Using haptic feedback as an aid in the design of passive mechanisms

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Abstract

This paper presents a novel investigation of the effectiveness of haptic feedback for designing a class of interconnected multi-body systems such as passive mechanisms. The traditional application of haptic feedback in the design process has been in applications such as parts assembly or mold design. The design of the mechanism discussed in this paper is for applications where the user needs to manipulate the mechanism in order to interact with an environment. The objective of the design is to have the link ratios so that it can allow the user better movement control of the mechanism and thus give a better force amplification when there is a sudden change in the contact reaction force with the application environment. A haptic device is used as a design interface between the designer of such mechanisms and the virtual mechanism model. For this preliminary investigation, we used a four-bar mechanism. In our case study, we choose, as an example, to use the net distance travel of a tool when penetrating inside a model of a deformable surface as the design objective to minimize. The effects on the variation of this distance travelled can then be studied by adjusting some of the key design parameters used in the mechanism. To evaluate our proposed haptic-aided design environment, an informal preliminary user study was conducted, where each subject explored a sampled design space of the mechanism. The results of the user study suggest that the usage of a haptic device in the design of this class of mechanism can expedite the design process.

1. Introduction

Computer Aided Design (CAD) is a useful tool for facilitating various design processes. For example, designers can specify the geometric, material, and other properties of mechanisms using a CAD system. They can then piece them together, specify relationships between the parts, simulate/analyze movements of the mechanism, and export the results in a form that manufacturers can use to build the mechanism. For some applications where the designs need to be used by a human operator, it is important to determine if the design is suitable for human interaction. Since most current CAD systems do not provide this feature, physical prototypes have to be built for such an evaluation.

With the advancement of the development of mechanical user interfaces with force feedback, i.e. haptic devices, and their utilization and integration with the design environment, these haptic devices may have the potential to offer a suitable design tool for evaluating CAD models or interconnected multi-body systems such as mechanisms through user interaction, e.g. see for example [9]. Here, the designer can interact with the mechanism through a haptic device, and is able to feel the interaction forces between the virtual mechanism and the expected application environment. Haptic force feedback gives the designer an idea of the way the mechanism interacts with the intended environment in a much more direct and intuitive manner. Such a concept in design may extend the boundaries of the notion of CAD to a point where the user can virtually interact with the models, and where one can explore the paradigm of what is referred to as the “Haptic Aided Design” or HAD.

Some previous research has made contributions towards incorporating force feedback into traditional CAD systems. For example, [1] describes a haptic interface coupled with CAD software, allowing the operator to see and feel both geometrical shapes and dynamic forces. In the work described by [2], the author formulated inverse kinematic and inverse dynamic equations involved in simulating open chain mechanisms and single closed chain mechanisms. [3] describes a formulation for the force calculation in a virtual mechanism manipulation system in order to simulate the mechanics of two-finger grasping. [4] describes a virtual prototyping system with
the capability of simulating two-finger grasping. Collision detection, force feedback, and a graphical representation of the operator’s arm are also parts of this system.

Ref. [5] describes a system that integrates a full-body simulation environment called JACK™ and a Rutgers Master II four-finger haptic feedback device. In this system, the user uses verbal commands to control the body of a virtual human agent, while the hand movements of the virtual agent follow the user’s hand movement via a haptic device, i.e. the Rutgers Master II. The user can control the virtual agent to grasp a tool on a workbench in the virtual environment, and command the virtual human agent to walk to another workbench and drop the tool there. Other promising lines of work in the application of virtual reality in the design of mechanisms can be found in [6-8]. Especially, the work of [6] presents a novel comparison between the design mechanisms using a traditional 2D CAD environment and designing mechanisms using immersive virtual reality.

Most recent works in the utilization of haptic devices in the design process are concerned with the manipulation of CAD models for the purposes of interactively designing the surfaces of objects, or defining an interactive virtual rake where the user can shape the surface of the virtual objects while feeling the reaction force, for example, see [10-13]. Through a user’s study, the Refs. [10,11] concluded that for the particular design cases (forming the CAD model of a surface) and the current state-of-the-art haptic technology, introduction of haptic feedback in design did not significantly improve the design process.

One of the key novelties of this paper is that it proposes and evaluates the usage of a haptic device in a design environment where the designer can move a passive interconnected multi-body mechanism for a special class of applications, where sudden changes in the reaction forces between the passive mechanism and its contacting environment are expected. Through this design environment, the user can feel the reaction force which can be created between the mechanism and its contacting environment at any location of the mechanism. Our objective in this paper is to also conduct a preliminary study in order to suggest whether or not haptic rendering helps expedite the mechanism design process for this particular application.

