scale factor decreased as zero velocity was approached from either positive or negative directions, and became identically zero when velocity was zero.

The second step is collision detection, performed to determine whether the cutting point on the scissors is intersecting the material. Figure 3 is a diagram of the scissors showing the cutting point, x_c, with respect to the pivot point of the scissors.

$$x_c = \frac{t(\theta)}{\sin(\theta/2)}, \tag{1}$$

where $t(\theta)$ is half of the width of the scissor blade (which changes along the length of the blade) and θ is the angle between the scissor blades. As an approximation, we assume that the value of t changes linearly from t_{max} at the pivot to t_{min} at the blade tips. Thus, t is calculated by:

$$t(\theta) = t_{\max}\left[\frac{\tan(\theta/2)}{\tan(\theta/2) + \frac{t_{\max}-t_{\min}}{l_t}}\right], \tag{2}$$

where l_t, the length from the pivot to the tip, is shown in Figure 3.

If the edge of the uncut material is at a position x_m with

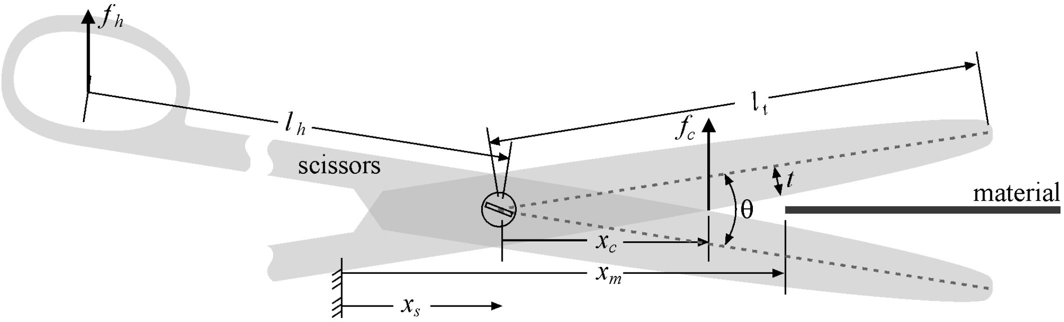

Figure 3. Diagram of scissors and material to be cut, with constants and variables used in haptic rendering.

respect to ground, a collision is detected if $(x_c + x_s) > x_m$. When a collision is detected, the cutting force (generated by torque at the pivot), f_c, applied to the user is determined by one of the three cutting algorithms presented in Section 3. Although data acquired from instrumented scissors handles show the forces displayed to the user, they do not provide information about the state of the material. Thus, we define a cutting threshold, f_{max}, above which the material begins to cut away. When the cutting force is below the threshold, the uncut material edge position, x_m, remains unchanged. If the threshold is exceeded, the material edge position moves, maintaining $x_m = x_c + x_s$. Translational forces are displayed as

$$f_t = k_t(x_m - x_c - x_s), \qquad (3)$$

where k_t is the predefined stiffness of the material in the translational direction.

3. Cutting Algorithms

To analyze the sensation of cutting on the haptic scissors, we used tissue-cutting data acquired as described in [3,4]. We used data from cutting nothing (empty scissors) and three rat tissues (liver, skin, and tendon) with a pair of Metzenbaum scissors. We have developed three different methods for displaying the cutting data: haptic recordings, segmented empirical models, and analytical models.

3.1 Haptic Recordings

Haptic recordings are implemented by replaying an angle to force mapping of the acquired data on the haptic scissors. The primary advantage of haptic recordings is their computational efficiency (a simple lookup table can be used). A disadvantage is that contextual information (e.g., velocity and grip force) that may affect the force output is not considered. In contrast, analytical and empirical models are difficult to create, due to the complex material interactions that give rise to forces during the cutting of biological tissues. However, they provide a much better fundamental understanding of the scissor cutting activity. Current analytical models of tissue deformation and fracture are nascent, and have not been verified by experimental data. Similarly, accurate empirically based models would require a significant data acquisition effort in order to characterize the many parameters affecting cutting forces.

