Investigating the suitability of Maya for biomedical modelling and simulation

Final Report

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Abstract

The development and simulation of anatomical models is an important task in biomedical research. The resulting models can be used for virtual surgery, simulations for improving the understanding of diseases, diagnosis and education. In most cases biomedical models are constructed from medical imaging data using highly specialized techniques by experts in respective areas. This process can be unnecessarily time-consuming and complicated. In our research we investigate whether a general modelling package such as Maya can be used to create realistic anatomical and functional models for use in biomedical applications. We analyze and classify common biomedical structure and capabilities of Maya. Using the result of this investigation we assess under which circumstances Maya can offer an easier alternative to current methods and what solutions Maya provides to capture biomedical properties for modelling and simulation. The findings are supported by some basic user testing.

Contents

1. Introduction

In this dissertation we investigate the use of Maya for biomedical modelling and simulation. Biomedicine is an important field of research which is concerned with applying biological and physiological principles to clinical practice in order to better understand and treat diseases. Modelling and simulation are important tools in biomedicine since they enable scientists to model organs and diseases not possible by observation of patients. Such models and simulations can also be used for related tasks such as 3D image analysis and virtual surgery. The modelling and simulation of healthy and diseased organs is however very complicated because of their complex geometry and behaviour.

The package we will look at is called Maya. It is one of the most popular modelling and animation software packages in the movie and game industry. Unlike expert software packages used for biomedical modelling or simulation, Maya is suitable for artists, animators and designers without experience in computer graphics.

Most modelling and simulation packages used in the medical field are highly specialized and complex. Anatomical structures are generally modelled from medical imaging data sets and tissue dynamics is obtained by recording movement over time or by using physically accurate simulation methods. This sometimes is vital for biomedical applications where accuracy and precision is critical such as computer aided surgery but at times it's over complex and highly unnecessary. Often when a medical expert wants to present visual information to the viewer, they want to communicate across certain concepts, statements or allow viewers to understand certain ideas. The exact spatial relation and physically correctness of the biomedical structure is not critical. For example, there are many hand drawn medical illustrations and animations which can be found in biomedical textbooks and internet sites [3].

In the past decade hardware and software tools have improved dramatically enabling the development of more realistic biomedical models and simulations. The research field has become increasingly complex and is now including diverse disciplines such as physics, mathematics, computer graphics and bioengineering. Many computer graphics or engineering researchers are taking advantage of these advancements to exploit new uses or applications in medicine. The field of medicine on the other hand is slow and cautious in adopting new technology and practice such as use of computer graphics in surgery guidance [7]. Also the use of new technology and computer graphics is often avoided by typical doctors or medical experts, because of the lack of knowledge in the areas of computer graphics or bioengineering mechanics, the development of virtual representation and simulation of anatomies and surgery procedures are left for computer graphics or engineering experts.

Hence points out that in order to actively take advantage of the advancements in technology and hardware, medical experts and doctors either have to learn computer graphics or suitable tools must be provided [4]. Such a tool would need to allow medical experts to model, animate and render the biomedical structure of their interest. In this project we investigate whether a general purpose modelling tool and animation such as Maya can be used in biomedical research. We will also investigate whether Maya can be integrated into biomedical application and whether Mayas modelling and animation capabilities are suitable for representing and simulating biomedical structure and their behaviour.

2. Background

The previous chapter outlined the importance of modelling and animation in biomedicine. The Maya package was then introduced and the motivation of applying Maya to biomedicine was explained. In this chapter we will survey the background areas related to this topic. Starting with biomedical applications of computer graphics, looking at different areas of how computer graphics is used in biomedicine and what requirements and functions are needed.

We will review existing modelling and animation techniques and discuss trade offs. Also we will survey previous uses of Maya in the biomedical field.

2.1 Biomedical applications of computer graphics

2.1.1 Image acquisition, analysis and visualization

Image acquisition, analysis and visualization falls under the category of 3 dimensional medical imaging [11]. It is a field that has evolved ever since early 70s where doctors are able to diagnose patients' internal structures using image acquisition modalities. These technologies allow us to obtain information about patient's internal structures without cutting or physically intruding into the patient's body. There are many different types of image acquisition modalities available. They are generally differentiated by the form of the energy that is produced, such as, x-ray based computer tomography (CT), magnetism based magnetic resonance (MR), sound wave based ultrasound and radioactive material based positron emission tomography (PET).

When the information of the patient's internal structures are obtained as images, they need to be interpreted and evaluated by specialists. This process is called Image analysis. Image analysis is an important part of diagnostic for many areas of medicine. It can be used for the detection and segmentation of internal structure, quantification of properties like volume or size, localization of problem like a fracture or screening of abnormal features. Traditionally image analysis are done by radiologists, clinical knowledge are used to interpret the images for diagnosis.

Today computer graphics techniques and algorithms make it possible to reconstruct and visualize 3D structures from medical imaging data sets. Image data sets usually consist of stack of 2D image slices and hence can be interpreted as a regular grid of sample points.
These data can be restored from noise and distortion and enhanced by sharpening or contrast enhancement. Then the images can be registered, the world coordinates of the image can be determined in respect with other image, or an organ. This is used to match different images together with a common set of world coordinates with respect to the actual organ structure. Images can also be segmented to separate organs or structures and is used to isolate the areas of interest.

These 3D data although acquired in discrete samples, they can also be represented as volumetric data in voxels. The data is interpolated if there are less sampling data than voxels. These volumetric data can be rendered and visualized using methods such as direct volume rendering or surface extraction method where the isosurface of the volume is extracted and then rendered. A popular surface extraction method is the marching cubes method [5].

2.1.2 Computer Assisted Surgery

In order to simplify tasks for surgeons and to increase surgical accuracy, applications or prototypes are being developed where computers are used to aid the surgical procedure [8]. Computer graphics are involved for many of these applications, for example neurosurgery, robotic assistance, radiation therapy and minimal invasive procedures. In many cases computer graphics and image acquisition modalities are used in combination to provide accurate and insightful guidance for the surgeon to work with the anatomic structure. Popular applications include surgery planning where surgery procedures are planned and simulated to help surgeons to plan for surgeries. Surgery guidance is where a computer graphics interface is used to help guide surgeons through a surgery procedure. These are very challenging tasks [7] because of the demanding nature of medicine, applications are not only required to improve results but also need to have reliable and accurate clinical results, decrease cost to hospitals and most importantly improve the patient welfare.

2.1.3 Virtual Human and Anatomy Modelling

In medicine, illustrations of biological systems or organs are traditionally displayed as coloured drawings or diagrams in text books. With the introduction of computer graphics, a 3D view of a biological system or organ can be modelled and rendered virtually. Traditional drawings are generally informative because they are easier to produce while 3D models are more difficult to produce and the right tools are needed. But the advantages [4] that come with 3D models are accurate 3d perspective and spatial relationship of structures, use of hidden, translucent, highlighted or coloured surfaces to display additional or hidden information. For example the use of translucency to show hidden structures that would have been otherwise obscured form the viewer, or the use of a colour spectrum to visualize the stress and strains of the heart. Also with the power of computing it comes with ability to model, compute and display detailed structures with complex behaviour with high accuracy and can be interactive or animated.

Anatomies can be modelled and rendered together to display a virtual human or biological structure. To represent a biomedical structure a surface representation can be used or volumetric data can be used [11]. But unlike visualization types mention in section 2.1.1, anatomy modelling uses surface representation rather than volume representation. Often the surface models are light weighted and only have minimal data points to represent its shape. This is so that processes like rendering, texturing and dynamics can be easily applied to the models. Also the possibility of the model running interactively at real time or be able to be used on a normal workstation. The advantages that comes with a surface model includes allowing the use of, high quality surface rendering with material type, texture/noise mapping or rendering effects to simulate wetness on surface. Translucency and presudo–colour can be used to help visualize and identify individual anatomies that's obscured or clustered by other anatomies. Dynamics can be applied to show anatomies behaviours to forces.

To model the surface of these anatomies, in most cases three dimensional reconstructions are used. This requires the acquisition of real data and then under going processing and enhancement before the outline of the anatomy can be identified and a suitable polygonal surface is fitted around the data points. There are lots of methods available for these processes, some are automatic and some are very labour intensive. It is often important for medical illustrators or anatomists to manually refine the shapes to remove "granularity" (noise and sampling artefacts within the data) and smooth the surface to make it appear natural. This process can be divided into two main processes. First the identification of the contour shape from the medical data and then secondly the generation of surface model from contours. For example in [10] a heart is modelled by first using an automated boundary extraction method then surface representations are generated and a volumetric model is created by blending the surface representations.

A collection of virtual anatomies can form a virtual body. Virtual body can be used for many applications, often for education [9] [30], simulation or visualization. The main applications includes, virtual human atlas where it allows users to navigate within the body and can be interactive, educational images and videos that can be found from medical illustration in text books to documentaries on discovery channel and lastly surgery simulation which can be used for education, training, planning or guidance of surgery. Surgery simulation is a big and fast growing area of research and will be covered in more details in the following section.

2.1.4 Surgery Simulation

Surgery simulation [16] [11] [6] also known as virtual surgery requires the use of computer graphics, physics and bio-mechanics to simulate a surgery procedure. This includes the modelling and rendering of biomedical structures and surgery tools and if needed the dynamics to respond to users interactions. Surgery simulation is an important area of research because it provides an affordable and available solution to surgery training.

Surgery training for medical students takes a traditional apprenticeship approach. A group of students or interns would get clinical experience by observing or working with a doctor. The opportunity of apprenticeship may have poor availability and this is also a hassle for the doctor and patients and a time constraining process for everyone. Simulation of surgery procedures that students can do by themselves or with an instructor are normally done on animals, cadavers or simulation machines. While animal organs can be quite different from human organs, they are also expensive to run and considered immoral in certain countries. Cadaver has similar organs to living humans but they can be expensive and have poor availability and most importantly the tissue does not behave like real living tissue. Physical simulation tool are generally unrealistic, can train users on a limited set of skills and users can get bored very quickly [16].

Virtual surgery can cover multiple levels of details as described by [6]. The first generation of virtual surgery occurs at the morphological level. They allow users to navigate through a virtual environment but are generally static models or limited interactions. The second generation virtual surgery also includes physical properties into the model and can respond to user interaction in a realistic manner such as deformation or cutting. The third generation of virtual surgery as well as modelling the morphological and physical properties it also models the physiological properties of how things function.

The different types of surgeries [16] that are simulated include needle based procedures, minimally invasive surgery and open surgery. These can be differentiated by their limitation of interaction and level of realism that is enforced on the user. Needled based procedures are highly constrained and only train a limited set of skills. Minimal invasive surgery has a limited area of interaction because of the small insertion into the body, but has more details and realism and has been clinically tested. Open surgeries involves larger incisions in the body, there is normally an open environment to interact with hence the level of complexity and realism are harder to achieve.

A typical virtual surgery would include an interface and a graphical display for the user to operate with. The interface could be anything from a mouse to a custom built unit to simulate the operation tool with force feed back. The graphical display is normally a monitor but can be a virtual reality headset. A metaphor used for virtual surgery as pointed out by [31] is flight simulation. Flight simulation can be seen as having similar benefits as surgery simulation. It allows for the user to practice a set of essential skills, a chance to create and correct mistakes and to build experience and confidence. Although surgery simulation can never replace the real thing, it is cheaper, safer and can be readily available. Surgery simulation can be used along side with clinical training for cost efficient and effective training.

Challenges [17] in surgery simulation not only include the modelling of the biomedical structures and its natural behaviours but the interaction of tissues with surgical instrument also needs to be captured. This requires the modelling of organ and tissue dynamics. Common dynamics issues in surgery simulation includes, nonlinear deformation of tissues, cutting and bleeding. Also because of the real time requirements of virtual surgery other problems arise such as, collision detection, haptic feedback and real time interaction.

2.2 Modelling and Simulation Techniques

2.2.1 Modelling representations

In order to represent or model objects geometries, we have to choose a suitable form of representation to work with. Representations can occur at many levels, an object is commonly represented as a volume, a surface, faces, or points. Each representation can be displayed in many ways. A surface representation can be displayed as wireframe, faces or shaded view and so on depending on the type of surface representation. We will now discuss the common types of representations used today.

Polygons (fig. 1) are one of the oldest and simplest representations. Polygon representation composes of vertices, edges and faces. Discrete points in a surface are represented by vertices. An edge is a straight line joining neighbouring vertices on a surface. Faces are areas enclosed by planar edges and represent the surface interpolated between neighbouring vertices. These faces are normally made up of triangles, quadrilaterals or other simple convex polygons, in order to maximize the efficiency and simplicity of the polygon mesh.

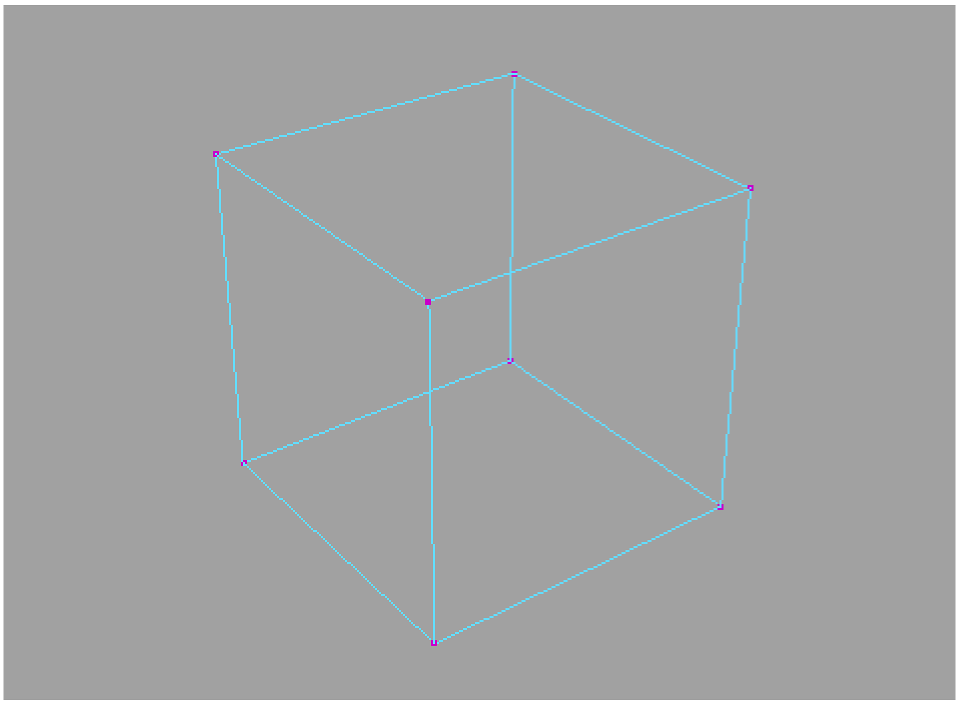


Fig. 1 An example of a Polygonal cube produced with Maya

Polygon meshes tend to be jagged and “piecewise” because the surface is linearly interpolated between vertices. Smooth surfaces can only simulated by having a high number of vertices.