To achieve this goal, we have developed an environment where a simple mechanism (i.e. 4-bar) is simulated, and the user can interact with it through a force feedback haptic device. In this environment, the user is also able to change some of the main design parameters. An informal user study was then conducted to further evaluate the user performance using the haptic feedback. The objective of our case study is to suggest a design of passive mechanisms in such a way that when it is manufactured, it can be used by a human operator and can give a better control to the user in the presence of sudden changes in the interaction force. As it will be seen in the case study, we use the penetration of the mechanism into the virtual environment as one possible performance criteria for the user of the mechanism.

Our approach in this paper is a case study. Our HAD example takes the form of designing a simple mechanism for assisting with amniocentesis or similar procedures [14-16]. Amniocentesis is a delicate procedure, during which a needle is inserted through layers of tissue in the abdominal area of the patient until it penetrates the amniotic sac. Amniotic fluid is then extracted for further examination. If the procedure is performed poorly, the foetus might be endangered. Currently, this task is accomplished by the physician directly manipulating the needle. This direct procedure may be subject to various uncertainties arising from operator strength and skills, and the movement of the foetus. We seek a design of the passive mechanism which would provide for indirect manipulation of the needle and thus offer better control of the insertion task in the presence of sudden changes in tissue elasticity as the needle penetrates various layers. This paper describes an initial approach to incorporating haptic feedback in the design of such mechanisms, where the designer can interactively manipulate the mechanism while interacting with virtual models.

In our proposed HAD environment, a user can manipulate the mechanism, inserting the attached needle through a simplified multi-layered mesh structure used to model the tissue layers, and feel the interaction forces created as a function of mechanism movements. For our multi-layered tissue simulation, we have used a surface mesh model where each vertex represents a mass element, and the connecting edges are represented by springs. When the tip of the mechanism (i.e. the needle) makes contact with the surface of a triangle, the triangle is sub-divided and the deformation of the mesh as a function of the penetration of the mechanism (needle) is computed numerically. More detailed discussions about this approach for modelling deformable objects can be found in Refs. [17-20]. The designer of the mechanism can adjust important design parameters to achieve desired force characteristics of the mechanism that gives the best operator performance. In our case study, this is measured by the amount of overshoot into the amniotic sac.

The rest of the paper is structured as follows. Our interactive HAD environment is presented in Section 2. The description of the interactive kinematics and force characterization of our mechanism is in Section 3, followed by the model of our contacting environment in Section 4. It is important to note that in Section 4, a model is represented that can create sudden changes of reaction forces as a function of the penetration of the mechanism, which is discussed in Section 3. The combination of these sudden changes of force, while being felt by the user through the haptic device given the kinematic design parameters, allows the designer to interactively define suitable design parameters. This is done by the designer to actually feel his or her reaction to the sudden changes of forces while manipulating the mechanism using a haptic device, and highlighted in Section 5 followed by the discussion section about the case study of this paper. Finally, some conclusions are also presented.

2. Overview of the HAD platform

Fig. 1 shows our proposed haptic-aided design (HAD) environment. An SGI workstation with an R10000 processor.
Fig. 1. Haptic Aided Design environment. The figure to the left shows the user interacting with the physics-based scene through a haptic force feedback device. The figure to the right shows the interactive design environment of the mechanism for the case study of this paper.

and 128 MB of memory and a Phantom\(^1\) 1.5 Premium, a point force feedback device with 6 degrees of freedom in position and rotation and 3 degrees of freedom in force output, were used in the experiments. The position sensing resolution of the Phantom is 0.03 mm. The position of the end point of the Phantom stylus held by the operator is input as the location where the operator interacts with the virtual mechanism. As we will describe later, our computational model will then compute the reaction forces and the new position of the mechanism as a function of the user’s motion. The force data is then sent to the Phantom and the actuators display this force by exerting it on the user’s hand. The software was written in C++, using GHOST (API for the Phantom) for haptic rendering and OpenGL, GLUT and GLUI for graphic rendering. The GHOST API also manages the collision detection events in the scene. A screenshot of our graphical user interface is shown on the right side of Fig. 1.