To create the haptic recordings, the data was first segmented and filtered. In each set of the data shown in Figure 4, there are several cuts, resulting in overlapping lines. When surgeons cut, a repetitive motion is used, and the scissors are never fully closed. The data loops can be segmented into four phases: (1) opening scissors, (2) switching from opening to closing, (3) closing scissors, and (4) switching from closing to opening. The lower section of the plots, where the force appears to remain relatively constant as the angle increases, corresponds to the opening of the scissors. The upper section, where the force fluctuates more, corresponds to the closing of the scissors. At the left and right of the plots, the forces change dramatically at a single angle; these regions result from friction when the scissors are in the stiction state while changing between opening and closing.

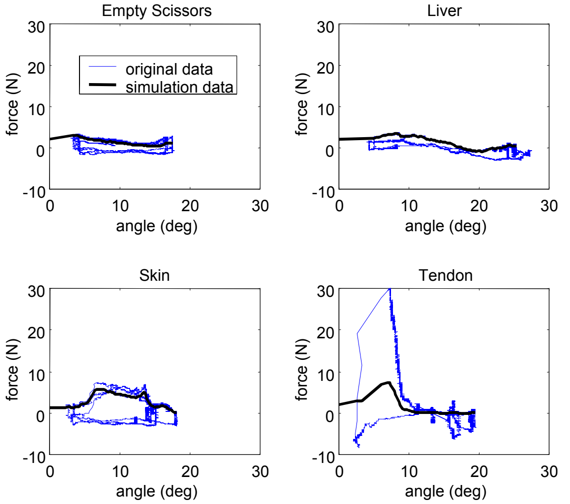

Figure 4. Data used for haptic recordings. The original data was obtained from instrumented Metzenbaum scissors while cutting rat tissues. The simulation data uses filtered data from one closing of the scissors.

Using these haptic recordings alone, it is difficult to create a realistic simulation; we could not guarantee that the users would maintain the scissor angles used in data acquisition. To provide forces for complete closure of the scissors, forces were smoothed and the force trend at the minimum angle was maintained to zero degrees. In addition, the tendon forces were scaled down to match the real rat tissues available for comparison in [2]. Details of the haptic recording method for single degree-of-freedom scissors (cutting/rotation only) are provided in [2]. That method has been improved as follows.

A simulation using pure haptic recordings creates sharp discontinuities when the scissors move between opening and closing. To create a smooth display of cutting forces from the initial point of contact of the scissors with the material until the scissors lose contact with the material, a force scaling method was used. Consider the force displayed to the user at the handle, f_h. In a pure haptic recording, this force is calculated from a lookup table $f_{open}(\theta)$ or $f_{close}(\theta)$, for opening and closing of the scissors, respectively, and linear interpolation is used to find the forces corresponding to intermediate values of θ:

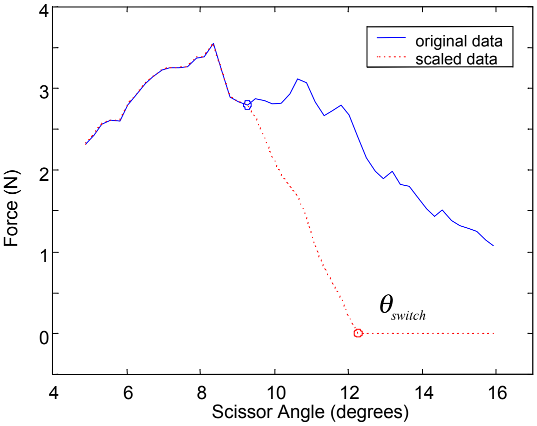

Figure 5. Illustration of the force scaling technique for smooth display of haptic recordings.