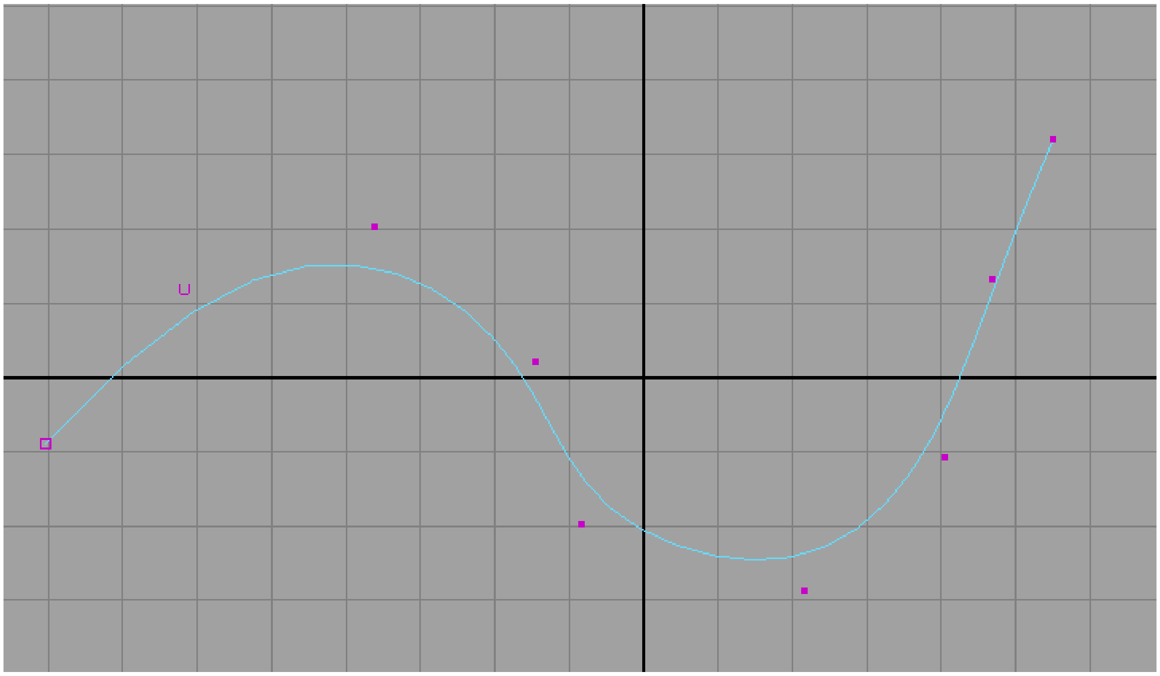


Fig. 2 Example of a spline curve this is particular one is a NURBS curve produced with Maya

Splines (fig. 2) are a general category of mathematical functions used to represent free form curves. These are commonly used in computer aided design (CAD), useful for designing curved surfaces such as ship hulls. A spline surface is generally made up of multiple patches, in order to capture its complex shape. A patch is composed of multiple spline curves and control points are used to control the shape of the patch. A spline is a parametric curve where at any parameter along the curve the position of the point can be calculated by the mathematical equation used and the control points around the point. The influence of each control point is depended on the weight of the control point and how close the control point is compared to the point. There are many variations splines. We will take a look at the most popular type Non-Uniformed Rational B-Spline (NURBS). NURBS is the type of spline that is used by Maya. The benefit of free form modelling is that they are easier and more efficient to represent curves compared to polygon representations.

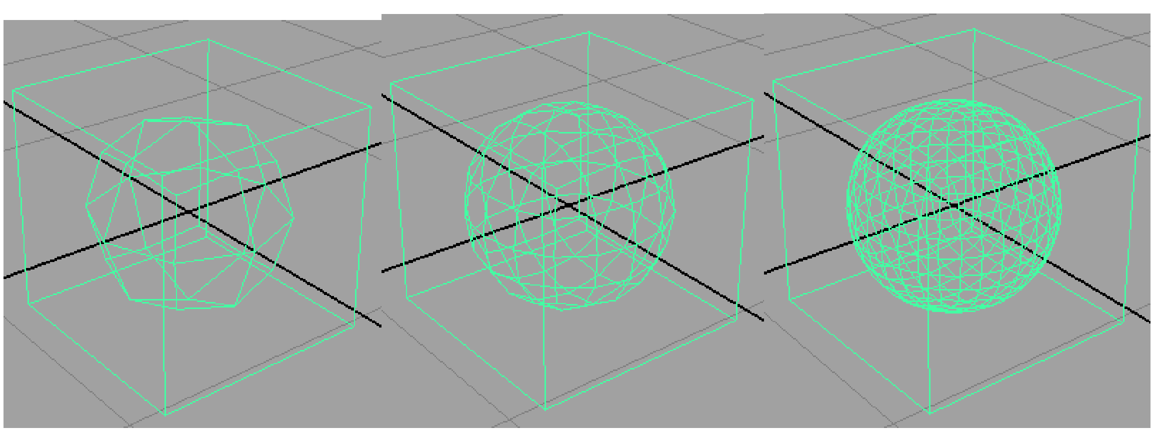


Fig. 3 An example of a cube being subdivided, produced with Maya. The iterations of the subdivision increases from the left to the right.

Subdivision (fig. 3) is a newer form of smooth surfaces representation, first invented by Catmull and Clark [18]. Subdivision surface starts with a polygon surface and a smoother surface is generated by subdividing the edges and vertices. This method can be applied multiple times to create finer levels of detail. Subdivision surface is considered to be a superior method compared to splines surfaces because topological limitation of spline surfaces [19]. Subdivision surface is able to ensure overall smoothness while being able to apply to polygon surfaces of complex topologies.

The above representations we have looked at are all surfaces representations. They represent only a surface with no thickness. To represent a solid object with surface representation an enclosed volume with a surface. There are two types of common volume representations, particle based models and voxels. Particle systems are generally used to represent fuzzy effects and natural phenomenon such as clouds, explosions or mists. They can also be used to represent a solid volume. Voxels is another type of specialized volumetric representation, commonly used in the medical field. Voxels in medical imaging are described more in [section 2.1.1]. Voxels are like its 2D equivalent pixels, except it represents a value (colour for pixels) in 3D. Each voxel represent one or more properties of the space it occupies, such as the density, stress/strain or diffusion values.

2.2.2 Deformation models

In order for us to animate an object, it is not always as simple as translating, scaling or rotating the object. For many objects, its shape can change, we call this deformation. To animate this realistically we need to capture how the object would behave as if it is in the real world. In computer graphics we consider an object that changes its shape as deformable and if the shape does not change we consider it as rigid. For deformations there are elastic deformations where after deforming the object tries to return back to its original stable shape like rubber and plastic deformation is where an object's stable shape is changed upon deformation such as plastic or metal if you bend it over its tolerance.

There are many types of deformations depending on the material and structure of the object. For example we would expect metals, plastics and rubbers to deform differently between them and deform similarly within each type. In order to simulate or capture some of these deformation characteristics we can use deformation models to model how an object can deform. There are many types of deformable models used in computer graphics [20] they can be categorized into two main groups, kinetic models and physically based models. The difference between these two methods are that kinetic methods tend to be simple but can be time consuming or require experience and skill to use effectively, where physically based methods can achieve more realism but can become complex, requires good understanding of objects physical properties and is computational expensive.

Kinetic deformation methods are mainly used in the design, gaming and movie industries. They are purely based on geometric information and normally react to the movement of components. Kinetic methods have no physical principles involved hence they are generally computationally efficient. Common kinetic methods are parametric surfaces and free form deformation. Parametric surface such as splines allows the smooth deformation of a surface by the movement of one or more control points. They are computationally efficient and allow interactive modification. Free form deformations are a type of space warping deformation which deforms the space which the geometry or points lays in with a series of mathematical matrices.

In order to capturer the behaviours of an object more accurately we can model the deformation based on the physical properties of the material and structure. Physically based deformation methods [21] are always based on or approximates some kind of physical principles such as the Newton law, hooks law or continuum mechanics. Normally an object will be deformed when reacting to an unbalanced external force. Physically based methods tend to be computationally expensive, but can trade efficiency and realism with physical correctness. The common physically based methods we will look at here are Mass-spring models and the more complex continuum models such as Finite element, finite differences and boundary element methods.

Mass-spring model is one of the simpler methods with well understood dynamics. Mass spring model is a collection of nodes of mass connected with springs in a lattice structure. The spring forces are often linear but nonlinear forces can also be used. When the spring between two mass are compressed or stretched this applies a force on the attached masses and affects the shape of the object. The collection of masses can each be assigned a weight and a damping factor can be applied to each spring. The behaviour of the objects deformation is dependant up on the weight of each node and the damping force of each spring and most importantly the structure that the nodes and the springs are arranged in.

The equation of motion can be described as:

$$Ma + Cv + Tx = f$$

- a , v , x each describes the vector of acceleration, velocity and positions of each node respectively.
- M is the mass matrix applied to the current acceleration from the total force
- C is the damping matrix. Damping is proportional to the velocity
- T is the stiffness matrix that composes of the spring forces from neighbouring masses. This can be calculated from the distance between the neighbouring masses (Hookes' law).
- f is the vector of the total external force on each node.

Hence the acceleration is calculated by

$$a = M^{-1}(F - Cv - Kx)$$

v and x for the next time interval can then be found through numerical integration.

Mass-spring method is an approximate way of solving the dynamics problem of a continuous volume by dividing the problem up into many discrete and directional elastic springs. This level of approximation depends on the complexity of the springs and weights used. This allows us to have a simplified version of a physically based model that is capable of having good computational efficiency. Of course the tradeoffs are that the realism is less compared to other complicated physically based models.

Continuum models are a category of models which looks at an object as a continuous volume. These models achieve realistic results by modelling the object with a differential equation and solving it at discrete points. An example of a continuum model used to simulate the deformation of biomedical structures is to approximate equilibrium by minimizing potential energy. Hence whenever a new external force is applied to an object, the equation can work out the new equilibrium position for the object to deform to. Finite element method is where a continuous volume is divided into elements joined by a discrete number of nodes. A partial differential equation can then be solved numerically for each node. Compared to mass-spring model a spatially continuous equation is used but it is only solved approximately at discrete positions. There are many variations of these Continuum methods such as finite differences method, finite volume methods and boundary element method. Continuum methods are able to achieve realistic results but the drawback is that they are generally computationally expensive and cannot run in real time. Another drawback is that they are physically complex and requires good understanding of the object in order to model realistically, such as the stress-strain relations.

There are other types of deformation models such as point based methods where the geometry of an object is disregarded, deformation are directly applied to points for example in [22] where shape matching is used based on the centre of mass. Reduced methods are used where more complex equation or methods are simplified or approximated for example in [23] where modal analysis is used. Hybrid methods are used where complex methods and simple methods are combined and applied to different parts of an object for example in [6] where FEM and spring system is combined in order to run in real time.

2.3 Past work with Maya for biomedical application

Although Maya is a modelling and animation tool predominantly designed for the games and movie industry, there have been several applications of it in the biomedical field as explained in this section.

A noteworthy international biomedical project involving Maya is “smile train” which helps to provide free cleft lip and palate surgeries for children in developing countries and free cleft lip and palate surgery training for surgeons and medical professions [13]. A part of the virtual surgery project of smile train is to produce video CDs (fig. 4) to educate surgeons and medical experts in the form of animated surgery simulation. These animations are created under the software package Maya. The responses were positive, included in the feedback was that 95% of the CD recipients felt that the animation made the cleft surgery easier to understand. At the start of the project, the version was Maya 3.

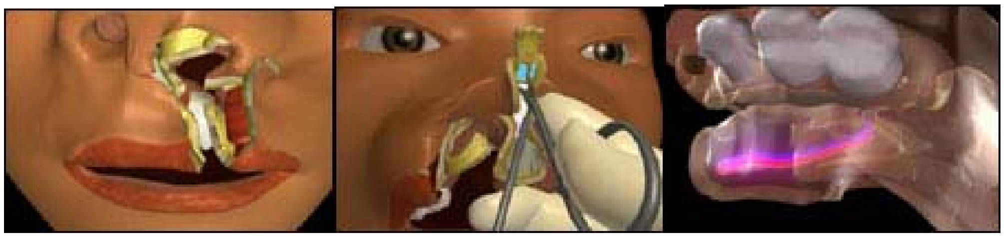


Fig. 4 Screen captures of the surgery training CDs produced by smile train [13]

The models used in this animation are created and assembled in external programs from CT scan data and data from the visible human project [24]. The reference model is imported into Maya and then NURBS surfaces are created along the surface and then the whole model is converted to Polygons. Finally the polygon mesh is resampled into a more usable reduced number of polygons.

During the animation stage the animation team experienced difficulties with simulating the volume of flesh and realistic tissue dynamics with the existing animation functions. Hence plug-ins was created to aid in the creation of animations which includes tools for incision, suture, texture, fat and hook or forceps. An incision plug-in is required because it changes the topology of the model. This may result in creating more points on the surface. Fat plug-in solves the problem of representing thickness/volume of the fat underneath the skin. At the start Boolean operations and double layered model was considered but the difficulty of this was that it made it difficult to animate both layer of surface while maintaining coherence. In the end a fat plug-in is created where the model is treated as a single surface and after the surface is modified or animated the fat surface is then automatically generated bellow the skin and textures are also automatically attached to the cut view of sides and bottom. This way the fat layer always coheres with the skin creating an illusion of thickness. Lastly the hook or forceps plug-in tool allows surgical tools to interact with the model. The animation team found tissue retraction difficult to simulate realistically with existing deformers and were able write their own simple algorithms for the plug-in.

The current CDs created for smile train is the phase one of the virtual surgery project. For the second and third phase of the project work are already in progress to create an interactive surgery simulation allowing users to make mistakes trying out surgery procedures and also to create their own surgery procedure or animation.

In [25] digital three dimensional model of human anatomy are developed for surgical education. Maya is being employed in this paper to create light weight polygon surface from the imported point-cloud data (fig. 5). NURBS curves are used to trace the surface contours of the structure of the point cloud and the surface curves acts as guidelines to form the new surface model.

Fig. 5 The processes of producing anatomical models in Maya by [25]

As pointed out by this paper there are other applications that interpolate the contours image slices to produce volumetric representation of anatomical structures. These models are generally complicated, making animation, deformation and rendering difficult. The advantage of Maya is that the light weight model generated by Maya is found to be easy to deform and to texture map. The reduced surface also has less hardware requirement. Other advantages of Maya noted are that the shader system within Maya can be configured for better visualization. For example turning objects translucent, to get a better view on something behind. Handlers/deformers can be added to objects to simulate surgery manoeuvres.

Other minor applications include Maya being used again for facial surgery simulation [26], where it is used to sculpt a 3d mesh models and also in modelling of skeletal structures. In [27] again a custom plug-in was created, this time it allows the interactive placement of bones and adjustment of join parameters. The advanced Maya modelling environment is used to assemble all the components interactively.

Maya has also been used for other biomedical application in the lower cellular and tissue level. Although not related to our focus we will brief mention about these two papers. In [26] Maya is used to generate the visual representation of cellular metabolism from output of an external program, 3D graphics and animation can then be produced. In [27] the author of the article found the learning process of Maya extensively large but they are impressed with the work flow efficiency of the numerous capabilities of the software. They believe that programmable, visually robust systems such as Maya have the potential to serve as a visual simulation tool for their studies.

2.4 Summary

Our review of biomedical applications of Maya suggests that it is not suitable for image acquisition, processing and visualization and computer assisted surgery. The reasons for this are that Maya is not designed to process 2D images and has no object volume representation. Maya might be useful for 3D surface reconstruction but the data has to be prepared externally and then imported to Maya in a recognizable format or as image files. Maya also seems to be unsuitable for computer assisted surgery and applications where a lot of accuracy and precision are required. As mentioned before Maya is designed for an artistic style of animation rather than industrial, so it focuses on aesthetics appearances and not physical realism. So applications where Maya would seem to be suitable and capable for are application where accuracy and physical realism is not crucial but usability, motion and visual quality is more important such as for visual surgery simulation, medical education.

