Survey of modelling approaches for medical simulators

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ABSTRACT

Medical simulation, in particular that used for training and planning, has become an established application of Virtual Reality technology. This application became an active area of simulation development in many academic and commercial institutions around the globe. A reasonable number of successful commercial medical simulators have been launched, while others remain hostage in research laboratories undergoing further developments and improvements. This paper provides a dichotomy of modelling techniques in the context of deformation and cutting, giving examples of how these are applied in medical simulation, comparing their strengths and weaknesses, outlining limitations and pinpoint expectations for the future. We focus on mapping the aim of the simulator to the adoption of particular modelling approaches. A case study pays special attention to the simulation of human organs where we uncover advances and limitations in the application of these modelling approaches.

1. INTRODUCTION

Surgery is a critical process requiring both detailed planning and experienced practitioners. However, live humans are not readily available for dissection in order to support training and planning. Furthermore, the use of animals is inaccurate, expensive and introduces difficult ethical questions. A real need therefore exists for simulated planning and training. Virtual Reality technology encompasses 3D modelling, simulation and associated display and input devices that lend themselves well to the nature of surgery. Considerable research and development have been applied to this application and many tools have been evaluated, often with great success. Although early systems are gaining appreciation from some surgeons, there is still much work to do before the technology can offer the true faithfulness required for universal acceptance. Realistic results in simulating complex surgeries are still far from ideal, but the simulators produced so far are promising to be the training and simulating tools in future medical training laboratories. Due to the nature of the human anatomy and the complexity of surgical procedures, many issues must be considered while developing such systems. Factors such as, the purpose of the system and the nature of the human organs involved determine requirements on faithfulness to organ, tool, and procedure. A variety of technologies and techniques may be adapted and matched to meet these requirements. In this paper we cover these approaches in the context of deformation and cutting when applied to both endoscopic and open surgeries, and illustrate their usage by introducing a number of solutions developed in research, uncovering their advances and limitations. We emphasize that this survey only covers the main modelling approaches that are commonly used.

In section two we will introduce a number of modelling, deformation, and cutting approaches used and examples of medical simulators that have been developed around them. In section three we will make a comparison between the different techniques and highlight their advantages and disadvantages. Current limitations and future expectations of the present systems will be outlined in section four.

2. MODELLING APPROACHES

An important decision in designing a medical simulator is the choice of modelling approaches. What we mean by modelling is the way objects or models are represented, whether they are represented geometrically by mathematical procedures or abstractly by basic shapes and primitives. This decision is lead by concerns including both the body material to be simulated and the way in which it will be manipulated. A new and demanding problem might require a unique combination of approaches. Here we highlight the main approaches used together with some examples to illustrate how and why they are applied. We begin by describing modelling approaches and then explain approaches better suited to model deformation and cutting.

2.1 Object Modelling and Datasets

As datasets used in the simulated models are normally generated using different tools, and the modelled systems have distinct simulation goals to address, different modelling approaches and datasets have been used for different simulators. Here we outline the main data representation techniques and datasets used.

2.1.1 Volumetric models from scanned images. Data may be taken from Magnetic Resonance Imaging (MRI), Computer Tomography (CT), or Positron Emission Tomography (PET) scans in order to generate 3D volumetric models of the human organs. The generated models can be visualized as high quality voxel-based (3D) volumetric objects. These objects are seen as 3D array of data, where each element represents a sampled point from the acquired 3D scans. The main advantage of this method is that it maintains the original volumetric data from the scans and full volumetric representations can be produced. This technique has other advantages such as (Gibson et al, 1998),

- Voxel-based modelling is a natural way to represent 3D images, because the organization of represented data is the same as that acquired, i.e. true reflection of the original data.
- Volumetric objects can hold detailed data about the internal anatomical structure of the tissues.
- Voxel-based modelling is only suitable if the number of volumetric elements is relatively low, due to reasons mentioned below.

An example of a simulator which was developed using high resolution MRI images is the knee arthroscopy simulation system (Mitsubishi, 2001; Gibson et al, 1998). The images are first segmented, and then used to produce 3D volumetric models of the knee bones and other tissues. The simulator was developed using T-1 weighted proton density MRI images. These images then segmented into different tissue types. It was assumed that the data stored in a regular grid of evenly spaced volume elements. Good deformation results were obtained, but they were not tested against other accurate approaches such as, finite element method (Zienkiewicz and Taylor, 2000).

The main draw back of volumetric representation is that it requires high storage space and high computational power to handle such huge data. This cost of computation comes from accessing and computing the huge number of elements in the dataset. This eventually will have practical implications on the rendering speed (Gibson et al, 1998).

2.1.2 Indirect volume rendering. With this technique only the desired surfaces of the volumetric data are rendered (Radetzky and Nürnberger, 2002). This can be achieved by a process known as segmentation, which extracts the surfaces or areas of interest from the volumetric data. Segmentation subdivides the image into specific areas of distinguishing properties. The main advantage of indirect volume rendering is the increase in rendering speed obtained from the dramatic reduction in data. A further advantage is gained by the use of texture mapping, which allows the addition of realistic images obtained from real organs or structures to be applied to the surface.

