

CREATING A 3D MODEL OF THE STOMACH FOR USE WITH HAPTIC INTERFACES

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Abstract

A three-dimensional model of a stomach and a spleen was created for Laparoscopic Nissen Fundoplication surgery simulation. The model needed to be visually accurate for the surgeon and digitally accurate for computations. To support both needs, the model was created using only quadrilaterals. This allows B-spline surface evaluation to be performed, and results in a smoother surface when using the *subdivision operator* function of Blender. A prospective surgeon will interact with the stomach model using haptic interfaces and the simulation program, Simulation Open Framework Architecture (SOFA); however, SOFA is only capable of representing objects using straight lines, and represents curves as series of line segments. This inherently limits the accuracy of 3D models. SOFA cannot represent curved surfaces because it cannot calculate the energy and force of curved surfaces as is necessary to apply forces during surgery simulations. Expressing the formula for the energy in terms of curved surfaces will solve this problem. The formula was found by differentiating the parametric equations of a Bézier curve with three control points, substituting them for $\frac{dx}{du}$ and $\frac{dy}{du}$ in the arc length equation, differentiating, substituting the results for $\frac{dl}{du}$ and $\frac{dl'}{du}$ in the equation for the energy of a spring, and then integrating. The final formula was found to be $E = \frac{YA}{2} \int \frac{(\sqrt{A'u^2+2B'u+C'} - \sqrt{Au^2+2Bu+C})^2}{\sqrt{Au^2+2Bu+C}} du$, where $A, A', B, B', C,$ and C' are expressions containing the initial control points and the displaced control points.

Introduction

Laparoscopic Nissen Fundoplication (LNF) is a surgical procedure considered to be the primary treatment for gastroesophageal reflux disease (GERD). GERD is characterized by stomach acid frequently flowing back into the esophagus. LNF corrects it by wrapping the gastric fundus 360 degrees around the esophagus. After this procedure, when the stomach contracts, the esophagus is compressed, and thus blocked; this prevents the stomach from spewing acids into the esophagus.¹

Prospective surgeons needed extensive training in advanced technical skills—like speed, precision, hand-eye coordination, gesture accuracy, and camera navigation—to operate in such small margins. Experienced surgeons who supervised the medical students operating on a live patient initially administered this training; however, this led to laparoscopic surgery being associated with high complication rates. Surgeons then trained with animals to diminish these complications, but other scientists raised concerns about infectious disease transmission and the expensive cost of animals.

In the aviation industry, pilots successfully used Virtual Reality (VR) technology to train prospective pilots. The potential medicinal applications are evident: VR simulators offer tactile and force feedback and allow the training of skills, knowledge, and judgment for laparoscopic surgery. Also, engineers created low-cost systems that were inexpensive compared to animal surgery. Using VR three-dimensional (3D) modeling software to simulate surgery is clearly the superior training method.²

The University of Florida does not currently have a viable model of the stomach for use in the simulation of LNF with haptic force-feedback devices. Doctors could use such a model to train University of Florida medical student.,The force-feedback device program, Simulation

Open Framework Architecture (SOFA), and the program that transforms the model into a volumetric object, Computational Geometry Algorithms Library (CGAL) Tetrahedralize, must interpret the model correctly without crashing when the student performs the surgery.

Currently, SOFA approximates curves using line segments; therefore, SOFA cannot display curved lines because it cannot calculate the energy and force of curved lines, which is necessary for modeling applied forces. Curves are not made up of straight lines, so SOFA's current method inherently limits the accuracy of 3D models. But SOFA is an open source software, so if the code for calculating the energy and force of curved lines is written, it can be implemented into SOFA.

Curves are represented in SOFA as Bézier curves, which are parametric curves commonly used in computer graphics. So, writing the formula for calculating the energy of Bézier curves in particular, and then converting it into code, would significantly enhance the appearance of curved lines—such as veins and arteries—in procedures like adrenalectomy. Once the required formula for a 2D surface is written, 3D objects will be the next area of focus. That advancement could enhance the appearance of 3D objects such as the stomach.

The first objective of this study is to create a 3D model of the stomach in Blender that is both visually and digitally accurate. If the first objective is successful, the second goal is to write the formulas for the energy and force of a curved object so that the stomach is as visually accurate as possible.