In general, the optimal design of a mechanism for our proposed application should consider other mechanisms such as Stephenson, WATT I, and WATT II. However, for the purpose of this paper, i.e. investigating the effectiveness of using haptic feedback in the design process, we consider only a 4-bar mechanism (links 1, 2, 3, and 4 correspond to \(l_1, l_2, l_3,\) and \(l_4\) in Fig. 2). A needle is attached to link 2 and a handle is attached to link 3. The tip of the Phantom stylus which represents the user’s presence in the virtual design environment is represented as a small sphere in the virtual environment. On the left of Fig. 1 is our interacting contact environment which, for our case study, is represented as a very simplified three-layer human body model, representing the skin, muscle, and amniotic sac layers. (The user only sees the outer skin layer.) The skin and amniotic sac layers are lumped-parameter mass–spring models. The second layer is represented as a force field between the first and the third layers.

The user’s “presence” in the design environment is represented as a small sphere (corresponding to the tip of the Phantom stylus) where he/she can make contact with the links or handle of the mechanism in the scene, and can feel their presence and (for our model) the cylindrical shape when sliding along the link. The user interacts with the scene by manipulating the Phantom stylus, viewing the small sphere representing the stylus tip, and feeling the force feedback when the tip/sphere touches a link or the handle.

When the user is in contact with a link or the handle and presses the button on the Phantom stylus, the virtual representation of the stylus (small sphere) is attached to the link or handle at the point of contact. As a result, subsequent movements of the user’s hand connected to the link become an input to the mechanism. The user can also feel constraint forces when trying to move in directions restricted by the kinematic configuration of the mechanism [22]. For example, all the links of the mechanism are constrained to lie in a plane; if the user tries to move the mechanism out of the plane, a constraining force is generated which is felt by the user.

The three tissue layers generate forces as the needle tip makes contact with and penetrates them. These forces are then mapped to the contact point coordinates (small sphere) and then to the haptic device.

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\(^1\) Phantom 1.5 Premium, SensAble Technologies Inc.
Fig. 3. Schematic showing the basic interactive geometrical parameters used for determining the movements of the handle due to movements of the user.

Fig. 2 shows the 4-bar mechanism parameters. The designer can interactively modify the kinematic parameters of the mechanism (such as the ones shown) by interactively changing the values of these parameters via the input controls shown on the right side of Fig. 1. By interactively modifying the kinematic design parameters, the designer can arrive at a set of suitable parameters such that when the user contacts the handle of the mechanism and moves the needle toward the skin for penetration, the amount of penetration of the needle into the skin layers will be as low as possible in the presence of sudden changes in contacting forces.

3. Interactive-haptic mechanism simulation

For our case study, the needle is attached rigidly to link 2 of the mechanism and a handle is attached to link 3 (Fig. 2). The links and handle are modelled as cylindrically shaped objects. For our case study, link sizes, the length and orientation of the handle and the location of the handle on link 3 were selected as the design parameters. In this design environment, the user grasps (i.e. makes contact with) the handle and moves the mechanism which causes the needle to make contact with the skin and then penetrate the three-layer mesh model.

3.1. Kinematics and calculation of constraining forces

In this section, we show how the positions and orientations of the links and the needle are computed when the user interactively moves the handle of the mechanism or makes contact at any location on any of the moving links. For example, Fig. 3 shows the geometry of link 3 and the connecting handle; the user can contact the handle at any point, say point $G$, and move the linkage. The user controls the position of the contact point, point $G$, by moving the Phantom’s stylus.

In general, the mechanism follows the user’s movement if the movements of the hand of the user are in accordance with the kinematic degrees of freedom of the mechanism. However, while the user is in contact with the handle, we do not want the user be able to slide on the handle, and the user should feel the reaction forces.

Referring to Fig. 3, the solid lines represent the orientations of link 3 and the handle at time $t_0$, and the dashed lines represent their orientations at $t_1$. The user moves the Phantom endpoint from point $G$ to $T$. Given the coordinates of $O$, $B$, $C$, and $D$ at time $t_0$, we wish to find the orientations for link 3 and the handle at time $t_1$. Link 3 and the handle form a rigid body. When the user attempts to move from $G$ to $T$, we rotate this rigid body by the corresponding angle, so that the linkage rotation follows the user’s movement. Since the coordinates of $G$, $O$, and $T$ are known, angle $\angle GOT$ can be calculated. The new orientation of link 3, $\overrightarrow{OB}'$, is then obtained by rotating $\overrightarrow{OB}$ counterclockwise by $\angle GOT$. The position of $D'$ is located by the length of $\overrightarrow{OD}$ along $\overrightarrow{OB}$. The orientation of the handle $\overrightarrow{DC}'$ is then obtained by rotating $\overrightarrow{BC}$ clockwise by angle $\angle BDG$.