$$f_h = \begin{cases} f_{open}(\theta) & \text{for } \dot{\theta} > 0 \\ f_{close}(\theta) & \text{for } \dot{\theta} < 0 \\ 0 & \text{for } \dot{\theta} = 0 \end{cases} \tag{4}$$

Consider the quantity $\Delta\theta = |\theta - \theta_{switch}|$, where θ is the current angle of the handle and θ_{switch} is the angle at which the user changes from positive to negative velocity or vice versa. A constant scale factor k_s is chosen so that when the scissors have just changed direction (at angle θ_{switch}), $\Delta\theta\, k_s = 0$, and when the normal look-up table force is desired, $\Delta\theta\, k_s = 1$. Then the force output to the user at the handle is

$$f_h = \begin{cases} f(\theta)\Delta\theta\, k_s & \text{for } 0 \le |\Delta\theta\, k_s| \le 1 \\ f(\theta) & \text{for } |\Delta\theta\, k_s| > 1 \end{cases}, \tag{5}$$

where $f(\theta)$ is the lookup table value of force at the current angle θ. Figure 5 shows how this scaling method affects the haptic recordings.

3.2 Segmented Empirical Models

The segmented empirical model is an attempt to mathematically model the data collected by cutting real tissues using a piecewise linear function. The goal of the model and associated experiment is to ascertain exactly how complex a haptic representation of the scissor cutting forces must be. The advantage of this method is its simplicity and adaptability.

As can be seen from Figure 6, raw data of scissor forces is not easily characterized by a mathematical function. It is also not clear exactly how accurately a "good" model must fit the data. The criterion we selected for this was qualitative human perception. That is, if human users could not distinguish the difference through the feel of the haptic device, the model was considered to be acceptable.

To create segmented empirical models for each kind of tissue as well as the empty scissors, the following algorithm was used. First, the data from each complete cycle of opening and closing of the scissors was averaged with the other cycles to create an average data run. A user-defined piecewise linear fit was applied to this average using a software program developed for the purpose. This program plots the cutting data for the user and allows him or her to design a piecewise linear model by clicking on the plot at various points. The resulting model is then superimposed on the original data plot, allowing the user to see how closely the model matches the data. When a qualitative visual inspection indicates a good match, the resulting function is displayed on the haptic scissors.

To assess the success of this modeling method, an experiment was conducted using subjects who had experience cutting the same group of real rat tissues with Metzenbaum scissors in [2]. Each of the three subjects was asked to compare the feel of a haptic recording to an empirical model for each type of tissue. The order of haptic display presentation (model or recording) was random, as well as the tissue order. Subjects were blindfolded so that the computer graphics and appearance of the haptic scissors did not affect the results.

For each type of tissue, the subjects were told what kind of tissue they were cutting and asked to determine if "sample A" or "sample B" felt more like cutting the real tissue. The subject was allowed to freely manipulate the scissors. That is, they could open and close the scissors as many times as they liked, at whatever speed they desired, changing directions at whatever angle they preferred, etc. They were also allowed to switch back and forth between the two samples as many times as they felt necessary. The results are summarized in Table 1.

As can be seen, aside from the Blank case, there was no tissue on which every subject agreed. Additionally, each subject said that they could feel extremely little if any difference between the haptic recordings and the models, and had a very difficult time making up their minds. In the Blank case, it is probable that users expect to feel linear forces (friction) when they open and close empty scissors, and that the haptic recordings were influenced by noise and/or other factors in the data

Table 1. Subject responses comparing the realism of the haptic recordings and the segmented linear model. The display identified as most realistic is listed for each subject and tissue type.