Methods

Stomach-and-Spleen Model

A model was created in Blender by adding a mesh circle and extruding the vertices repeatedly. The vertices were moved, scaled, and rotated after each extrusion to fit the outline of

the stomach. A picture of the stomach was inserted into the background of the model to facilitate the approximation. The model, essentially a circular tube, was scaled by half along the y-axis to simulate the stomach's ovular shape. It was given smooth shading, a solidify modifier to thicken it, and a diffuse material to give it a pink color.

The spleen was created by deforming a mesh circle into a two dimensional shape of the spleen and extruding, moving, scaling, and rotating the vertices along the outline of the spleen. At the top and bottom of the spleen, the vertices were scaled to zero, thus combining all the vertices into one vertex. Proportional editing was used to create the four indentations seen on most spleens. Smooth shading and a diffuse material of purple were then added.

While the model of the stomach was open on each end, the model of the spleen was closed. The significance of this difference is that in order to be closed, the spleen needed to use triangles on each end (Figure 1). In order to maintain uniformity with the rest of the quadrilaterals, the triangles had to be converted into quadrilaterals by dissolving half of the edges. This allows the vertices that were previously connected to the edges to be moved away from the polar cap, creating quadrilaterals (Figure 2). In order to perform certain computations with the model, such as B-spline surface evaluation, and to create a smoother surface when using subdivision operator, the model must contain only quadrilaterals.

Calculating energy of Bézier Curve with three Control Points

The equation for the energy of a spring is seen in Equation 1, where k is the stiffness constant of the spring, and Δl is the length of the displacement.

$$E = \frac{1}{2}k\Delta l^2$$

Equation 1

k was substituted for Young's modulus, Y ; multiplied by the cross sectional area, A ; and divided by the length of the displacement, l (Equation 2); according to the definition of Young's modulus.

$$E = \frac{1}{2} \frac{YA}{l} \Delta l^2$$

Equation 2

Δl was substituted for $dl' - dl$, which is the difference of the displaced length and the initial length; l was substituted for dl , which is the initial length; and E was substituted for dE , which is the change in energy (Equation 3). Then, the dl' , dl , and dE terms were divided by du (Equation 4).

$$dE = \frac{1}{2} YA \frac{(dl' - dl)^2}{dl}$$

Equation 3

$$\frac{dE}{du} = \frac{YA}{2} \frac{\left(\frac{dl'}{du} - \frac{dl}{du}\right)^2}{\frac{dl}{du}}$$

Equation 4

A Bézier curve with three control points is defined by a parametric function, as seen in Equations 5 and 6. The equations were evaluated (Equations 7 & 8) and then derived (Equations 9 & 10) to solve for $\frac{dx}{du}$ and $\frac{dy}{du}$.

$$x = c_{0x}B_0^2(u) + c_{1x}B_1^2(u) + c_{2x}B_2^2(u)$$

$$y = c_{0y}B_0^2(u) + c_{1y}B_1^2(u) + c_{2y}B_2^2(u)$$

Equations 5 & 6

$$x = c_{0x}(1 - u)^2 + 2c_{1x}u(1 - u) + c_{2x}u^2$$

$$y = c_{0y}(1 - u)^2 + 2c_{1y}u(1 - u) + c_{2y}u^2$$

Equations 7 & 8

$$\frac{dx}{du} = -2c_{0x}(1-u) + 2c_{1x}(1-2u) + 2c_{2x}u$$

$$\frac{dy}{du} = -2c_{0y}(1-u) + 2c_{1y}(1-2u) + 2c_{2y}u$$

Equations 9 & 10

Equations 9 & 10 were substituted for $\frac{dx}{du}$ and $\frac{dy}{du}$ in the equation for the arc length of a parametric function (Equation 11).

$$l = \int_0^u \sqrt{\left(\frac{dx}{du}\right)^2 + \left(\frac{dy}{du}\right)^2} du$$

Equation 11

$$l = \int_0^u \sqrt{(-2c_{0x}(1-u) + 2c_{1x}(1-2u) + 2c_{2x}u)^2 + (-2c_{0y}(1-u) + 2c_{1y}(1-2u) + 2c_{2y}u)^2} du$$

Equation 12

Equation 12 was derived (Equation 13), then simplified and factored in terms of u^2 , u , and constant (Equation 14).