So far, we know how to orient the link and handle. Since we would like to constrain the user not to slide on the handle, we now need to calculate the user’s new contact position on the handle and the constraining forces (i.e. needed to “glue” the user’s hand to that position). In Fig. 3, $G'$ can be located along vector $\overrightarrow{OT}$ with $|\overrightarrow{OG'}| = |\overrightarrow{OG}|$ satisfied. The constraint force $F_c$ is calculated as:

$$F_c = K_c \overrightarrow{TG'},$$ (1)

where $K_c$ is a positive constant. This force is then is used to create a sense of haptic feedback at the hand of the user, through the haptic device.

We can now determine the the positions and orientations of the remaining links, i.e link 1 and link 2. Fig. 4 illustrates the required angles, which can be calculated using basic trigonometry given $\alpha_1$ and link lengths.

3.2. Mapping force from needle tip to phantom tip

The eventual computed force that is sent to the Phantom to be felt by the user comes from two sources: the force due to tissue resistance described in the next section and the constraint force described in the section above. In order for the user to feel the net force, the tissue resistance force must be mapped from the needle tip to the position where the user grasps the handle.

This section first describes how to map the tissue resistance force to the position where the user grasps the handle (most of the following derivations are trivial, but highlighted here for completion). In this section, the case of grasping link 2 is
discussed in detail, as an example of dealing with grasping one of the three movable links. The force is determined by force balancing and torque balancing using a basic analysis of pinned structures. Fig. 5 shows schematics of some of the forces which can act throughout the mechanism. \( F \) is the vector of the tissue resistance force. \( f_1 \) and \( f_3 \) are the support forces from link 1 and link 3 on link 2. \( f \) is the effect on link 2 of the force that the user exerts on the handle to move the mechanism. \( \gamma_1 \) is the angle between the tissue resistance force and the vertical direction, which can be computed from the tissue resistance force \( F \). The remaining symbols have the same meaning as those in Fig. 4. We first calculate the external force magnitude \( f \) needed to balance link 2, then map \( f \) to point \( G \) on the handle.

In Fig. 5, in order for link 2 to be in static equilibrium, we have:

\[
-f \sin \alpha_1 - f_3 \cos \alpha_1 + f_1 \cos(\alpha_3 + \beta_3) + F \sin \gamma_1 = 0. \tag{2}
\]

With upward defined as positive, the balance of the vertical forces gives us

\[
-f \cos \alpha_1 + f_3 \sin \alpha_1 + f_1 \sin(\alpha_3 + \beta_3) + F \cos \gamma_1 = 0. \tag{3}
\]

In Eqs. (2) and (3), \( \alpha_1, \alpha_3 \) and \( \beta_3 \) have been determined in Section 3.1. Therefore, we have three unknowns \( f, f_1 \) and \( f_3 \). To solve for three unknowns, we need another equation, from the moment equilibrium of link 2 given as: (Fig. 6):

\[
-f l_2 \cos(\pi - \alpha_2 - \beta_2) + f_3 l_2 \sin(\pi - \alpha_2 - \beta_2) + F l_1 \gamma_2 = 0.
\tag{4}
\]

Combining Eqs. (2)–(4), after algebraic manipulation, yields

\[
f = \frac{F l_2 \cos(\gamma_1 + \alpha_3 + \beta_3) \sin(\alpha_2 + \beta_2) + F l_1 \gamma_2 \sin(\alpha_1 + \alpha_3 + \beta_3))}{l_2 \sin(-\beta_1)}.
\tag{5}
\]

To obtain the final force \( f_u \) felt by the user, we need to take one more step to map the force from point \( B \) to point \( G \) in Figs. 5 and 6. The magnitude \( f_u \) is computed as

\[
f_u = \frac{|\vec{OG}|}{|\vec{OG}|} f,
\]

because \( f_u \) causes the same rotational effect as \( f \) on link 3. The direction of force \( f_u \) is perpendicular to vector \( \vec{OG} \), pointing to the right. Force \( f_u \) together with the constraint force computed in the next section form the force sent to Phantom, which is exerted on the user’s hand.

4. Multi-layered contacting environment

In this case study of HAD, the work context is a very simple representation of an amniocentesis operation, where the operator drives a needle through several layers of tissue into the amniotic sac and returns. The tissue layers include skin, fat, abdominal muscles, uterus, and the amniotic sac. To realistically simulate all these layers of tissue haptically and graphically is beyond the scope of this paper. This study uses a simplified model which represents the three layers: skin, muscle, and amniotic sac. Skin and amniotic sac are modelled as deformable mass–spring models with a local contact area surface subdivision. The muscle layer is modelled with force properties between the skin and the amniotic sac that generates a resistance force when the needle tip tries to move inside it. The muscle layer has no graphical representation.