Tissue Type	**Subject 1**	**Subject 2**	**Subject 3**
Tendon	Recording	Recording	Model
Skin	Recording	Model	Recording
Liver	Recording	Model	Recording
Empty	Model	Model	Model

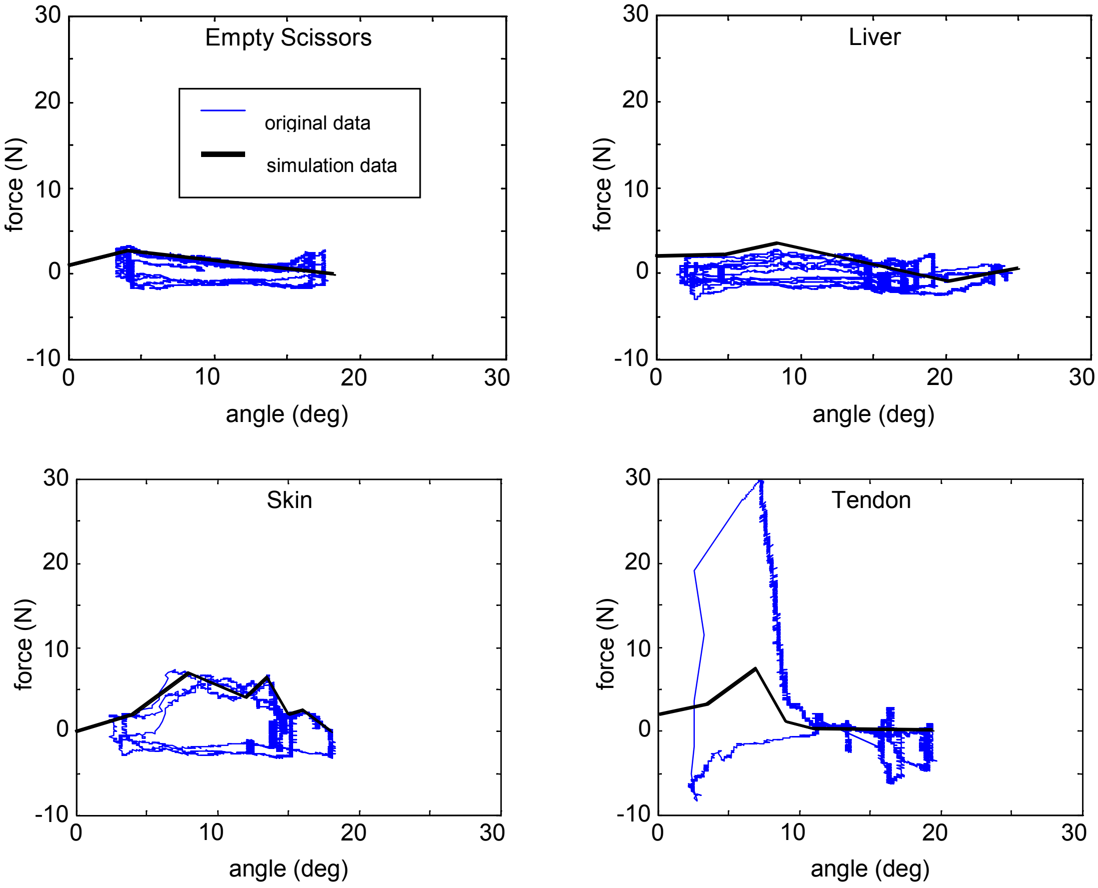

Figure 6. Data used for the piecewise linear empirical models.

collection process (e.g., forces not directly in the plane of the scissors' motion generated inadvertently by the hand of the experimenter) that the empirical model does not include. The piecewise linear models used for this experiment are those shown in Figure 6, demonstrating that a small number of line segments (2 to 7) is generally sufficient.

Figure 6 shows the data taken from cutting real tissues overlaid with the scissors closing empirical model. Note the visual similarity between these plots and the haptic recordings shown in Figure 4. For the scissors opening segment of each loop a frictional simulation model of scissors opening was displayed to the user. This model was equal to -½ the model for Empty Scissors (pictured above). All users agreed that this felt realistic.