From the past work reviewed we can see that Maya is used for its ability to produce quality light weight surface models and its powerful animation capabilities and to be able to produce expressive videos. Although most of the articles reviewed have only used Maya as a part of their project but nearly all of them has used Maya as their rendering solutions. This shows the value of Maya as a renderer. Another major advantage of Maya that many articles seem to take advantage on is that they created their own custom plug-ins and had resulted in positive effects on their projects. One article has praised Mayas usability and work flow, it described as highly efficient and very impressive. Other advantages mentioned are, Mayas modelling tools and interface is powerful and intuitive.

While there are many positive results but there are also negative ones. First of all, all of the articles seem to have used Maya for a short and specific task in their project. Only the smile train project where Maya is used for majority of the work. But the writer is already an experienced user in Maya and had many year of experience before hand. One comment from a new user of Maya for tissue modelling was that Maya has a very steep learning curve and takes new users a long time to get used to. More detailed short coming of Maya as pointed out in the smile train project was that Maya had a lack of representation for "thickness" or volumetric objects. Although this could be simulated by using Booleans and offset surfaces but becomes problematic during animation. For the animation side of Maya, although many deformers was included in Maya but the smile train team still found them self fine tuning each scene and spending a lot time on making adjustments.

One other thing that was mentioned in most papers is the version of Maya that they have used is quiet old, mostly Maya 3, 4 or 5. It was mentioned that although the older version of Maya may have some shortcomings or incompetence the functions of newer version seems highly impressive.

3. Investigation of Biomedical Structures

Areas of biomedical structures commonly modelled can be separated into four levels [4], organelle, individual cells, tissues, organs and systems. Although Maya can be applied to a wide range of areas as pointed out in section 2.4, the biomedical structures we will focus on are surgery related structures like organs and systems. In human anatomy the human body is normally divided up into functional parts, such as cardio vascular, respiratory and digestive systems etc [31]. Because we are only interested in the modelling and simulation of biomedical structures we will only investigate the geometric and the dynamic aspects of biomedical structures. Common functional properties of biomedical structures are ignored. First we will divide up the types of biomedical structures with our own categorization (fig. 6) according to their morphologies rather than their functionality. This will dramatically lessen the number of types and hence will simplify our analysis.

Type of biomedical structure	**Examples**	**Description**	**Related surgery**
Skeletal system	Bones, joints and teeth.	Includes all types of ceramic/hard tissues	Present in orthopaedic surgery and facial/dental surgery
Layered flesh	Skin (for outer layers), fat, muscle.	Layer flesh covering the whole body and bones.	Present in most surgery types. Often would be interacted with where a cut or insertion is required through the layer.
Blood vessels	Veins, arteries, capillaries.	Commonly found attached to most organs	Found in all types of surgeries because blood vessels are present in all organs and muscles.
Brain and Nerve system	Brain, Nerve fibres	The nervous system	Neurosurgery
Heart	Heart	Heart	Heart surgery
Hollow organs	Lungs, stomach, bladder, intestines, etc	Organs that is hollow because of containing air, blood or food.	Surgery involving any of the related organs.
Solid organs	Liver, kidney, Pancreas, etc	Organs that are solid, or at least can be treated as a solid object.	Surgery involving any of the related organs.

Fig. 6 Table describing the type of biomedical structures we have categorized

After identifying the main types of human biomedical structures we will now look at these structures in two aspects, firstly the shape and topology which relates to the modelling capabilities of Maya, secondly the mechanics which relates to the simulation capabilities of Maya.

3. 1 Shape and topology of biomedical structures

In this section we will look at the geometries of biomedical structures and this information will be used as a guide to modelling properties that Maya needs to capture. We have identified the following types of properties and its different characteristics.

- Surface - smooth surface with no sharp points and wrinkled surfaces
- Structure – solid, hollow and multiple chambers
- Outer shape- long string like, ellipsoid, branching
- Topology – sphere, pipe, complex (with holes)
- Symmetry – symmetrical, slightly symmetrical, no sign of symmetry

We create a table (fig. 7) of the above properties against the types of biomedical structures and a tick is drawn where ever one of the organs of the structure type displays the property.

Part 1	**Surface**			**Structure**			**Outer Shape**	
Structures	**Discontinuous surface**	**Smooth surface**	**Wrinkled surface**	**Solid**	**Hollow**	**Multiple Chambers**	**Long String Like**	**Ellipsoid**
Skeletal system		√		√				√
Layered flesh		√		√				√
Blood vessels		√			√			
Brain and Nerve system			√	√				√
Heart		√				√		√
Hollow organs		√	√		√		√	√
Solid organs		√	√	√				√

Part 1 of the table of biomedical structures and structure characteristic

Part 2	**Outer Shape**	**Topology**			**Symmetry**		
Structures	**Branch structure**	**Sphere**	**Pipe**	**Complex**	**Symmetric**	**Slight Symmetry**	**No Sign of symmetry**
Skeletal							

system			√	√		√	
Layered flesh		√		√		√	
Blood vessels	√			√		√	
Brain and Nerve system	√	√		√		√	
Heart				√			√
Hollow organs			√			√	√
Solid organs		√				√	√

Part 2 of the table of biomedical structures and structure characteristic

Fig. 7 Table used to describe the relationship between biomedical structures and the comprising structure characteristics.

As we can observe that most of these properties can occur in biomedical structures except discontinuous surface and axis of symmetry. Properties that are lacking in biomedical structure that maybe cause problems are complex topology, branching structure, no axis of symmetry and no parallel lines.

3.2 Mechanics of biomedical structures

The mechanics [28] [29] of biomedical structures is a very complex topic. Because of the complex morphology of organic biomedical structures it is difficult to measure and understand its behaviours. In the study of biomechanics the behaviours of biomedical organs are studies and modelled often with physically complex equations and highly mathematical. Because of Mayas "approximate appearance over physics" approach, again we will take a different approach to analyzing biomechanics of organs. We will focus more on apparent effects of dynamics on a higher level rather than going over physical details of mechanics.

The mechanics of an object is dependant up on an object's morphology. And the morphology of an object can be divided up to material property and structural property [29]. Both can affect the dynamics of an object. We will now take a look both individually.

3.2.1 Structure related dynamics

The dynamics of an object is highly dependant upon its structure and the orientation of the force for example a rubber band twice as thick as another rubber band is twice as hard to pull. Same principle applies to biomedical structures. Depending on the structure, different behaviour can occur in different directions or orientation of the force.

In biomedical structures there are obvious effects we would observe from the structural information. These characteristics should be captured in animation to improve realism. For example thin materials would deform easier and be less elastic, lose skin are easier to pull because it depends on what the skin is bound to. Because skin surfaces are elastic so when a cut is opened on the surface, the tension reduces and wrinkle is formed at the opening of the cut. A layer of skin and fat because each has different elasticity when cut open would cause the layer to curl outwards. When a strand of muscle is cut, each half squashes towards the end that it is attached to.

Structure related dynamics are more predictable to us compared to material based dynamics because we see structure and visualize it. Hence we can often predict or understand a lot of the effects that can happen. This allows us to be able to mimic the effects deformation of real organs in our animation.

3.2.2 Material related dynamics

There are two main types of tissues in the human body, hard tissues and soft tissues. Hard tissues refers to all types of ceramics, bones teeth etc. Soft tissues refer to all types of composites that are soft, such as muscles. Muscle tissue exists in three forms which all have different functions and behaviours. All organs contain one of the three muscles tissues. The skin of organ walls are made up of a different type of tissue called Epithelium.

- Skeletal muscle – muscles attached to the skeleton
- Cardiac muscle – muscles found in the heart
- Smooth muscle – muscles found in hollow organs such as digestive organs, blood vessels

Skeletal muscles are very strong and can contract as a response to nerve signals. Cardiac muscles are also highly responsive but contracts without excitation in a rhythmic pattern. Smooth muscle contracts slower but can maintain long duration of contraction and is used to move food or blood around the system. Smooth muscles contracts without excitation but can be influenced by its neighbours.

In order to better understand highly complex material properties it is often necessary to study the material's microscopic structure (microstructure). However, in order to model the overall behaviour of a material it is frequently sufficient to look at its overall behaviour (macrostructure). In our research we will once again limit the depth of physical simulation and we will only look at common biomedical characteristics reflected at the macrostructure level.

- Nonlinear elasticity – The deformation of the material changes nonlinear with the deforming force. Usually such a material is easy to deform at low strain and becomes difficult to deform as strain increases. Once the strain reached a threshold, additional stress will cause rapture in the structure.

- Anisotropic – The stress and strain relations of the material is directional dependant, common result of fibres such as the skeletal and cardiac muscles. Often orthotropic model is used as an approximation where three axes are used to define the stress and strain relations in the orthogonal directions.
- Viscoelastic – The material consisting of both viscous and elastic properties. Hence the deformation is dependant upon the time duration of the force. For example if a force is applied hastily the material would have a resistance to move but if the force is applied gradually then the material deforms easier. This viscous property is commonly seen in water or hydraulics problems.
- Large deformation – Because of the large deformation that most of these biomedical structures are capable of when they deform they change the shape and orientation of the original structure hence changing its dynamics. This is also difficult to model because the model used must be capable of handling large deformation without error.
- Incompressibility / Volume preservation – biomedical structures which contain a high amount of water are almost and can be assumed incompressible, i.e. their volume does not change with deformation. Then effects that will occur will be for example when a surface has to be deforms inwards, to preserve the volume the surface has to be deformed out wards in another deformation. The effect becomes especially apparent under large deformations.

In biomechanics, for each type of organ or structure, complex mathematical equations can be used to model its behaviours. Often different models can be used and each can have its own assumptions, approximations and approach. In a single structure such as the heart, there can be a huge area of research just on its dynamics.

4. Investigation of the Capabilities of Maya

Maya is a popular 3D modelling and animation computer graphics software package. Other popular modelling and animation packages today includes Softimage, 3D studio max, Light Wave 3D and blender. Maya is often regarded as the best 3d animation tool of its range [6] and it has a large user community. Maya is frequently used in the movie and game industry and is employed in the field of architecture, design and for the creation of promotional materials. Most of the current film and movie companies currently use Maya as part of their production [15]. Maya is highly integrated, flexible and open to plug-ins and customization. It comes with a good range of tools for the processes of modelling, animation, dynamics and rendering.

When Maya was first created, it aims to be a tool that is designed for artists [2]. It takes on an artistic perspective, with more focus on appearance rather than physical correctness. Maya aims to gathers functionalities that an “artist” would need to create his work and presents it in a user friendly graphical user interface eliminating the understanding of low level concepts and how things work.

In this section we will look at a few parts of Maya which are related to this project. First we will take a brief look at general benefits and highlight of Maya and the general advantages that it brings. For the main two focus of this project we will explore Mayas modelling capabilities and also its animation and dynamics capabilities. We will focus on functions that are important for biomedical applications. Lastly we will look at some of the flexibilities which distinguish Maya from its market.

4.1 General functions

Maya is a high end computer graphics package which means it hides tedious technical aspects and presents itself in an abstract and integrated package with an easy to use graphical user interface (fig. 8). Like all other integrated graphics packages with a long proud history, Maya is user friendly and contains a wide range of functions that increases usability, flexibility and customizability.

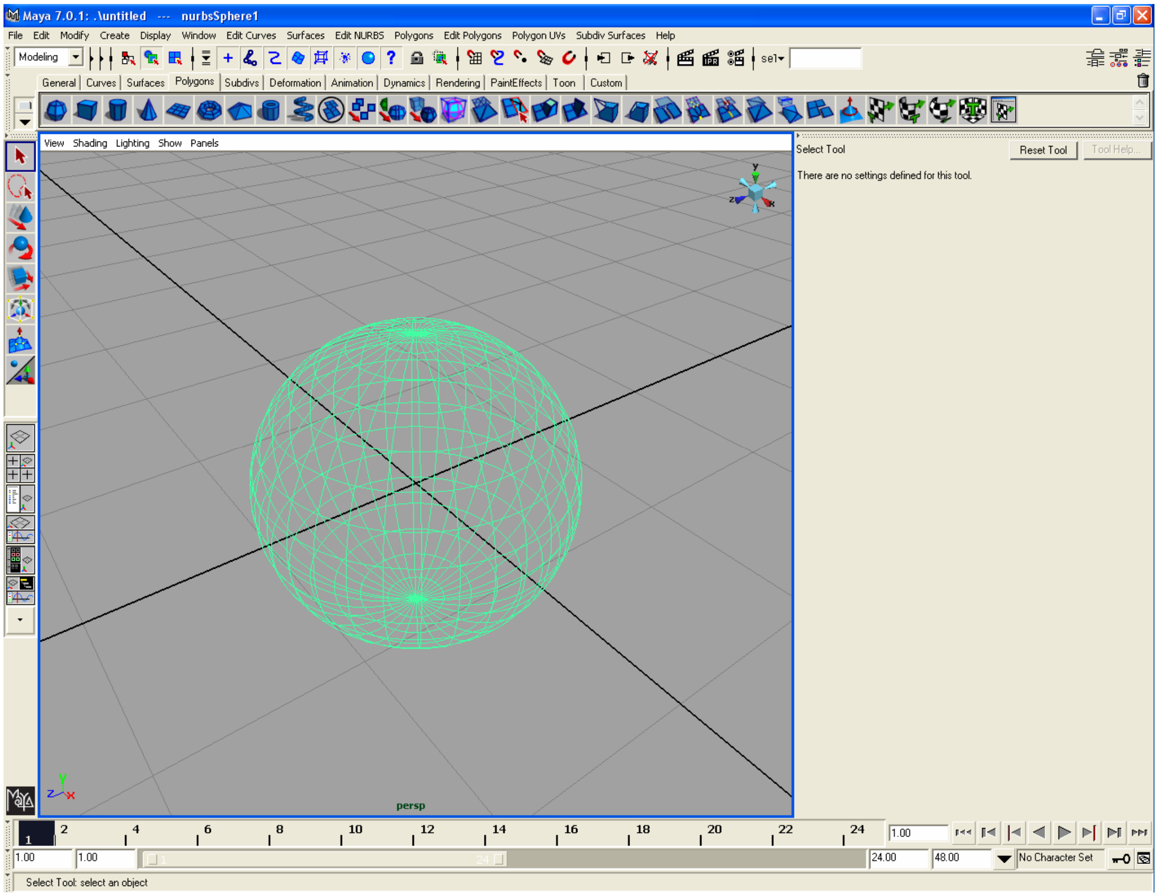


Fig. 8 Screen capture of Maya's graphical user interface

Mayas allows user to setup their own layout from the multiple views and menus available. In each view the user can configure the view such as the display type, camera type and hide/show components. The settings and parameters of tools and functions also can be saved and customized. The menu is categorized into the different sections of the process of computer animation, modelling, animation, dynamics, rendering. There are hot keys and right button quick menu to speed things up.

When creating a complex scene or object, there can be many components. This is complicated to organize or manage and creates problems for applying processes to the correct components. In Maya components can be arranged in parent/child hierarchies, a process applied to the parent will also affect its children. Processes such as textures, deformations or transformation are arranged as pipelines of processes applied onto a component. The processes are ordered and changing the order will affect the effect on the component. These can be viewed in the hypergraph for geometries and the hypershade for materials and textures.

Maya also allow the user to keep a history of all the modification, this not only allows the user to undo/redo but also allows to go back in history and to make changes to something and the changes can then the current state. For example if the user creates an ellipsoid by deforming a sphere, then we can go back in history and make a hole the shape of circle in the sphere the current ellipsoid will have a deformed hole in the shape of an oval.