4.1. The first layer

Once the needle tip makes contact with the first layer, the contacted triangle on the polygonal mesh that represents that layer is determined and local surface subdivision occurs in its neighbourhood. A new contact triangle in the subdivided area is then identified. The new contacted triangle then follows the user’s hand movement, and as a result, its neighbouring vertices are thus deformed due to extension or compression in the springs. The force that is exerted on the needle tip due to the first layer mesh deformation is calculated as

\[
F_{l_1} = F_{c_1} + F_{c_2} + F_{c_3},
\tag{6}
\]

where \( F_{l_1} \) is a part of the force that the user feels due to the deformation of the first layer, as illustrated in Fig. 7. \( F_{c_1} \) is the force to which the \( r \)th vertex of the contacting triangle is subject to. \( F_{l_1} \) is applied to the needle tip, and then mapped to the handle, where the user is grasping the mechanism, before being sent to the Phantom for force display.

If \( F_{l_1} \) exceeds a preset threshold (set by the designer), the first layer is penetrated and the needle tip enters the second layer. The contacted triangle no longer follows the user’s hand movement and the mesh representing the first layer remeshes to its original configuration. After penetration, the first
layer contributes only a small constant resistive force to the movement of the needle tip:

\[ F_1 = C_1. \]

### 4.2. The second layer

The second layer is the space between meshes representing the first and third layers. The second layer does not have a graphic representation, as the first and the third layers do. The user feels the presence of the second layer through its distinct force properties.

The force that the user feels in the second layer corresponds to the movement characteristics of the needle tip. If the needle tip stops moving, the position \( P_s \) where it stops is recorded, and a linear spring \( K_{l_2} \) is attached between \( P_s \) and the needle tip. The stopping can be identified by successive identical coordinates returned by Phantom as the stylus position. The force exerted on the needle tip is then described by

\[ F_{l_2} = K_{l_2} \vec{T}_s + C_1, \] (7)

where \( F_{l_2} \) is the force exerted on the needle tip, \( K_{l_2} \) is the spring constant, and \( \vec{T}_s \) is the vector from the current needle tip \( T \) to the recorded stop position \( P_s \). Note that one of the terms in (7) is the constant force from the first layer after it is penetrated. If \( F_{l_2} \) exceeds a preset threshold, the spring is removed and the needle tip is subject to a force described as

\[ F_{l_2} = -D_{l_2} V_T + C_1, \] (8)

where \( D_{l_2} \) is a preset damping factor and \( V_T \) is the velocity of the needle tip. At this point \( F_{l_2} \) is a damping force that is proportional to the velocity of the needle tip. We remove the spring so that the force the user feels does not rely much on her previous stopping position. The parameters \( K_{l_2} \) and \( D_{l_2} \) in Eqs. (7) and (8) are experimentally chosen such that the user does not feel an obvious force transient upon removal of the spring. \( F_{l_2} \) is mapped to the handle, where the user grasps the mechanism, before being sent to the Phantom for display.

### 4.3. The third layer

As the user pushes the needle further into the layered tissue model, the needle tip will make contact with the third layer, the amniotic sac. Local subdivision, deformation, and force calculations for this layer are similar to those for the first layer. The force exerted on the needle tip at this point comes from forces from all three layers:

\[ F_{l_3} = F_{c_{l_1}} + F_{c_{l_2}} + F_{c_{l_3}} - D_{l_2} V_T + C_1. \]

If the force due to deformation of the third layer is beyond a specified threshold, the third layer ruptures (i.e. the spring mesh model of this layer does not deform) and returns to its original shape, and the needle tip enters the amniotic sac. After this point, the third layer only contributes a small constant force to the needle tip. The force that the user feels now is

\[ F_{l_3} = C_3 - D_{l_2} V_T + C_1. \]

The force must also be mapped to the handle, where the user grasps the mechanism, before being sent to Phantom for display. The position where the user makes contact with the third layer is recorded. The user tries to stop as soon as possible, after penetrating the third layer. Once the needle tip stops, the amount of penetration (e.g. overshoot) is reported to the user. In our preliminary study, we are using the assumption that a smaller overshoot signifies a better performance of the user (see Fig. 8). After puncturing the third layer and having stopped, the user can extract the needle from the three-layered tissue model and perform another needle insertion.