$$\frac{dl}{du} = \sqrt{(-2c_{0x}(1-u) + 2c_{1x}(1-2u) + 2c_{2x}u)^2 + (-2c_{0y}(1-u) + 2c_{1y}(1-2u) + 2c_{2y}u)^2}$$

Equation 13

$$\frac{dl}{du} = \sqrt{\begin{aligned} &u^2[4(c_{0x}^2 + c_{0y}^2) + 16(c_{1x}^2 + c_{1y}^2) + 4(c_{2x}^2 + c_{2y}^2) - 16(c_{0x}c_{1x} + c_{0y}c_{1y}) + 8(c_{0x}c_{2x} + c_{0y}c_{2y}) - 16(c_{1x}c_{2x} + c_{1y}c_{2y})] + \\ &2u[-2(c_{0x}^2 + c_{0y}^2) + 6(c_{0x}c_{1x} + c_{0y}c_{1y}) - 4(c_{1x}^2 + c_{1y}^2) - 2(c_{0x}c_{2x} + c_{0y}c_{2y}) + 2(c_{1x}c_{2x} + c_{1y}c_{2y})] + \\ &[4(c_{0x}^2 + c_{0y}^2) - 8(c_{0x}c_{1x} + c_{0y}c_{1y}) + 4(c_{1x}^2 + c_{1y}^2)] \end{aligned}}$$

Equation 14

Equation 14 was simplified to combine the x and y control points (Equation 15).

$$\frac{dl}{du} = \sqrt{\begin{aligned} &u^2[4(c_0^2) + 16(c_1^2) + 4(c_2^2) - 16(c_0c_1) + 8(c_0c_2) - 16(c_1c_2)] + \\ &2u[-2(c_0^2) + 6(c_0c_1) - 4(c_1^2) - 2(c_0c_2) + 2(c_1c_2)] + \\ &[4(c_0^2) - 8(c_0c_1) + 4(c_1^2)] \end{aligned}}$$

Equation 15

$\frac{dl'}{du}$ is the same as Equation 15, except with displaced control points.

$$\frac{dl'}{du} = \sqrt{\begin{array}{l} u^2[4(c'_0{}^2) + 16(c'_1{}^2) + 4(c'_2{}^2) - 16(c'_0c'_1) + 8(c'_0c'_2) - 16(c'_1c'_2)] + \\ 2u[-2(c'_0{}^2) + 6(c'_0c'_1) - 4(c'_1{}^2) - 2(c'_0c'_2) + 2(c'_1c'_2)] + \\ [4(c'_0{}^2) - 8(c'_0c'_1) + 4(c'_1{}^2)] \end{array}}$$

Equation 16

Since the control points are constants and will not affect the integration, they were substituted with letters A, B, and C for simplicity (Equations 17-19)

$$A = 4(c_0^2) + 16(c_1^2) + 4(c_2^2) - 16(c_0c_1) + 8(c_0c_2) - 16(c_1c_2)$$

$$B = -2(c_0^2) + 6(c_0c_1) - 4(c_1^2) - 2(c_0c_2) + 2(c_1c_2)$$

$$C = 4(c_0^2) - 8(c_0c_1) + 4(c_1^2)$$

Equations 17-19

In addition, A' , B' , and C' were interpreted as the same as A , B , and C , except with displaced control points (Equations 20-22).

$$A' = 4(c'_0{}^2) + 16(c'_1{}^2) + 4(c'_2{}^2) - 16(c'_0c'_1) + 8(c'_0c'_2) - 16(c'_1c'_2)$$

$$B' = -2(c'_0{}^2) + 6(c'_0c'_1) - 4(c'_1{}^2) - 2(c'_0c'_2) + 2(c'_1c'_2)$$

$$C' = 4(c'_0{}^2) - 8(c'_0c'_1) + 4(c'_1{}^2)$$

Equations 20-22

Thus, $\frac{dl}{du}$ and $\frac{dl'}{du}$ are defined as follows (Equations 23 & 24).

$$\frac{dl}{du} = \sqrt{Au^2 + 2Bu + C}$$

$$\frac{dl'}{du} = \sqrt{A'u^2 + 2B'u + C'}$$

Equations 23 & 24

$\frac{dl}{du}$ and $\frac{dl'}{du}$ were substituted into Equation 4 (Equation 25), then integrated and simplified