All these functions that may be lacking in expert biomedical computer graphics packages become very handy when managing complex scenes, working on projects or reusing components.

4. 2 Modelling

The modelling part of Maya concerns with the geometric representation of objects. The three main representations available in Maya are polygons, NURBS and subdivision surfaces. These are all surface representations. They describe the geometries of an infinitely thin surface in 3D rather than volumetric data such as voxels. The only volume representation in Maya is particle systems and it is only used for dynamic effects such as water, fire, explosions etc. Because volume representation of objects is so crucial in biomedical applications, volumes can only be simulated by closed surfaces.

A general rule of thumb for modelling is that the more time invested on a model the greater detail and realism can be achieved. Hence theoretically most objects can be modelled by all types of representations. But different representations have its advantages and disadvantages. Each is suitable for certain types of models and types of techniques.
We will now investigate the three types of surface representation in Maya. For a full documentation of Maya functions refer to the Maya Documentation Lessons & Extras CD. We will only be discussing the advantages and disadvantages here.

4.2.1 Polygon

Polygons (ref sec 2.3.1) are the main type of representation in Maya. Components that the users can work within Maya are vertices, edges, faces and normals. Polygons can be created from geometric primitives such as cubes, cylinders, cones. Or they can be created from scratch using the create polygon tool. When manipulating polygons they can be extruded, subdivided or smoothed. Faces can be cut or a hole can be made. Polygons can also be sculpted and mirrored. To adjust the smoothness of edges the normals can be manipulated.

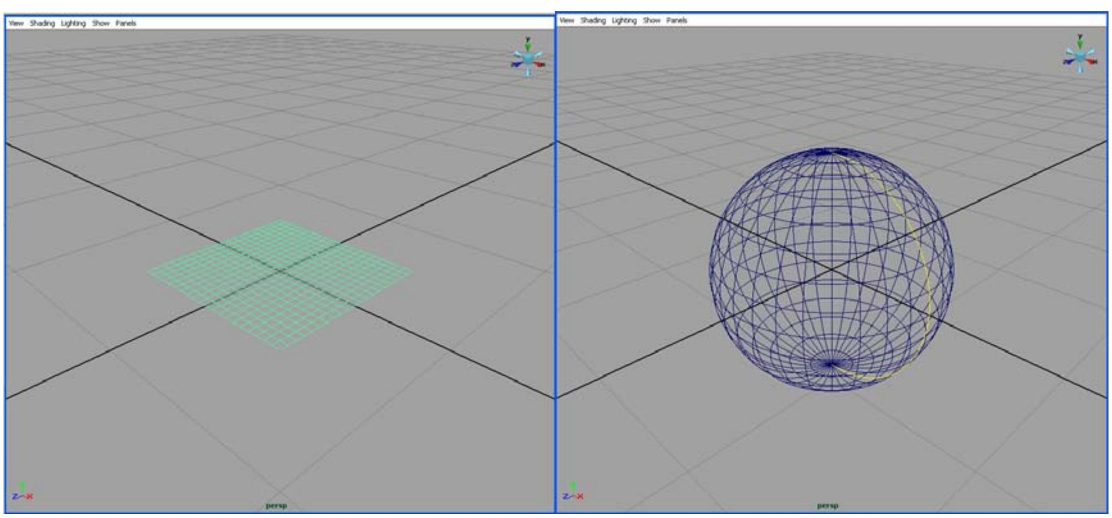
Polygons serve well for most industrial designs and blocky shapes. Most objects can be created by using polygon geometric primitives as building blocks and manipulating the shape. Even rounded objects, different techniques exist like rounding the corners or deforming a sphere. Polygons become difficult to use when trying to represent complex curves. Geometric primitives do not help with producing complex curved surfaces and trying to manipulate vertices while maintaining smoothness becomes unintuitive and difficult.

Because of polygon’s simplicity of representation they are easier and faster for texturing, rendering and applying dynamics. Also they ensure continuity and can represent complex topologies. Polygon are also easier for the user to visualize and understand the structure compared to other more mathematically complex representations.

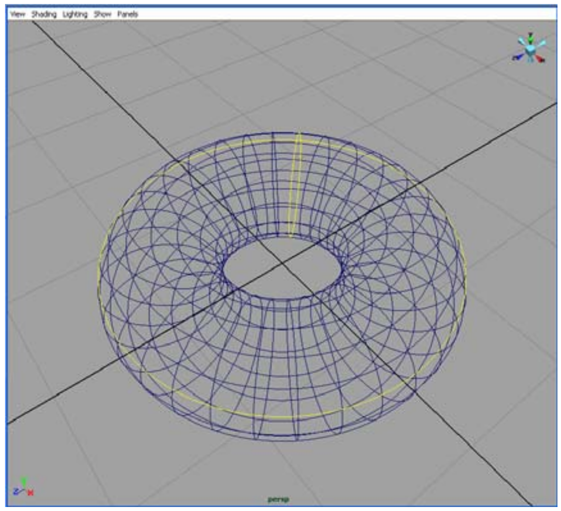
4.2.2 NURBS

Non-uniform rational B-splines (NURBS) are parametric splines used for curve and surface construction (ref sec 2.3.1), which are popular in computer aided design tools and are also used in Maya. The term "non-uniform" refers to the parameterization of the spline, the main advantage is that it allows multi knots. The parameterization can be uniform or chord length, each has its advantages and disadvantages. Rational refers to the mathematical property that the splines are normalized with the homogeneous coordinates allowing the exact representation of spheres and conics etc. B-spline refers to the type of basis function used in this spline curve. B-spline basis functions can be derived by repeatedly smoothing a box filter with another box filter which yields progressively smoother curves. A NURBS curve is defined by a series of control vertices, which influence the shape of the curve in a local area and usually do not lie on the curve. Edit points are also used to manipulate the curve but they lie on the curve and are composed of multiple control vertices. A NURBS surface is defined by a group of control vertices ordered in two directions u and v spanning a surface topologically equivalent to a plane.

When a simple NURBS curve is created it is considered open because in its ordered series of control vertices it has a start point and an end point. We can join the start of an opened NURBS curve to the end of the curve and make the whole loop of curve continuous. This would make the curve continuous through out and the joining position of the start point and the end point called the seam would appear smoothly. This NURBS curve is now considered to be closed. When a NURBS curve is closed it will enclose an area. When a NURBS surface is closed it will enclose a volume. Because a NURBS surface is ordered in two directions it can be closed in two directions. When a NURBS surface is not closed it is topologically equivalent to a plane, when it is closed in one direction it is topologically equivalent to a sphere and when it is closed in two directions it is topologically equivalent to a torus.



a. Plane　　　　　　　　b. Sphere



c. torus

Fig. 9 the three topologies that can be represent, by a single NURBS surface. The yellow line marks where the surface is joined together

This topological limitation restricts NURBS surfaces to the topologies plane, circle and torus (fig. 9). Like all things there are ways of going around this, in Maya stitching and trimming can be used. Think of NURBS surfaces as fabric and the two methods are self explanatory. Stitching is where NURBS surfaces are attached to each other at the edges. This is not particularly in solving the topology limitation but to attach two types of curves together. Trimming is where overlapping or unwanted surfaces are hidden which is normally impossible because of the topology limitations. For example if we want create a hole in the surface or attach two surfaces together. These methods are good ways of going around NURBS limitations and simplifying things. But is often difficult to use even by professionals [19] and is a hassle in post processes such as animation and texturing.

Now moving on to the positives, Maya provides an abundance of tool for the creation and manipulation of NURBS curves and surfaces. Advantages of using NURBS are that freeform shapes with complex curvature can be constructed from 3D curves. This generally limits the complexity to creating planar curves then they are interpolated or combine along a direction or curve to create the surface. Popular methods of surface construction from curves include by lofting, sweeping, bounding curves and rotation. Surface lofting is when contour curves are created then the surface is interpolated between the curves in order. Surface sweeping is when a curve is swept along one or more guiding curves which can alter the positioning and the shape of the sweep curve. Surface generation by bounding curves is when a surface is generated with one or more curves forming a closed area, different types of constraints can be applied. Surface generation by rotation is when a curve is rotated around an axis and the path of the curves forms a surface.

Because of NURBS long history with computer aided and industrial design it has a well evolved intuitive approach. It has been viewed as an intuitive way of creating and representing curved surface. Also because of its history, NURBS has been favoured by animators and modellers. But all this is starting to change with the introduction of subdivision surfaces.

4.2.3 Subdivision

Subdivision surfaces [18] are a surface representation used in polygon modelling where edges or faces are subdivided by computing new vertices as weighted averages of existing vertices. The subdivision operation increases the polygon count and smoothes the surface. The optimal subdivision level and hence the smoothness and resolution of the resulting polygonal surface depends on the user requirements.

In Maya subdivision surfaces are always converted from polygons or NURBS surface. There are two modes for subdivision surfaces, standard mode and polygon proxy mode. The standard mode represents the smoothed modelled after subdivision is applied. The proxy mode represents the original shape that you started with. This allows the user to at anytime modify the subdivided model or the original model and the effect will be reflected on the final result. Other than the two modes there is multiple level of interaction, in other words multiple level of subdivision. Higher level of subdivision having more components and each level is completely interactive. So for modelling if we want more global control we can do the modification in a lower interaction level and if we want more local control we can make the modification in a higher interaction level. As usual all of the changes in different interaction level reflect in the resulting surface and each can be applied in any sequence. Another benefit is that Maya only assigns more components to areas where it is modified in higher interaction levels. This allows models to be generally low detailed and partly higher detailed where there is complex curvatures. This cuts down on object complexity, computational time.

Because of subdivision surfaces' way of modelling, create a block model and subdivision will smooth it for you, it is widely welcomed by inexperienced users or users with little experience with freeform modelling. Experts and professionals on the other hand were slow and reluctant to let go of their spline curve techniques and habits. Both NURBS surface and subdivision surfaces are intuitive ways of modelling free form surfaces. But other than modelling techniques and type preferences, the topological limitations is where subdivision surfaces become superior in. In subdivision surface there are no topological limitations, the proxy can be used to model the blocky topology and rest can be modified in normal mode. The importance of this difference will soon be exposed in our results.

4.2.4 Summary

	Polygons	NURBS	Subdivision Surfaces
Description	Vertices are connected by linear edges to form a mesh representing the surface.	Parametric curve/surface representation using mathematical equations.	Surface defined by a low resolution polygon proxy and mathematical rounding operations resulting in a high resolution smooth surface.

Advantages	Standard representation suitable for fast rendering, animation, or portability. Can be mirrored to simplify modelling Good range of modification, manipulation and simplification tools. Can represent complex topologies	Smooth curves well suited for modelling organic forms. Have many functions and tools for easy creation and manipulation. Allows creation of surfaces from curves by sweeping, lofting and bounding curves. Allows creation of fillet curves and smoothing joints. Allows trimming and stitching to form complex surfaces.	Smooth curves well suited for modelling organic forms. Intuitive way to model, by modelling the rough blocky shape first and then smoothing it. Takes a hybrid approach, allowing users to modify the polygon proxy as well as the smooth proxy. Allows modification at multiple levels of detail. Allows creation of creases. Can represent complex topologies
Disadvantages	Unintuitive to model and manipulate	Can not represent complex topologies	Not all deformations can be applied to subdivision surfaces.

Fig.10 The advantages and disadvantages of the Maya surface representations summarized in a table

4.3 Animation

The term "animation" in Maya differs from the term "simulation" used in biomedicine. Simulation refers to the mathematical modelling of the real behaviour of a biomedical structure, whereas animation refers to the creation of motion over time. An animation is not necessarily realistic and usually is not the result of a physically-based equation, but is created by a human animator who changes an object's position over time. To animate scenes, Maya allows the user to use key frame animation which interpolates key framed objects in a scene over times. Nonlinear animation with Trax allows user to create animation by frame based and then the frames are fine tuned to time. Trax is a clips editor, which allows user to adjust the timing of frames in clips and to cut, edit and combine clips into an animation. Path animation gives users more control and power to animate nonlinear transformation of objects. Motion captured animation are available to animate motion from captured data. For a full documentation of Maya animation capabilities refer to the Maya Documentation Lessons & Extras CD. Because we are more interested to simulate the behaviour of biomedical structures, how objects deform. We will investigate the deformers supplied in Maya just as mentioned in the smile train article surveyed earlier.

4.3.1 Deformers

Deformers are effect nodes which deform a group of deformable objects. Deformable objects can be polygonal vertices, lattice points, NURBS curves and NURBS surfaces. In Maya unlimited subdivision surfaces are also deformable. Multiple deformers can be applied to a surface and the order of the deformers affects the result of the deformed model. We will now investigate the different types of deformers in Maya.

4.3.2 Blend shape deformer

Firstly, blend shape deformer is one of the main types of deformers because it can blend the effects of multiple deformers or transformations. Blend shape deformer is a deformer which morphs based shape to a target shape. The resulting shape of the deformer is called blend shape. Multiple target shapes can be blended to the blend shape. For example, one target shape can be a twisted based shape and another target shape can be a bent based shape. So when the base shape is blended towards the target shapes the resulting blend shape is twisted and bent. The influence of the target shapes on the base shape can be set. A number represents the influence, where 0 represents no influence and 1 represents full influence. Numbers less than 0 and greater than 1 can also be used but the effects can be unpredictable.

Blend shape can be used to morph shapes of equal topology or shapes of different topologies. When used for shapes of equal topologies, it is often that a copy of the base shape is made and the points of the shape are deformed using deformers or other methods. The blending moves the matching point of the base shape towards the new location of the point in the target shape.

4.3.3 Nonlinear deformer

This type of deformer is characterised by a non-linear relationship between the position of a material point and its deformation. Examples are bend, twist, sine, flare, squash and wave. The bend tool allows user to bend an object by assigning the curvature and the length that the curvature will affect. The twist tool allows the deformation of objects by twisting. The Sine tool allows the bending along an axis according to a sine function. The flare tool allows the scaling of objects in both ends. The squash tool simulates the squashing of an object, on either or both sides. The wave tools are similar to the sine tool except the sine way propagates in two directions creating a wavelet like a wave ripple in water.

4.3.4 Cluster deformer

Cluster deformers allow the users to apply a transformation to a group of points. The influence of the transformation can be dampened for each point so that a percentage of the transformation influences the point. Maya allows you to assign the point weights intuitively by painting the weights onto surfaces. This allows the user to create a fall off of a deformation along a surface according to users painted weights.

4.3.5 Soft modification deformer

Soft modification deformer allow the user to pull and push on a surface. The effect of the user is highest at the centre and falls off with distance. This deformer allows users to interact with a surface realistically like with skin, clay or cloth. Soft modification allows the user to adjust the fall off of the effect in order to better represent the material. Soft modification is often used to deform parts of the human body when fine tuning animated characters.

4.3.6 Sculpting deformer

Sculpting deformer use a NURBS surface to influence the shape of another surface, useful for sculpting rounded surfaces. This is common technique used in character setup and skinning. For example an ellipsoid can be used to help sculpt the shape of the elbow, to ensure that it stays rounded all the time.

4.3.7 Wrap deformer

Wrap deformer is similar to sculpt deformer where an influence object can be used to deform a surface. The deformation results in the appearance of the surface being wrapped around the influencing object.

4.3.8 Lattice deformer

Lattice deformer is a type of free form, space warping deformer which influences the space contained by the lattice. There are two parts of the lattice structure, the base lattice which is the original lattice that you start with and the influence lattice which is the lattice after you modify it. The deformation of the deformable object within the lattice is dependant on the differences of the points of the base lattice and influence lattice. You can modify the weights of lattice points to alter their influence on the deformable model.