### 5. An informal user study

In this section, we present the results of a preliminary user study of the proposed HAD environment. The main question we investigated was whether our HAD environment suggested that haptic feedback is an effective tool in designing interconnected multi-body mechanisms. This is specifically for the case where the user controls the movements of such a passive mechanism in response to sudden changes in the contacting forces. To investigate this question, we conducted an informal user study using our simplified 4-bar mechanism and the model of our contacting environment.

#### 5.1. Experimental design

The idea of this experiment is to use a haptic mechanism to guide the search for suitable values of the design parameters of the device under study. We used the amount of needle
Fig. 9. Basic parameters used to define 4-bar mechanism under study.

Fig. 10. Three representative configurations for our four-bar linkage.

penetration in the third layer as the evaluation criterion (Fig. 8). A good mechanism design is one that tends to generate a small amount of overshoot for an average user in the presence of sudden changes in the contact force.

The objective is to determine if we can find good mechanism configurations in easier and more intuitive ways with the help of haptic feedback. Since it would take a designer too long to completely explore this high dimensional parameter space, we asked subjects to try only a small number of mechanism configurations in easier and more intuitive ways with the help of haptic feedback. Since it would take a designer too long to completely explore this high dimensional parameter space, we asked subjects to try only a small number of mechanism configurations. For the lengths of the three bars that form the basic structure of a four-bar linkage, we identify three of configurations. These discrete values were chosen such that each portion of the design space has an entry in our set of configurations. For the lengths of the three bars that form the basic structure of a four-bar linkage, we identify three representative cases (Fig. 10). We chose two values of \( l_b \), three values of \( \phi \), and two values of \( h \) (Table 1).

Besides representing typical mechanism configurations, the parameter values were chosen such that: (a) the workspace and force magnitude were comfortable for a human operator, and (b) the workspace was not so large as to be out of the range that the Phantom arm could reach. An initial pilot study conducted with two users showed that these requirements were met.

Four students at Simon Fraser University participated in this informal user study. One was from the School of Kinesiology and the other three were from the School of Engineering Science. All participants were right handed. At the beginning of the experiment, each subject was given a short introduction to the interface and the simulated virtual environment. Subjects then did a short training session with a few randomly chosen configurations from Table 1. For each such configuration, the subjects were asked to grasp the end of the handle via the Phantom and penetrate the tissue layers five times. The subjects were asked to stop as soon as possible once they felt the third layer was penetrated. The subjects continued to practice until they felt confident and comfortable performing the task. The formal trials then began.

Each subject experimented with all the 36 value combinations (trials) in Table 1 in random order. In each trial, the subjects performed the same task as in the training session, namely five penetrations of the third tissue layer. Each time the third layer was penetrated, the amount of this penetration was calculated by the program and saved into a file for later analysis. The subjects were encouraged to make comments during the trials. The subjects were also allowed short breaks whenever they claimed fatigue. Each subject took about 1 h.

5.2. Discussion

We averaged over the five overshoots for each trial and then over the four subjects, to minimize variation within the trial and between the subjects. The results are summarized in Table 2.

If we mark the extreme cases (penetration greater than 15 mm is boxed and overshoot less than 5 mm is shaded), we find almost all the marked cells correspond to \( h = 80.0 \). This suggests that assigning \( h \) a large value can result in the best or the worst results in terms of minimizing overshoot, when combined with the other factors. The combination of \( h = 80.0 \) and \( \Phi = 5\pi/6 \) is particularly undesirable due to the larger overshoots produced by this combination. The second and third four-bar linkage configurations seem to be preferable over the first, from the distribution of the shaded cells.

Under \( h = 0.0, \Phi = \pi/2 \) seems to be the worst choice among the three angles we experimented with. This is in contrast to the combinations with \( h = 80.0, \) where \( \Phi = \pi/6 \) is the worst case. Therefore, the effect of the angles interacts with that of relative position of the handle on the third link.

If we compare the numbers under \( l_b = 140 \) with those under \( l_b = 180 \), in 14 pairs out of 18 a smaller overshoot is observed for \( l_b = 180 \), which may suggest that \( l_b = 180 \) is preferable over \( l_b = 140 \).

A complete analysis of the effect of the four variables \((h, \Phi, l_b, \) and the four-bar configuration\) that interact with one another would be difficult to interpret and hard to generalize to general complex mechanisms. However, a table like Table 2 is always easy to construct with a user study. By observation, we can identify better combinations of parameters based on the average overshoot with visual feedback alone.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1, l_2, l_3 ) (mm) and ( \theta ) (rad)</td>
<td>80, 150, 120, −0.31</td>
</tr>
<tr>
<td>( l_h ) (mm)</td>
<td>140, 180</td>
</tr>
<tr>
<td>( \phi ) (rad)</td>
<td>0, ( \frac{\pi}{2}, \frac{5\pi}{6} )</td>
</tr>
<tr>
<td>( h ) (mm)</td>
<td>0, 80</td>
</tr>
</tbody>
</table>
As is typical in traditional CAD, our overshoot data would not be as meaningful, as what we obtained because the operator’s performance depends on the force characteristics of the mechanism.