(Equation 26)

$$\frac{dE}{du} = \frac{YA (\sqrt{A'u^2 + 2B'u + C'} - \sqrt{Au^2 + 2Bu + C})^2}{2 \sqrt{Au^2 + 2Bu + C}}$$

Equation 25

$$E = \frac{YA}{2} \int \frac{(\sqrt{A'u^2 + 2B'u + C'} - \sqrt{Au^2 + 2Bu + C})^2}{\sqrt{Au^2 + 2Bu + C}} du$$

Equation 26

Results

Stomach-and-Spleen Model

The model visually depicts a stomach and a spleen well: It has the correct shape, proportions, thickness, color, and position (Figure 3).

It is anticipated that since both the stomach and the spleen are comprised solely of quadrilaterals, B-spline surface evaluation can be successfully performed and the subdivision operator will yield a smooth surface. This will be tested in future studies.

Calculating the energy of a Bézier Curve with three Control Points

The new formula is anticipated to correctly calculate the energy of a deformed Bézier Curve with three control points. It will be converted to code, implemented into SOFA, and then tested.

The result when the indefinite integral was entered into Wolfram Mathematica, an online integrator, was too long and complex to deal with. A numerical integration technique such as Gaussian quadrature needs to be used in order to calculate the energy.

Discussion

I encountered problems while creating the stomach-and-spleen model and expressing the formula for the energy of a curved spring. After creating a stomach model made of three cylinders that had polar configurations in three places, I was informed that the triangles involved in polar configurations complicated matters when doing certain computations. This is why I subsequently created the current model as essentially a long, deformed cylinder made entirely of quadrilaterals. When I created the spleen model, I needed to use polar configurations because the spleen is enclosed at the top and bottom. So, I converted the triangles into quadrilaterals by dissolving half the edges and extending the vertices that connected those edges.

The tedious nature of expressing the formula for the energy of a curved spring certainly frustrated me, especially simplifying and factoring Equation 13 into Equation 14.

$$\frac{dl}{du} = \sqrt{(-2c_{0x}(1-u) + 2c_{1x}(1-2u) + 2c_{2x}u)^2 + (-2c_{0y}(1-u) + 2c_{1y}(1-2u) + 2c_{2y}u)^2}$$

Equation 13

$$\frac{dl}{du} = \sqrt{u^2[4(c_{0x}^2 + c_{0y}^2) + 16(c_{1x}^2 + c_{1y}^2) + 4(c_{2x}^2 + c_{2y}^2) - 16(c_{0x}c_{1x} + c_{0y}c_{1y}) + 8(c_{0x}c_{2x} + c_{0y}c_{2y}) - 16(c_{1x}c_{2x} + c_{1y}c_{2y})] + 2u[-2(c_{0x}^2 + c_{0y}^2) + 6(c_{0x}c_{1x} + c_{0y}c_{1y}) - 4(c_{1x}^2 + c_{1y}^2) - 2(c_{0x}c_{2x} + c_{0y}c_{2y}) + 2(c_{1x}c_{2x} + c_{1y}c_{2y})] + [4(c_{0x}^2 + c_{0y}^2) - 8(c_{0x}c_{1x} + c_{0y}c_{1y}) + 4(c_{1x}^2 + c_{1y}^2)]}$$

Equation 14

To ensure that I did not err in one of the numerous steps, I performed the entire process of differentiating the parametric equations of a Bézier curve with three control points, substituting them for $\frac{dx}{du}$ and $\frac{dy}{du}$ in the arc length equation, differentiating, substituting the results for $\frac{dl}{du}$ and $\frac{dl'}{du}$ in the equation for the energy of a spring, and then integrating three times. I found the same formula each time.

Conclusion

The formula can enhance the appearance of univariate curves such as veins and arteries in procedures such as the adrenalectomy. This is done by integrating the formula with respect to the

control points and calculating the force. Then, once the formula is converted to code using Gaussian quadrature and implemented into SOFA, SOFA would be able to model applied forces during surgery simulations and represent those blood vessels using curved lines.