4.3.9 Wire deformer

Wire deformer is like using sculptors’ armature to shape objects. One or more NURBS curve is used to influence the shape of an object. The NURBS curves used here are all called wires. The base wires are the original positions of the wires, once the wires are transformed they turn into the influence wires and the deformation of the object is calculated by differences of the influence wire and the base wire. Holder wires can be used to limit the area of the deformation effect. Wire deformer is similar to the lattice deformer, except instead of manipulating the shape of the space around the surface it is manipulating curves on a surface.

4.3.10 Wrinkle deformer

Wrinkle deformer is yet another type of deformer driven by the need of shape manipulation for character setup used in the processes of simulating realistic wrinkle effects. Wrinkle deformer combines wire deformer with cluster deformer to create wrinkles on the surface in order to create detailed wrinkles.

4.3.11 Point on curve deformer

Point on curve deformer is a deformer applied to NURBS curves so that you can move certain points on the curve. This aids in the process of modelling where you can move the curve directly rather than only using control vertices.

4.3.12 Sculpting tool

Sculpt tool is a tool that influences the shape of an object by using an intuitive sculpting interface similar to that of a clay sculptor. It is similar to a deformer, except it is representation specific. The sculpting tool allows the user to push, pull or smooth the surface in the direction of the normal. Basically the sculptor changes the displacement of the points on the surface along the normal. It allows the user to define the sculpting interface which can change the area and the size of the influence. Although sculpting tool exists for all types of representations, it works best for NURBS surfaces because the smoothness of the surface is always guaranteed. Sculpting tool is useful for modelling objects and also useful as deformer.

4.3.13 Summary

While Maya implements a few physically based modelling functions, most of them use approximations to simulate the type of deformation and do not incorporate material properties. However, as can be seen from numerous movie special effects applications a skilled designer and animator can create visually impressive and realistic looking results with Maya.

5. Results

From our investigation and our back ground research we will now explore the functions of Maya by attempting to create implementations that would demonstrate or capture biomedical geometries and dynamics. We have tried different approaches and methods in trying to capture different geometries and dynamics. The following are our findings.

5. 1 Modelling

We have experimented and tested with the many models and the following are the successful approaches we have discovered and some limitations we have reached. We devised the following series of techniques to capture some of the biological geometric properties described earlier with Maya modelling techniques.

5.1.1 Spherical topology by Subdivision surface

First we attempted to model a simple round shaped organ that is topologically equivalent to a sphere. This is because from our investigation, we find that most of the organs outer surface is roughly topologically equivalent to a sphere. These types of organs are commonly used for surgery simulations where the main objective is that the user recognizes the object and can interact with it realistically. We chose a liver here, because it is often simulated with a simple overall shape but yet its flattened bottom and the curve near the bottom are unique characteristics which may prove difficult to capture. We will use subdivision surfaces because we want to be able to prototype these simple models quickly and efficiently and through our initial investigation we found that subdivision surfaces to be an intuitive type of surface representation. Because that livers tend to appear in different shape and sizes depending on the text that it appears in we have chosen to use the image of a liver (fig. 10) as a reference for our modelling.

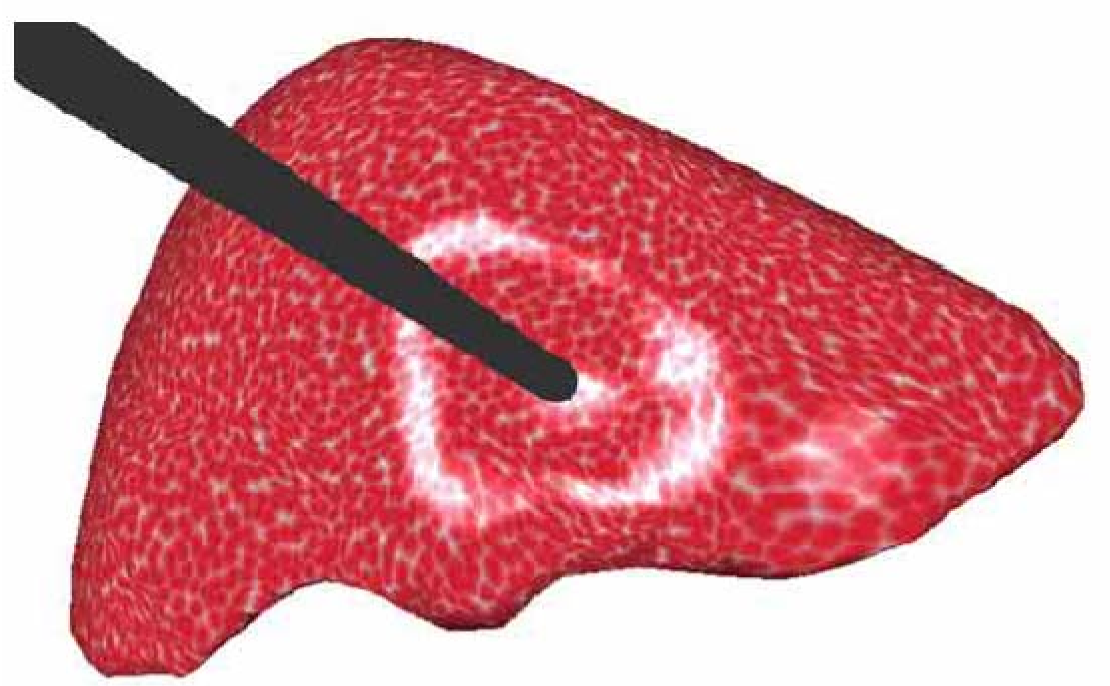
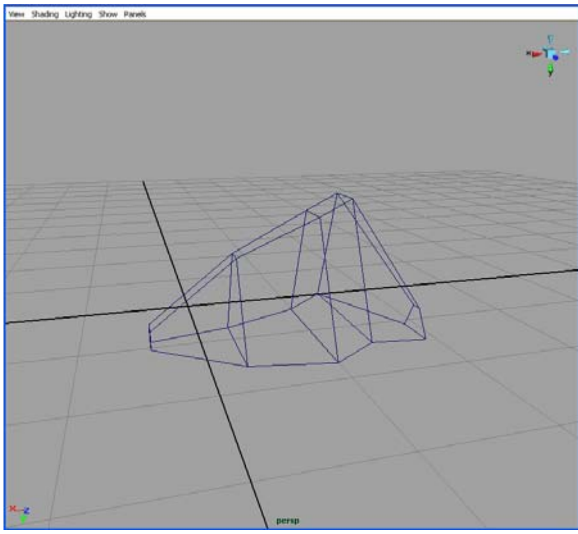
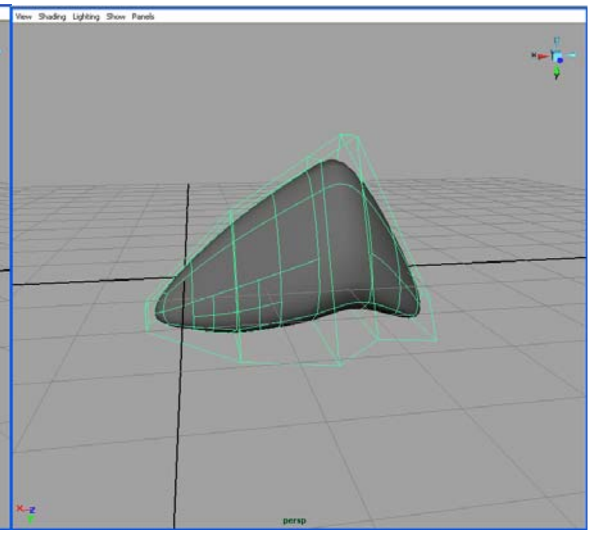


Fig. 10 Image of a virtual surgery simulation involving a liver model
(©1995 Communication of ACM [6])

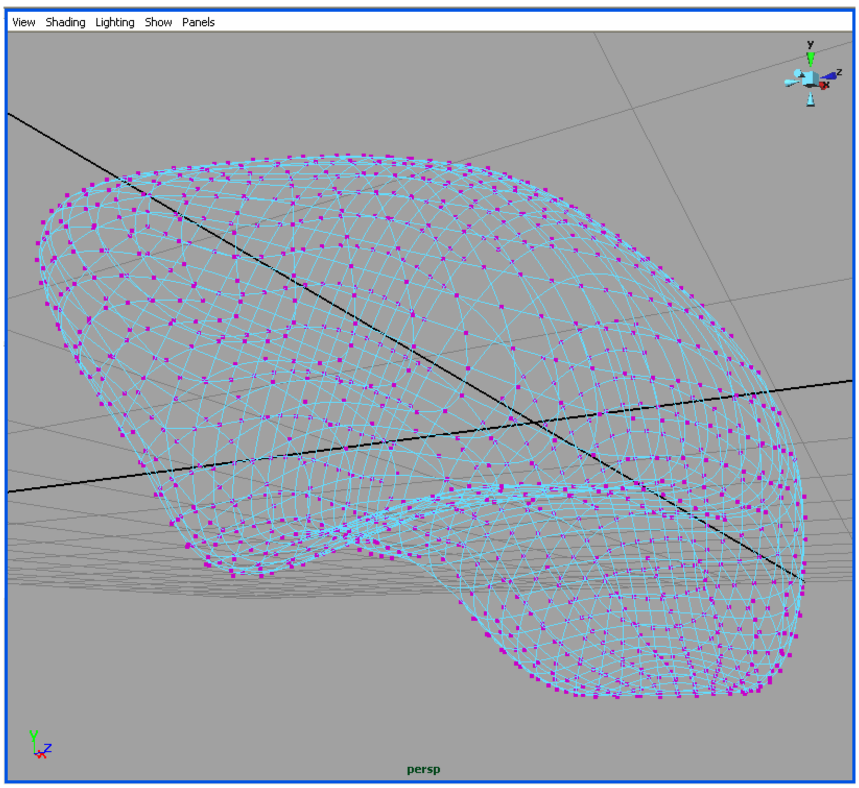
We first created the general shape (fig. 11a) of our liver using polygon representation. This shape then acts as the polygonal proxy which generates a smooth subdivision surface (fig. 11b). The polygonal proxy is resized and adjusted to make the shape of the smooth subdivision surface closer to our ideal liver. Then the interaction of the subdivision surface is turned up higher and we modified the details around the higher curvature areas trying to better represent the shape of the liver and also to add some irregularity to the symmetry (fig. 11c). Finally a quick procedural texture, lighting and props are added to the scene and it is rendered (fig. 11d). As you can see the results are reasonably good compared to the sample image used. In shape-wise, it looks naturals and smooth and the shaper bulges of the base can clearly be observed. The proportion, lighting and texture may need additional tweaking but it looks very good generally. Especially when it is created by hand from scratch and it only took around one hour to complete the model.



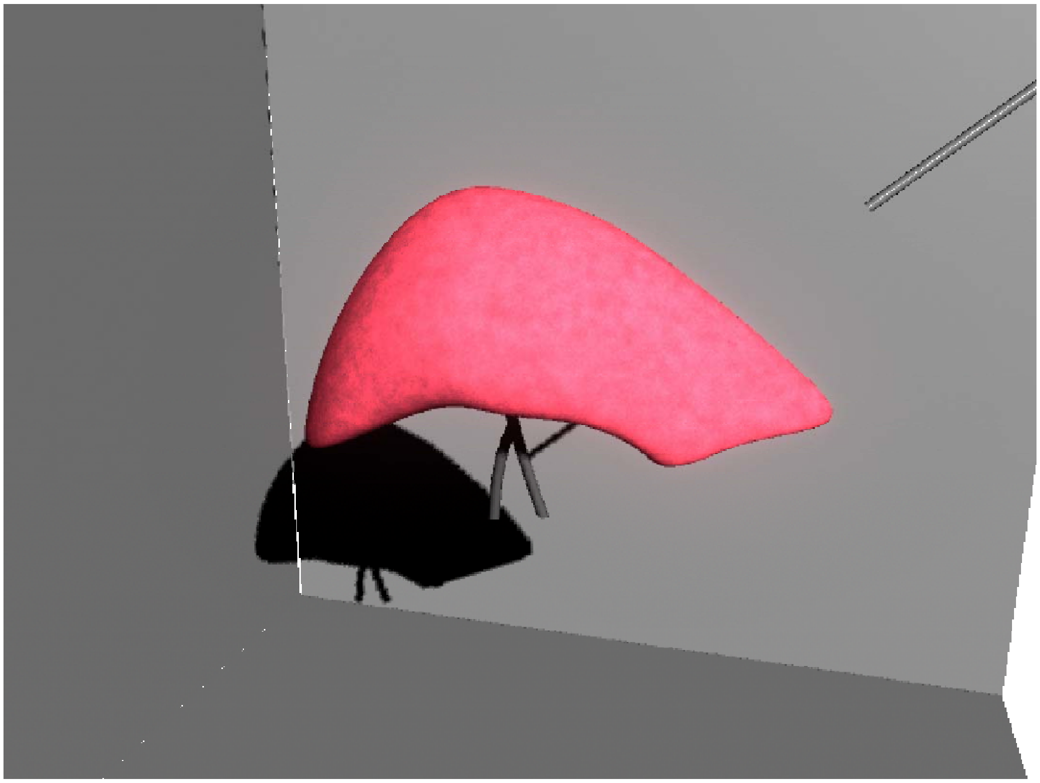
a. Polygon proxy



b. subdivision surface applied



c. The model further refined

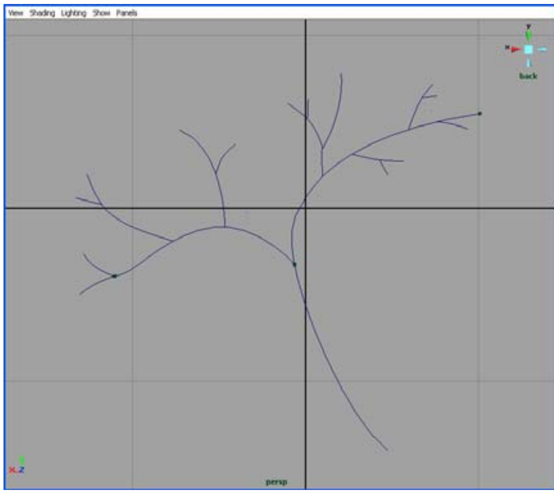
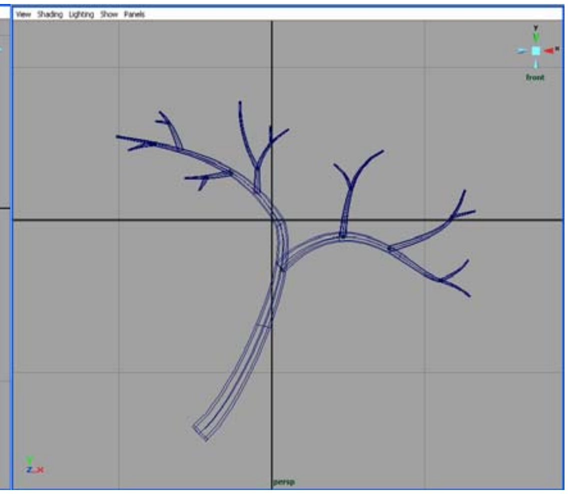


d. Rendered model

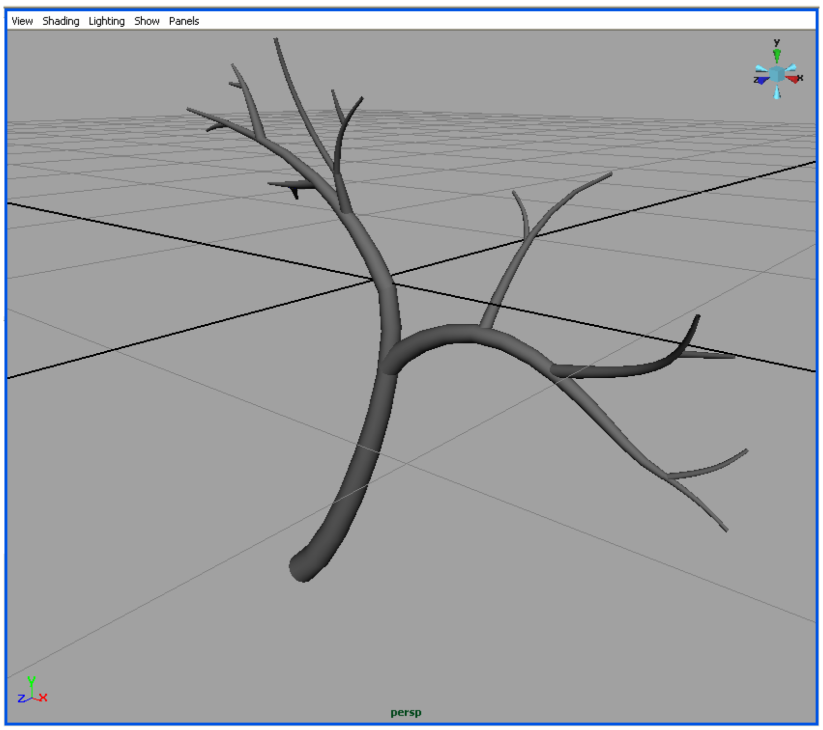
Fig. 11 Liver modelling using subdivision surface