Haptic feedback also seemed to lead to an intuitive understanding of the mechanism in our preliminary user study. During the experiment, all subjects commented that it was more difficult to manipulate the mechanism when \( \Phi = \frac{5\pi}{6} \). One subject observed that when \( h = 80.0 \) and \( l_h = 180 \), the lever arm was so large that the force change due to penetration of tissue layers became indistinct, which could not be predicted by calculations beforehand. Such observations are only possible when the mechanism is simulated haptically.

It can be suggested then that in the case study of a simulated mechanism for assisting with amniocentesis, haptic rendering can assist in designing passive mechanisms whose force characteristics are essential to the performance of human operators. Intended users can try out such mechanisms as if they were in the real application context, make intuitive evaluations of the mechanism, and identify better designs.

### 6. Conclusions

Haptic technology as a tool in the interactive design of a class of mechanisms is explored in this paper. Unlike previous works which mostly dealt with using haptic feedback for interaction with static CAD models or for carving surfaces, this paper presents a novel study of using a haptic device in designing a class of passive mechanisms which can be manipulated by a user in the presence of sudden changes in contact forces. The main objective of the design process is for the user to have a better control of the motion in the presence of sudden changes in force. As such, without using a haptic device in the design process, one actually may need to manufacture such a mechanism and physically experiment with a physical prototype to investigate the response of the average user to such sudden changes in force.

For this preliminary study, the four-bar mechanism was selected. The model of the interacting environment was based on a simplified three-layer tissue model having different force properties at each layer. To test the effectiveness of haptic feedback in the mechanism design process, we conducted an informal user study. The results suggest that haptic feedback can assist the designer in feeling the interaction forces while moving the mechanism in contact with the environment. Using the net amount of penetration into the contacting environment as a criterion which we wanted to minimize, it was found that haptic feedback can offer an interactive tool which can be used to expedite the design process. By interactively adjusting some of the key design parameters of the mechanism, haptic feedback allows the designer to characterize the controlled movements of the mechanism in the presence of sudden changes in contact forces.

This research can be extended in several further directions. First, the force properties of the layers in our tissue model may be tuned to match the force profiles obtained from real tissues, as described in [8]. This, combined with more advanced haptic feedback devices, can provide a better implication for the realistic case of sudden changes of forces. Second, the concept of HAD has been examined in a very narrow scope in this study – as an amniocentesis mechanism design and only confined to the case of the four-bar mechanism. In the future, other types of mechanisms can be explored that can allow variation of more parameters, which can widen the design space. This, combined with a more in-depth users’ study and more advanced statistical analysis such as ANOVAs may pave the way for determining an optimal mechanism type. In addition, a hybrid interactive design environment can be explored where some analytical synthesis can be combined with the proposed haptic aided design.

### Appendix A

#### A.1. Collision detection between the needle and the tissue model

In our proposed amniocentesis simulation, collisions between needle tip and mesh layers need to be detected. In our
polygon mesh data structure, neighbour elements of any given element are readily obtained. The basic idea of our specialized collision detection algorithm involves two steps, similar to [21] and [23]. First, we find the mesh vertex closest to the needle tip. Second, check triangles in the neighbourhood of this vertex for collisions.

Fig. 11 illustrates a one-dimensional mesh of connected line segments. At time $t = t_0$, the closest vertex is $B$, labelled with a small triangle. At $t_1$, the needle tip has moved to $P'$. We first check the neighbouring vertices of $B$, namely $A$ and $C$, and find the shortest distance between $AP'$, $BP'$, and $CP'$. In this case we find $CP'$ is the shortest, so $C$ is labelled as the temporary closest vertex. We then repeat this process on $C$ and find $D$ is closer to $P'$ than $C$ is, so $D$ is now labelled as the closest vertex. Repeating the same process on $D$ reveals that $D$ is still the closest to $P'$ among $C$, $D$, and $E$. This then suggests that $D$ is indeed the closest vertex at $t_1$.

For the second step of the collision detection, the closest point provides a hint as to where a collision might occur. We test to see if the line segment defined by the previous and current position of the needle tip intersects one of the triangles in the neighbourhood of the closest vertex. If no intersected triangle is found, there has been no collision.