3.3 Analytical Models

Preliminary work on analytical modeling has been performed to characterize the effect of the changing cutting point on forces sensed at the handle. The model presented here is based on the assumption that the force required to cut the material (at the exact location of the cut) is constant. Thus, it is a simplified model that does not take into account the material variations present in biological tissues. The forces felt by the user at the handle are assumed to be a summation of forces from friction at the scissor pivot, friction at the scissor blades, and cutting force at the cutting point x_c.

The effect of torsional friction at the pivot point is computed from a simple moment arm:

$$f_{h-pf} = \frac{\tau_{pf}}{l_h}, \tag{6}$$

where $f_{h\text{-}pf}$ is the force felt at the handle due to pivot friction, τ_{pf} is the torsional friction at the pivot, and l_h is the length of the scissor handle as shown in Figure 3.

Blade friction arises from a small contact area between the two blades. The scissor blades are shaped so that this area, approximated as a point, is the only source of blade friction. The friction at the handle is

$$f_{h-bf} = \frac{f_{bf} x_c}{l_h}, \tag{7}$$

where $f_{h\text{-}bf}$ is the force felt at the handle due to pivot friction, f_{bf} is the friction at the blade contact point, and x_c is the cutting point, as shown in Figure 3.

The force necessary to cut a homogeneous material is assumed to be a constant, f_{cf}. Thus, the force felt at the handle is

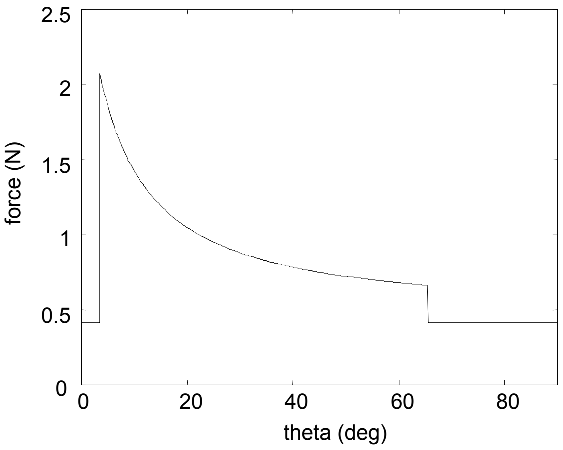

Figure 7. Handle forces versus scissor angle for a constant velocity scissor closing (blank).

$$f_{h-cf} = \frac{f_{cf} x_c}{l_h}. \tag{8}$$

A summation of these three forces provides the force at the handle:

$$f_h = f_{h-pf} + f_{h-bf} + f_{h-cf} \tag{9}$$

A plot of the handle forces calculated in this way is shown in Figure 7. The discontinuities in the plot result from the fact that the scissor blades do not actually cut at small angles, and at large angles the blades are no longer in contact. The analytical model does not closely match the recorded cutting data because several aspects, including the effects of user grip force, inhomogeneous tissue properties, and elastic forces in the tissue, are not modeled. However, it does capture the rise in forces at small angles, which can be seen in the blank data from Figure 6.

5. Conclusions and Future Work

Adding translational motion/forces and context-based force feedback to the haptic scissors has greatly improved the system by making the haptic interface feel much closer to the experience of using real scissors. In addition, experiments comparing the segmented empirical models and haptic recordings verified that users of the haptic scissors could not differentiate between a complex data recording and a simple piecewise linear model. This demonstrates that models of cutting forces need not be very precise to feel real. Thus, for practical engineering purposes, it is probably not necessary to formulate a precise model for cutting forces at all. A general idea of the proper shape of the curve for each type of tissue is all that is necessary for an adequate haptic rendering.

However, a complete understanding of cutting with scissors requires the development of a more complex analytical model. This would certainly yield insights for basic research in tissue modeling, and robot-controlled cutting. In future work, more cutting data must be obtained. This data should be acquired by a system with controlled position, velocity, and grip force. Further improvements on the scissors interface itself would include adding tilting (pitch) and steering (yaw) degrees of freedom to the scissors as a whole so that they could be rocked as a unit up and down and turned as cutting progresses.

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