5.1.2 Branching Structure by Sweeping

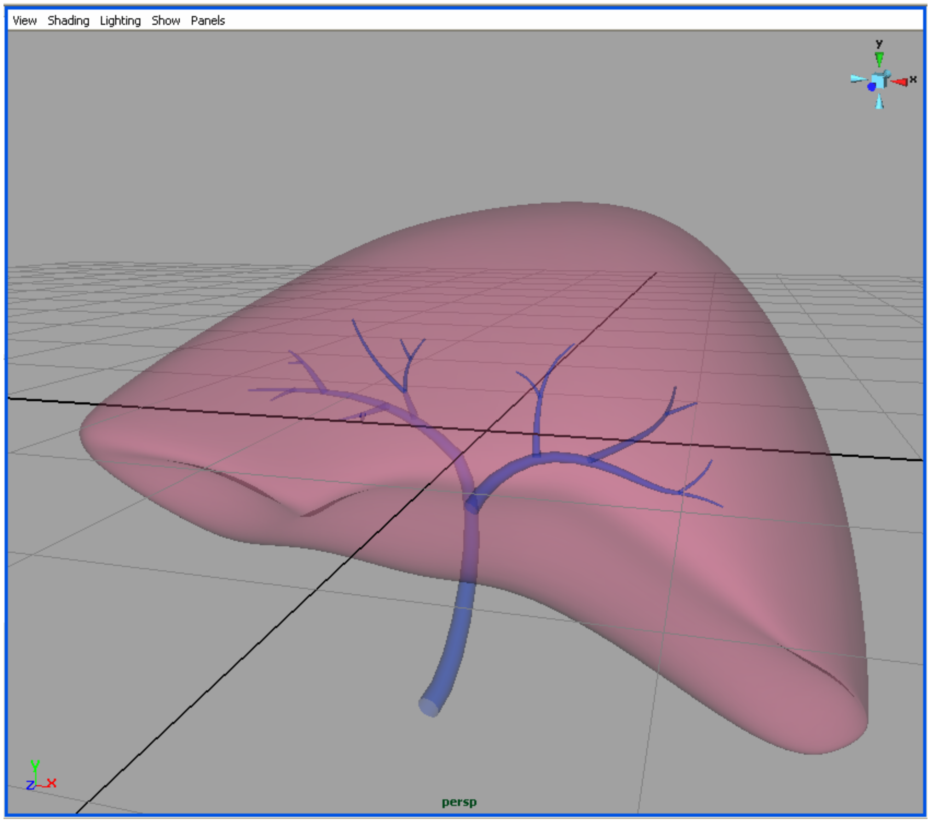
The second types of structure we attempt to model are branching structures such as airways and blood vessels. This is a common type of biomedical structure that we have identified earlier. It provides a complex branching topology and may require the joining of multiple models. We decided to model the Portal vein of the liver, because it fits well with our previous model and it is not overly complicated. This one it took longer to create, the first few days we ran into some problems but once the problems were solved it took around 2 or 3 hours to model. We had to have several attempts and the scene had to be restarted several times. The NURBS curves are hard to get use to at first. First we create NURBS curves representing the structure of the blood vessel (fig. 12a). Then circle is swept along the curves to form the 3D shape of the blood vessels (fig. 12b). Because of the branching structure is composed of many NURBS curves, we hand to attach the surfaces together (fig. 12c). Remember NURBS curves are ordered. Hence one NURBS curve can not span a branching structure. Lastly the portal vein that we have created is combined with the liver we produced previously and colours and transparency are applied to help with the visualization (fig. 12d).

a. structure curve lines b. swept surfaces of blood vessels



c. 3D blood vessels



d. blood vessel combined with liver
Fig. 12 Modelling of blood vessels using NURBS

5.1.3 Limitation of NURBS surfaces

One of the resulting limitations from the previous model is that each blood vessel "tube" is an independent NURBS surface. It became very difficult to join the model together. We used a method called trimming (fig. 13), which removes the surfaces that is within each other. It gives an illusion that the NURBS surfaces are joined together. This can seen below, it is not very realistic. The joint between the two NURBS surfaces are clearly creased and no rounding operations can be applied since the two surfaces are still physically apart. Painting and vertex adjustment methods might be able to be used to hide this visually.

This joining of multiple NURBS surfaces are forced because of the NURBS surface limitation problem mentioned previously. This provides difficulty when ever we want to model NURBS surfaces with more than 2 holes or openings.

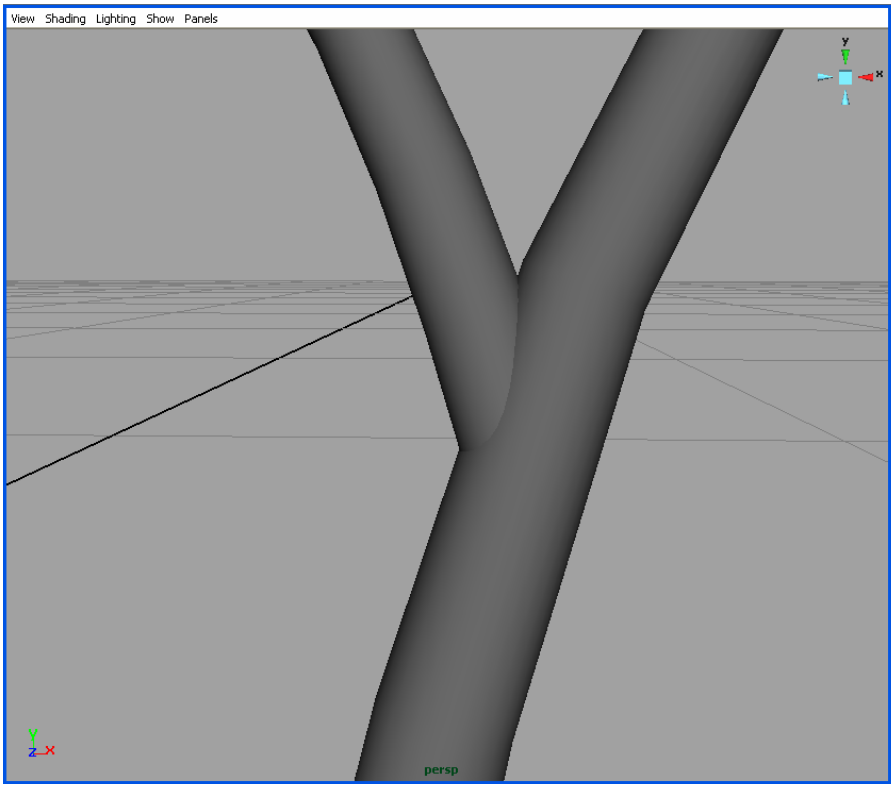


Fig. 13 the joint of two NURBS curves of branching blood vessels

5.1.4 Topology modelling with subdivision surfaces

A solution for this type of topological problem is subdivision surface. Subdivision surfaces allowing the modelling of structures with complex topology while maintaining the ability to model smoothly. Below is an example of the blood vessel brunch (fig. 14). A "blockish" blood vessel is first modelled with polygons. When the topology and shape is as desired, it is converted to subdivision surface. Then the vertices are further refined to get the shape of the blood vessel, especially around the joint area where tweaking is needed. Lastly the faces on the ends can be deleted to reflect the hollowness of the blood vessels.

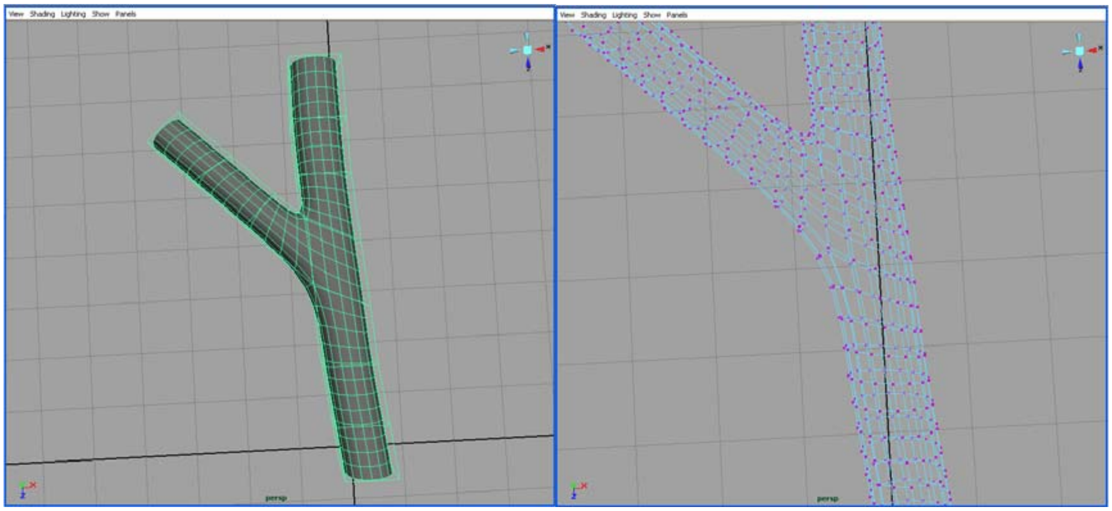
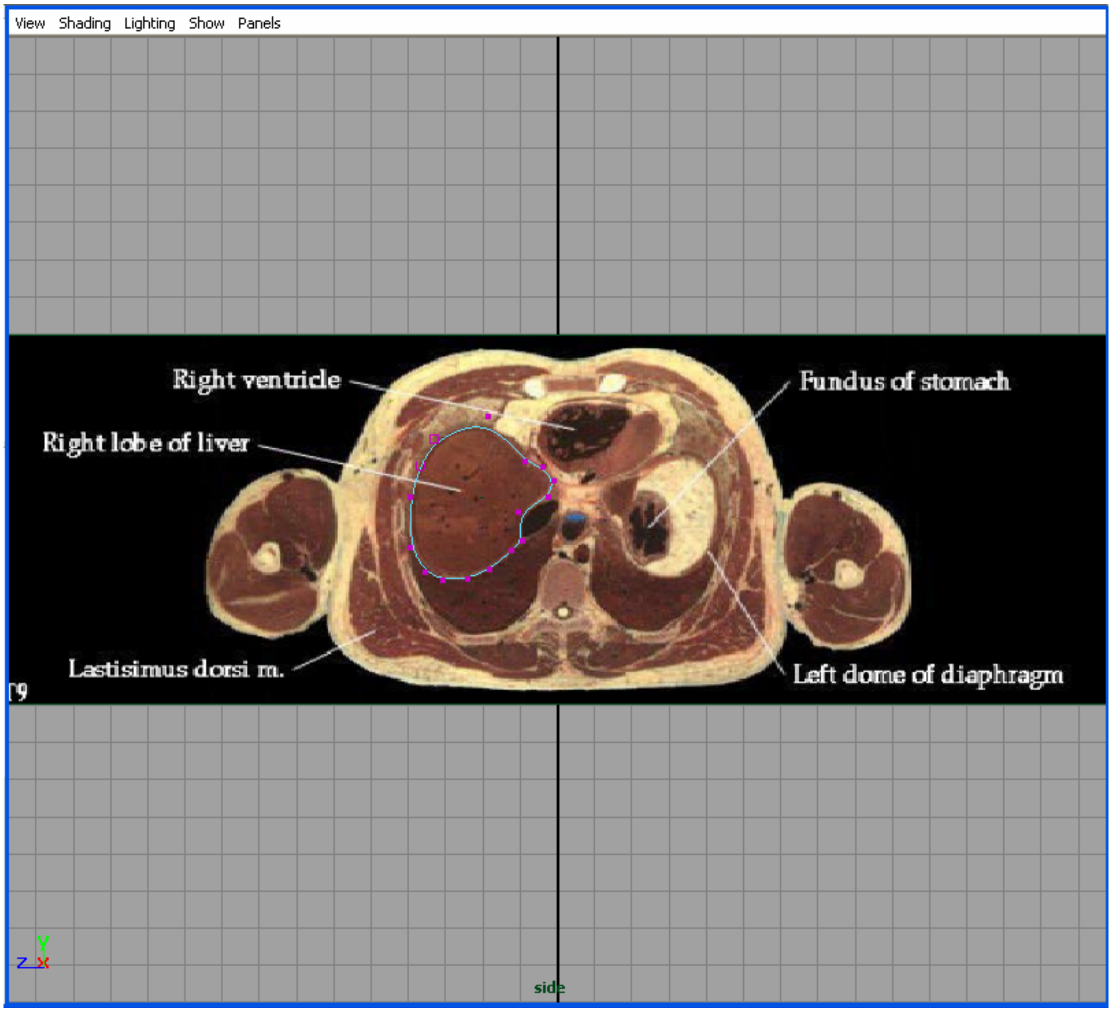


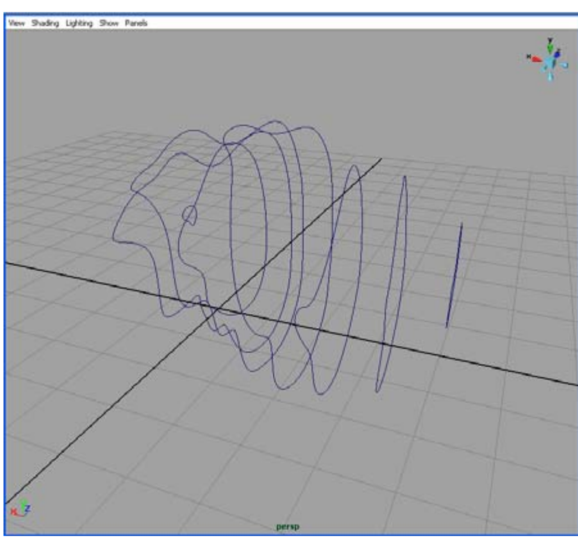
Fig. 14 a joint of blood vessels modelled by subdivision surface

5.1.5 Medical image modelling by contours lofting

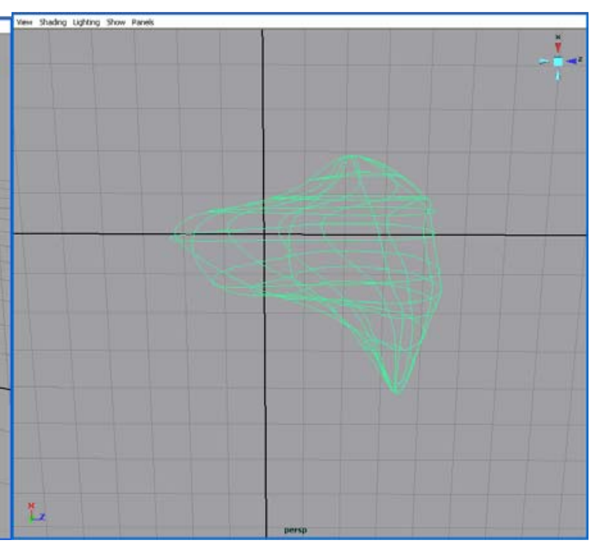
Next we attempt a more difficult but more accurate method. This method is similar to current methods surveyed that use CT scans to reconstruct 3D anatomy models. This is a good way to model biomedical structure because although biomedical structures tend to be complex but they generally have well understood contour information from medical imaging data. We will again model the organ liver and results can be compared to our first model. For this method we use prepared and processed images from the Visible Human Project [24] to build up our models. We first gather up all the slices of images required. Then for each image we identify the boundary of the liver by fitting a CV curve around it (fig. 15a). When this is done for every image, a series of contours are formed (fig. 15b). Then we can use these contours to interpolate into the surface of the liver (fig. 15c). This shape then need to be resample and smoothed to reduce the twisting caused by the different sized contours and the sampling artefacts (fig. 15d).