The formula needs to extend to three variables before it can be used to compute the energy of the stomach-and-spleen model. For the stomach to be represented in SOFA as a 3D Bézier object, another model must be created using a Non-uniform rational B-spline (NURBS) cylinder on Blender, the NURBS object must be converted to Bézier object, and the formula for calculating the energy of a trivariate Bézier object must be found.

The model that was made can and will be used for simulations of Laparoscopic Nissen Fundoplication. The only drawback is that it will be made of line segments instead of the curves the actual stomach contains.

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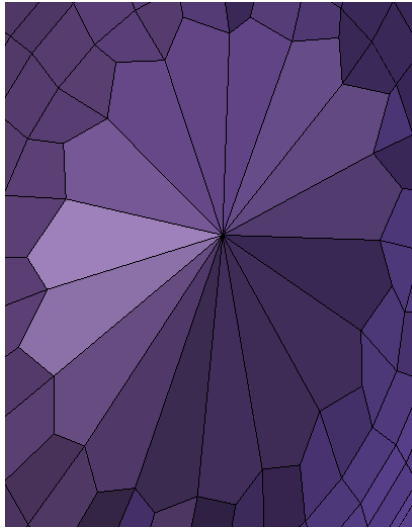
Figures

Figure 1 and 2: Screenshots of the cap of the spleen model before and after transforming the triangles into quadrilaterals.

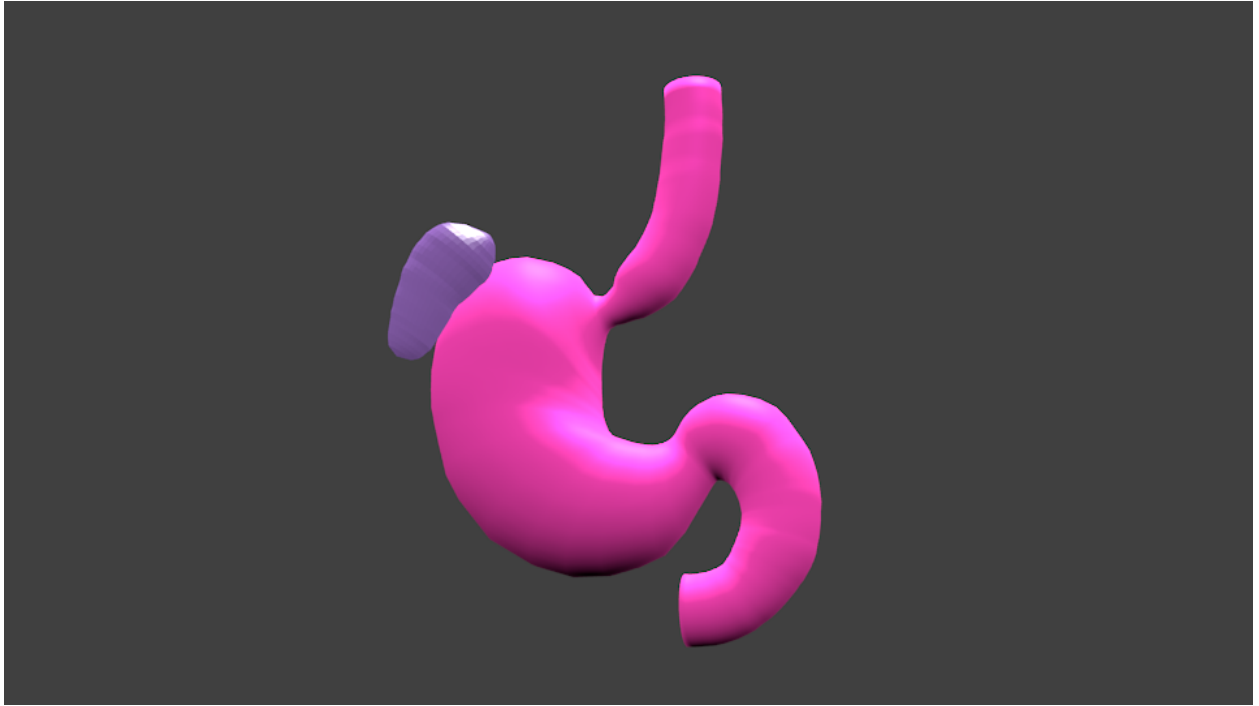


Figure 3: The final model of a stomach and a spleen.