The two meshes of our tissue model are the skin layer and the amniotic sac layer. Our implementation maintains the closest vertex on each of them and checks for collisions between needle tip and triangles in the neighbourhood of each of the closest vertices.

If the user’s movement between two consecutive model updates is small compared to the size of the mesh, computationally our collision detection algorithm needs only a very short time, because only the local area of the mesh is involved in the algorithm. Another advantage of our algorithm is that no additional computation is needed to update supporting data structures, such as the bounding volumes in some collision detection algorithms.

In the first step, we note that if the mesh is significantly concave, like the 1D mesh (connected line segments) shown in Fig. 12, the algorithm to find the closest vertex might fail. The 1D mesh in Fig. 11 illustrates this situation. The filled square is the probe tip. We want to detect collisions between the square and the mesh. At time $t_0$, vertex $D$ on the mesh is the closest point. At time $t_1$, the square has moved close to vertex $A$. If at $t_1$ we use the abovementioned algorithm, because no neighbour vertex $(C, E)$ is closer to the square than $D$, no new closest vertex will be found, which causes the algorithm to fail.

Fortunately, the tissue model we used does not have such extremely concave features, and a user’s normal movement between two consecutive model updates is small compared to the length of the polygon edges of the meshes, so our algorithm worked well during our user study.

A.2. Mass–spring model

In this study, we use the mass–spring model for modelling deformable surfaces. Although the mass–spring model is mathematically simple, it is capable of simulating a wide range of non-rigid behaviours found in nature. This section describes the details of our mass–spring model and its implementation. In our model, the surface of the simulated object is divided into small triangles, where a mass point (a node) is defined at each vertex. A linear spring is mounted along the edges of each triangle. These springs are called “mesh springs” because they are responsible for maintaining the distances between nodes on the mesh.

When a real elastic object deforms, the interior of the object contributes to both the shape of deformation and the force feedback to the user. To reflect this fact in our model, each node is also connected by a spring to its initial position, thus “home springs”. For simplicity, home springs are represented by linear springs with zero rest length. In our mass–spring model, damping is also implemented to dissipate energy, so that the nodes will eventually reach an equilibrium state. In this study we are mainly concerned with the mesh shape and node positions when the whole mesh reaches its equilibrium. In static states, forces due to damping effects are zero; therefore complicated damping calculations are not strictly required to make the dynamic process “physically correct” before the mesh reaches its equilibrium. The damping effect on a node in our work is implemented as a force proportional to the node’s relocation, but in the opposite direction.
This is a system of first order differential equations. Let $t$ denote the time variable; if the initial states of the system, $x(t=0)$, $v(t=0)$, and $f(t=0)$, are given, together with (A.2), then Eq. (A.3) can be solved as an initial value problem.

We use numerical techniques to approximate the solution. In our implementation, we use Euler’s method for its simplicity and efficiency. Let us rewrite (A.3) in the following form

$$
\begin{bmatrix}
\dot{x} \\
\dot{v}
\end{bmatrix} =
\begin{bmatrix}
v \\
\dot{v}
\end{bmatrix}
= 
\begin{bmatrix}
f_1/m_1 \\
f_2/m_2 \\
\vdots \\
f_n/m_n
\end{bmatrix}.
$$

(A.4)

Then with finite time step $\Delta t$, we can write the solution in its forward difference form

$$
\begin{bmatrix}
x(t_0 + \Delta t) \\
v(t_0 + \Delta t)
\end{bmatrix} =
\begin{bmatrix}
x(t_0) + \dot{x}(t_0)\Delta t \\
v(t_0) + \dot{v}(t_0)\Delta t
\end{bmatrix}
= 
\begin{bmatrix}
x(t_0) \\
v(t_0)
\end{bmatrix}
+ 
\begin{bmatrix}
v(t_0)\Delta t \\
\Delta a
\end{bmatrix},
$$

(A.5)

which becomes Euler’s method applied to this particular problem.

The program starts with initial values of the positions and velocities of the nodes, as well as the external forces. The initial internal force is zero everywhere. The total force on each node is computed, and then the new velocity and position are computed. The results of the computations, namely the components of the calculated force vector, are sent to a haptic device. The haptic device then exerts the force on the user’s hand. This process is repeated at every time step.

There are other numerical methods, such as the Runge–Kutta method, that can be used to integrate (A.4). Euler’s method generates the same result as other numerical methods when the equilibrium position of the mesh after deformation is the only concern, which is the case in this study. We chose Euler’s method because of its simplicity.

References