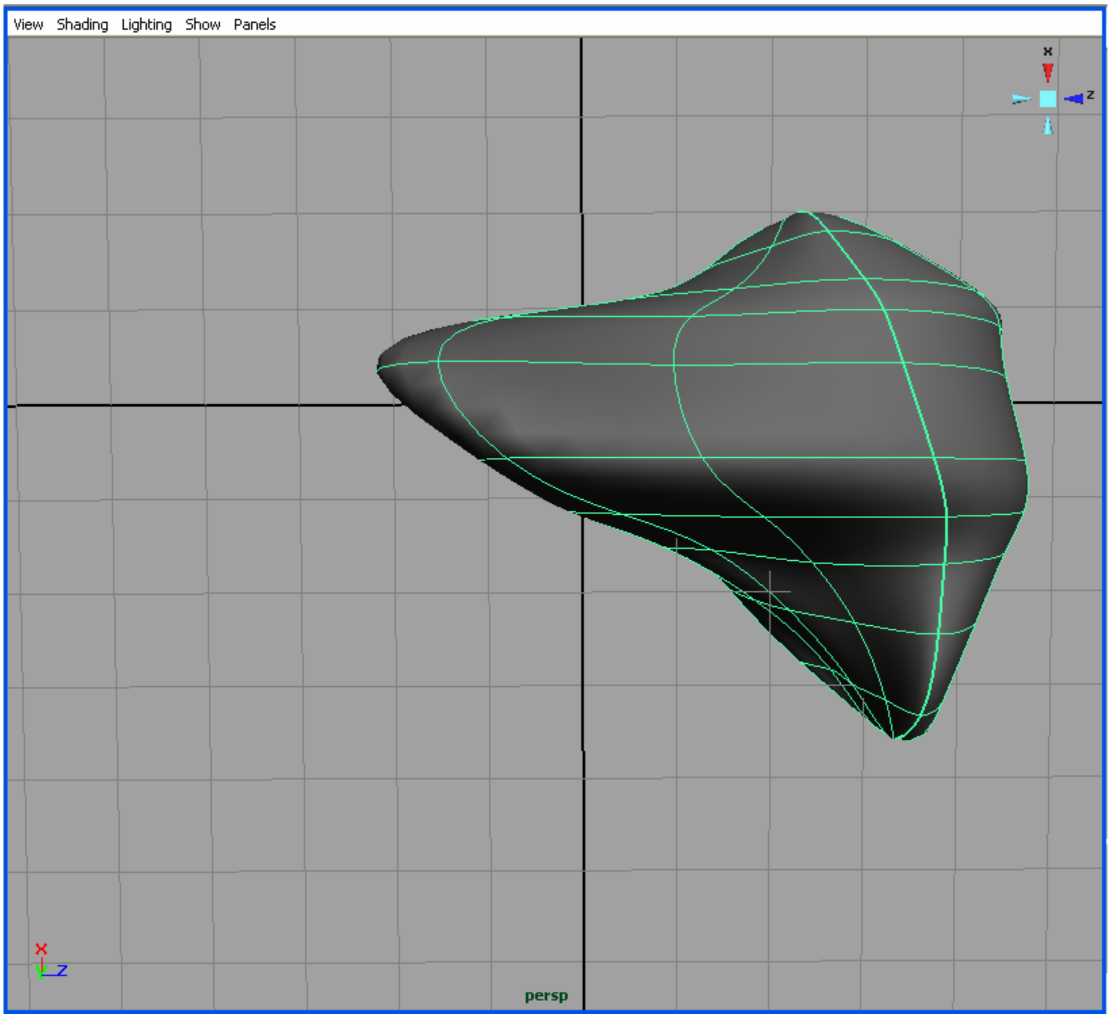
a. a NURBS curve used represent the contour of a medical image



b. a series of contour curves



c. the lofted model

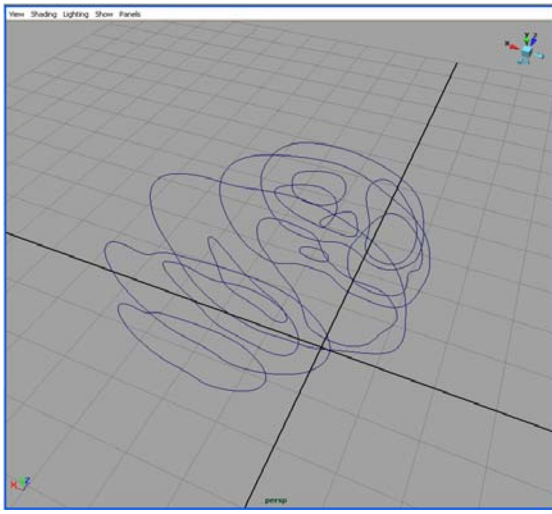


d. the final refined model.
Fig. 15 Liver modelling with NURBS surfaces

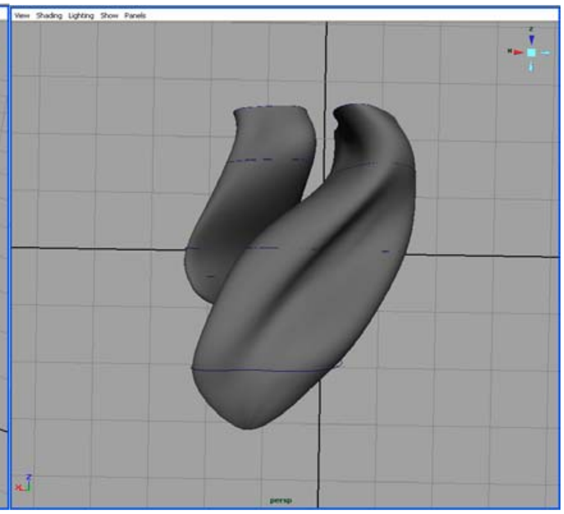
5.1.6 Complex topology modelling and its limitations

The next model that we will attempt is again difficult to model. But this time we will attempt to model something with complex topology. This is to test how well Maya handle objects with complex topology. We chose to model the heart because of its multiple chambers and also it has been modelled by many researchers. In this model again we went with the medical image modelling method. This is because of our limited medical back ground we find it easier to model based on medical images.

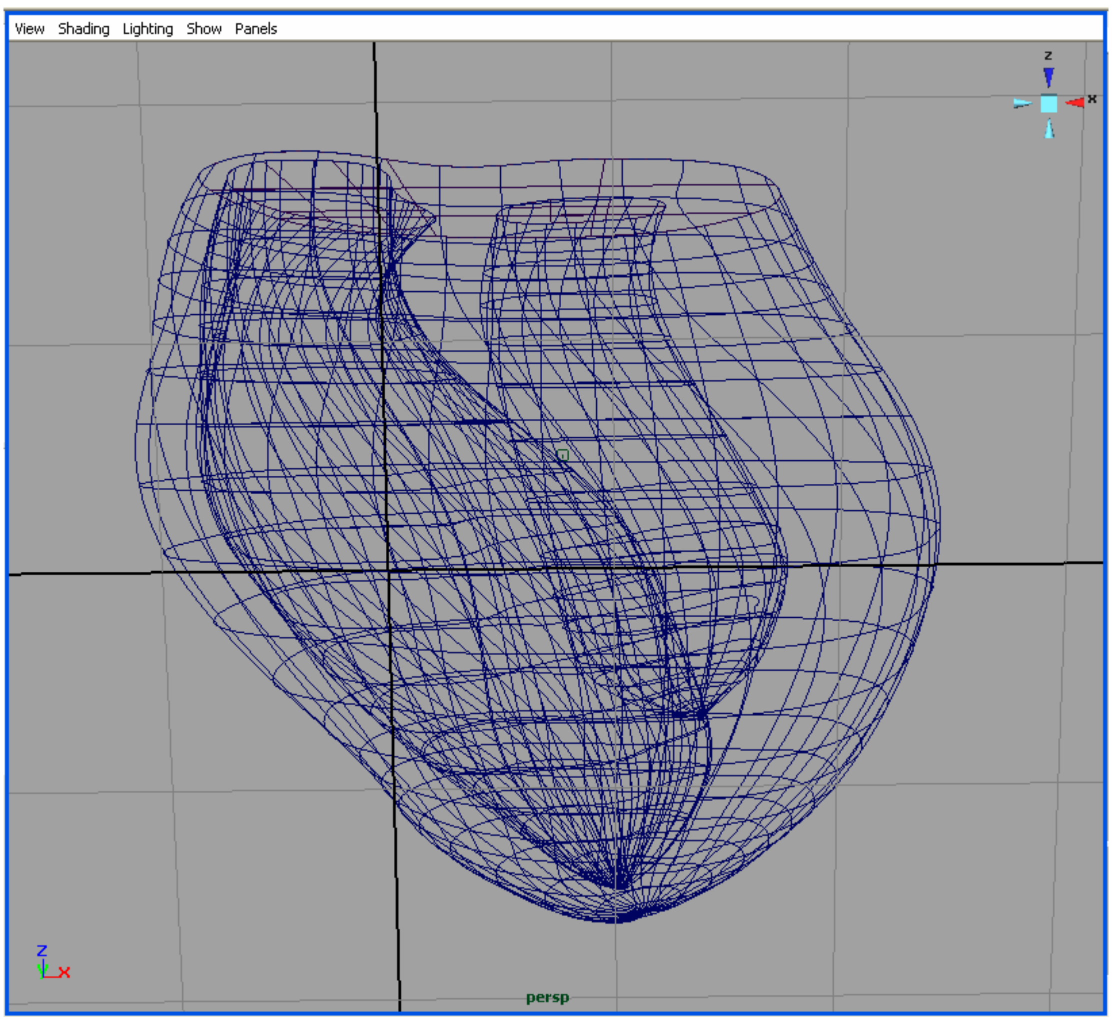
The same method as above is used, but except this time we have multiple contours (fig. 16a) because of the complexity of the topology. After studying a medical diagraph of a heart we were able match the boundaries with the structure of the heart. So we first lofted the inner surface of the left ventricle and the right ventricle (fig. 16b). Then the outer surface is produced in the same manner. Now we have produced the main part of the heart (fig. 16c). Afterwards we tried to also add on the additional blood vessels connecting to the heart but we ran into many problems and found it difficult to attach the NURBS surfaces together.



a. contours of the lower heart



b. the surface of the ventricles

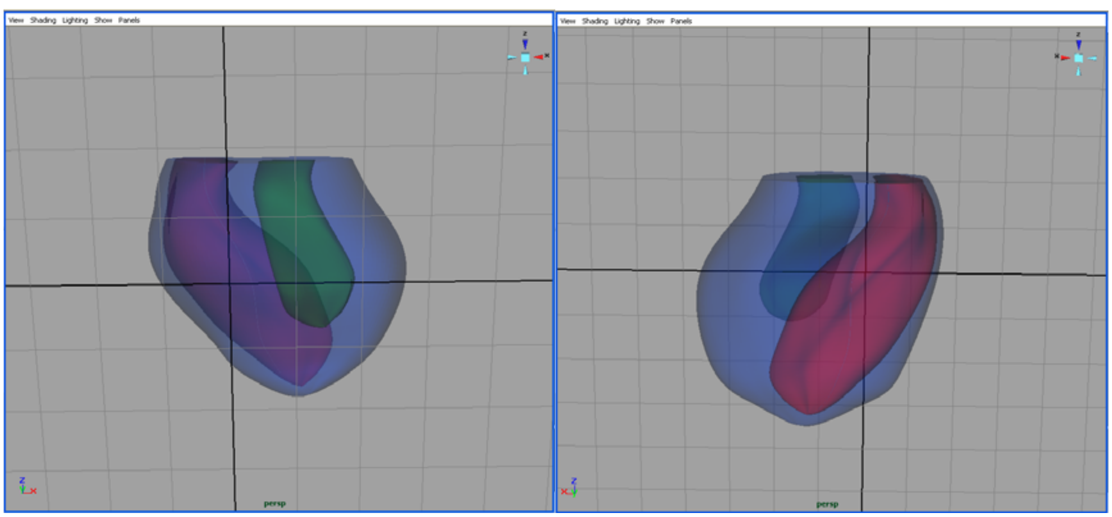


c. the model of the lower heart, including the outer surface and the boundaries of the left and right ventricles.
Fig. 16 modelling of heart with NURBS surfaces

5.1.7 Volume representation by Booleans

The previous examples all involved modelling the boundary surface(s) of a biomedical structure. Volumetric representations, e.g. thick sections of tissue, can be simulated using Boolean operations. A new mesh can be generated from the union, subtraction or intersection of the volumes of the enclosed surfaces.

For our model, because of the difficulties we ran into with using NURBS surfaces, hence we decided to convert the NURBS surface to polygonal surface. And a Boolean operation is used to take away the left ventricle and the right ventricle from the main body of the heart in order to form a new mesh. In the below images (fig. 17), colours were added to help visualize the structure of the heart. Our result can be compared with a similar heart in [10] and it can be seen that the two models are very similar. Our model although does not include connective information between the inner surfaces and the outer surface, it captures a very natural twisting characteristics of the left and right ventricles. Note the shape of the two models can never be compared in detail, because the heart came from different medical data. The heart can be in a very different state, especially when the data from the Visible Human Project came from a cadaver.



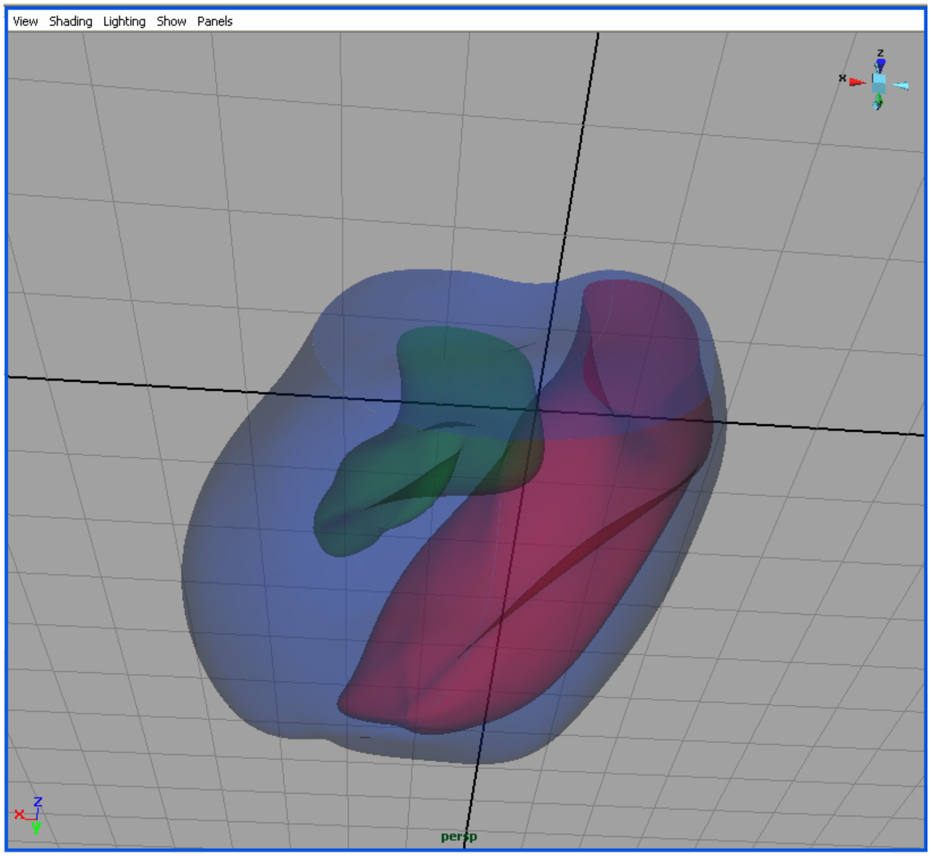
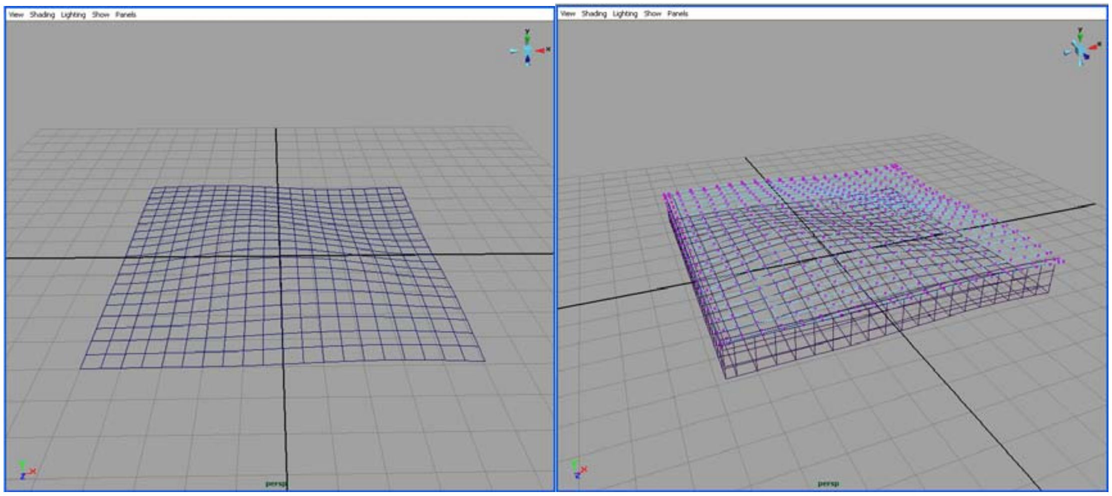


Fig. 17 The combined model of the heart with presudo-colour added

5.18 Volume representation by offset surface

We demonstrate an alternative method to model volume in the flesh by using offset surfaces. The top layer of the skin (fig. 18a) is modelled using a standard surface representation and a volumetric representation of the corresponding tissue section is obtained by offsetting the surface by a user specified amount (fig. 18b). This method is more suitable for creating layers of skin or flesh. It essentially allows the user to model the surface of skin and the layer is automatically generated using offset surfaces.



a. surface of the skin b. layer of the skin

Fig. 18 Volume representation by offset surface

5.2 Simulation

In our tests, we focused on using deformers to help us achieve the deformation that we need. But we were unable to obtain any nontrivial deformation. We had problems deforming multiple layers representing volume. We had problems with blending changes in topology. Also we had problems in applying the deformation to our models. This maybe caused by the mesh of the model or the setting of the parameters. We were unable to solve these problems.

We found the simulation of biomedical structures in Maya very different from physical based approaches that would that would typically be used. Since in our animation we do not deal with forces, then we don't have to worry about the physics of it. We can assume what ever we touch with our surgical equipment will move instantly. All forces acceleration and velocity are not accounted for. So the degree of deformation does not have to be calculated but still the way the object deforms still needs to be simulated realistically. Whether if the surface forms a small curvature around the surgical instrument or a large curvature depends on the elasticity of the object.

From the tests and experiments we ran on single surfaces we found that the soft modification deformer (fig. 19) and the nonlinear deformer were useful to simulate the elastic deformations of objects. Because they can capture homogenous dynamics common in everyday life such as bend in an iron bar, squash of rubber and ripple of water.

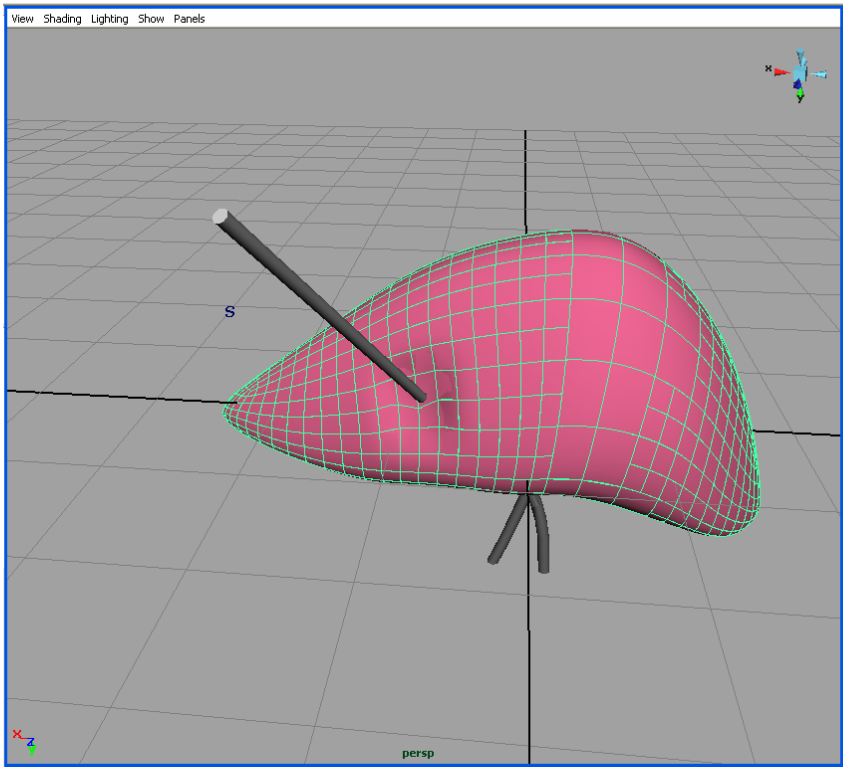


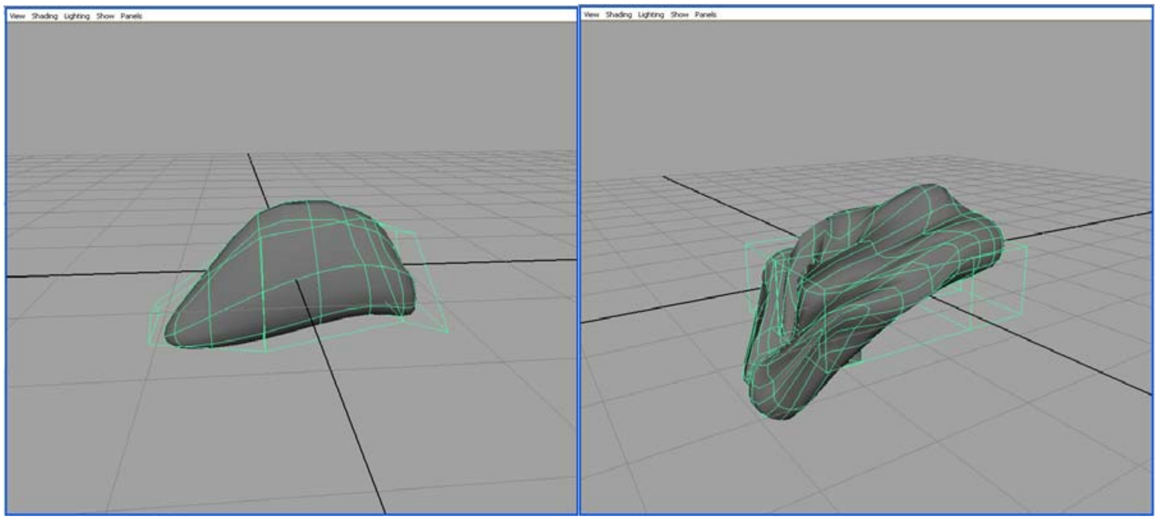
Fig. 19 Soft modification deformer being applied to our liver model

We found that cluster deformers are good for simulating structural dynamics because the cluster can be painted according to its structure, for example how extensible it is.
We also found with the long history of gathered work in the animation field over human character skinning and dynamics reflected in Maya, there are numerous deformers which simulates the effects of skin deformation excellently. Such as wrinkle deformer, sculpt deformer, wrap deformer and jiggle deformer.

5.3 Informal User Study

An informal user study was run with a small group of university students with no involvement with the areas of computer graphics and bioengineering. There were five students in total, one biology student, one commerce student and the rest were engineering and science students. All students had sufficient knowledge of at least high school biology.

First of all a 10 to 20 minute tutorial depending on the confidence of the student was given on the basics of modelling in Maya and subdivision surfaces. The first part of the test users were asked to model their perspective of a liver. A series of instructions of our method of model spherical topology organs using subdivision surface were give. Minor verbal assistance was also provided during this process. Then the users were asked to produce the model of the liver. The second part of the test asked the users to try to create some types of blood vessels attached to the liver by them selves, they were allowed to look up any resources of Maya and help was given if need with Maya functions. But they were left to decide how they want to model the blood vessels and what Maya functions to use. Verbal assistance on how to use Mayas is still provided.



a. The best result b. The worst result

Fig. 20 results from the informal user study

We found that all students were able to follow the given instructions for the first part of the test on producing a liver shaped object, although some cases were visually better than others (fig. 20). There was one case where the student failed in modifying the shape of the liver (fig. 20b), this generally caused by the students preference of not using undo function. Also minor help had to be given at times of the test, as students often make simple mistakes. It took around 20 – 30 minutes to model the liver. Because of the nature of the user study, students did not spend much effort on refining the models. For most cases if more time is spent, the result can be better.

For the second part of the test, nearly all of the students were completely lost and did not know what to do. The help manual was over whelming for the students in such a short time, more basic knowledge and skills needs to acquired. Only one person was able to produce a single cylinders pipe to be placed in place of the blood vessel but it was very crude.

After the test all students are briefly interviewed and feedbacks are gathered. We found that the success of the result is dependant on the users past experience with using graphical packages or interfaces for example 2D graphics packages like Photshop and Fireworks. Also we found that although students were able to follow instruction on using Maya, because of their lack of experience they fail to discover how to use Maya individually and often when they come across an error or mistake help is needed to solve the problem.

6. Conclusion

The obvious advantage of Maya is that Maya offers great usability which is often lacking in expert or specialized software. This is shown through Maya's excellent user interface. It is highly intuitive and can be used by non-experts as shown from our user study. Maya has a vast range of functions which simplifies the work flow and enhances the power of the user. Maya is also highly customizable and flexible, in general an excellent tool as found through our background review.

Other than the usability mentioned earlier, the benefits of Maya's modelling capabilities of NURBS surfaces and subdivision surfaces are capable and intuitive at capturing biomedical surface geometries. This is demonstrated by our results, Maya was successfully applied in manipulate the shape of spherical topology organs, capturing contour information from medical images, simulating volumes and capable of handling complex topologies. The benefits of Maya's simulation capabilities mainly come from its powerful animation functions. Maya is advanced when it come to producing animated videos. It has a large depository of tools and functions which handles the complete work process of animation as covered in our investigation.

The problem with simulation in Maya is that it is unable to simulate any form of physically realistic deformations. This is because in order to do the simplest physical simulation we need to take into account the factors of force and time. The Maya system of animation is frame dependant and hence it doesn't relate to time directly. The nonlinear animation Trax can be used to edit the frame-time distribution to fine tune animation in order to capture some time dependant effects. Since the Maya system does not handle physics or forces, force dependent effects can't be simulated at all. The force of the interaction has to be predicted by the animator and the appearance of the deformation animated through experience. Since the material properties of a deformable object cannot be reflected with force and time directly, this only leaves structural based deformation. But this again is a crude approach because Maya only contains surface representation and surface geometry is not enough for accurate dynamics. Even thou layered surfaces are often sufficient in modelling static biomedical structures, this is because when we look a volume we can only see its surface and the underlying volume will be obscured anyways. But for simulating biomedical deformations, the underlying structure would need to be known in order to compute accurate deformations.

Most of these advantages and disadvantages points to the fact that Maya's approach differs from the approach of biomedicine. Because of Mayas artistic background in movies and games, it tends to have a visual appearance focus and with minimal mathematics and physics in order to be easy to understand and usable by artists. While in biomedicine the heavy involvement of science has led to an approach where engineering and computer graphics principles are adopted. Included with the high standards and accuracy of medicine, this has led to volumetric representation of structure models and physically accurate dynamics models.

Just because that Maya has a different approach compared to traditional biomedical modelling and simulation techniques, it does not mean it is necessarily a bad thing. It can be used to an advantage, if the approach is correct as shown through smile train [13]. Especially with the recent development in virtual surgery and surgery animation animations, reduced surface models are becoming more important in biomedicine and a more visual simulation approach is starting to be adopted.

From the result of our investigation and our experience working with Maya, we make recommendations to users who are looking to incorporate Maya into biomedical application. We recommend user of Maya not to aim for high physical correctness but to focus more on the visual aesthetics, use Maya for what it can do and seek alternatives for more physical requirements. These alternatives may include a custom plug-in or a third party program. When modelling, medical data as a guide can enhance the spatial proportions of organs but to keep models complexity low to ensure smoothness, minimize twisting and simplify animation. When animating dynamics effects it is more useful to use an existing video as a guide to mimic rather than trying to capture the different physical properties in order to enhance visual realism. It is more efficient to stick to simple deformable functions or its combinations unless if experienced user.

Lastly we want to mention the fact that even thou Maya have high usability and are easy for experts to get into. We have found just like the past work surveyed that Maya has a high learning curve. Despite the fact that we can use Maya but we were unable to achieve certain effects and solve certain problems, because of our skill level. This is especially apparent for difficult processes such as creating objects from multiple NURBS surfaces, deformation, and animating with changing topology. Hence we can also conclude that Maya is highly skill dependant. From second part of our informal user study we can see that although users were able to follow clear instructions given, they fail to discover approach of modelling individually even for simple problems. This again demonstrates that the ability to use Maya is experience dependant. In order for a new user to use Maya effectively time and effort needs to be invested into Maya.

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