To reduce the needed graphical power, ROBO-SIM developers (Radezky et al, 2000) used a combination of direct and indirect volume rendering techniques. 3D brain MRI datasets of actual patient were used to model the pre-plan procedures and to simulate views of the outer and inner surfaces of the head.

2.1.3 Surface modelling. The geometric representation of tissue may consist of surfaces as well as volumes. Surface representations are normally modelled as a set of polygons. The choice between surface and volume based models is governed by two elements: computer power and visual accuracy (Delingette, 1998). In terms of computation power, surface models are advantageous because they have less vertices/polygons to render than volume based models, but are less accurate. Furthermore, surface models may produce undesired or unrealistic deformations especially in thin representations. Surface models are good representations for modelling cavernous tissues such as, vessels and the gallbladder (Delingette, 1998).

At the University of Colorado Centre for Human Simulation, a real-time algorithm has been developed to simulate a virtual scalpel making cuts on a constructed body (Colorado, 2004). The system is able to simulate cuts using MRI data from the Visible Human database (NLM, 2003). A texture mapped polygonal representation was employed to produce the desired effects. In real-time, the texture mapped surface is updated to simulate the cutting and the resultant new surface.

2.2 Organ and tissue deformation

Deformation and elasticity are two important characteristics of the human body tissue. These unique characteristics forced the developers to use unique and challenging deformation techniques in order to model such behaviours with the required acceptable fidelity. Tradeoffs must be made between responsiveness, in terms of frame and update rate, and realism in terms of graphical and haptic detail. A general solution is probably unobtainable with current technology, but a number of approaches have been introduced to meet specific requirements. These approaches are outlined below together with real implementation examples.

2.2.1 Finite element method (FEM). This method is one of the most common approaches to model tissue deformable behaviour. It describes a shape as a set of basic geometrical elements and the model is defined by the choice of its elements, its shape function, and other global parameters (Delingette, 1998). FEM treats a problem in a continuous manner, but solved for each element in a discrete way. The problem can be solvable by adopting an interpolation algorithm within the different elements of the model (Wagner et al, 2002). The main advantage of FEM is that they can produce more physically realistic simulations compared with other approaches. Because mass and stiffness matrices remain constant over time interval and only evaluated at each time step, this produces realistic deformations. But it requires high computation, which can only be reduced if the number of nodes is reduced. Undesirably, the reduction in the number of nodes will in turn degrade the accuracy of the model.

Finite Element Method (FEM) was used to model tissue deformation for a gynaecology endoscopic simulator (Székely et al, 1999). The prime aim of the system was to produce realistic organic models with their inherited deformation characteristics to mimic the real endoscopic surgery simulation. A body in FEM was segmented into a finite number of elements. Positions and movements in the element were calculated from discrete nodal values. A discrete system of differential equations was generated for every element from a set of differential equations controlling the motion of material points of a continuum. The resultant equation then had to be integrated in relation to time. Uterus deformation has been modelled by employing a reduced volume integration approach based on absolute strain formulation, while the abdominal cavity has been modelled using rigid surfaces (Székely et al, 1999).

2.2.2 Mass spring method. Mass Spring Method is the most common approach for real-time simulations. In this technique, masses are assigned to vertices and a set of springs are allocated to connect vertices. Strut springs are also added to keep the mass-spring surface maintain certain shape and position. In real time, the deformable objects then deform in a physically-based manner after solving a mathematical problem in response to external stimuli (Bro-Nielsen et al, 1998). Mass Spring methods are easy to build and simulation levels are not as high as those for FEM, but they can produce acceptable real time simulations using today’s hardware (Gibson and Mirtich, 1997). Despite these advantages, mass spring models have some drawbacks. Because they only approximate the true physics of the continuous body, spring constants are not always easy to derive and hence give inaccurate approximation of the physical behaviour of the material. Mass Spring models also have a problem called “stiffness” when the spring constants are high, this causes the system to be unstable and produces slow simulations (Gibson and Mirtich, 1997).

A standard mass-spring system was used to model surface deformation in the abdominal trauma surgery simulator (Bro-Nielsen et al, 1998). Cutting of surfaces was modelled using a number of functions applied to individual triangles. Another simple mass-spring model was used to model the arteries and other tubular models. This model was treated as the backbone of a tubular structure related to connected contours. Each one of these contours is connected to a vertex, which is then controlled by this vertex. The development of such system allowed the developers to investigate and apply different virtual technologies to model deformable objects and simulate other procedures such as, bleeding, cutting and haptic responses.

Mass Spring method was also used in the EyeSi simulator (Wagner et al, 2002). The system is a training simulator for intraocular surgery. In this system a Mass-Spring method had been used to model the following two different tissue deformation simulations:

- This simulation involves the removal of membrane. The rim of the membrane is normally connected to the retina, so in the mass spring model, the corresponding nodes are not moved. Removal or movement of the retina itself can be detected if the force on the rim nodes exceeds certain value.

- A common surgery procedure is to lift the retina by injecting salt solution beneath it. This procedure was also modelled by treating the retina as a mass-spring mesh.

2.2.3 Chainmail. This approach was first introduced by Gibson (1997). In this approach, the model maintains the original data resolution and allows the individual object elements (volumetric elements) to follow certain rules to do the required deformation. In a 3D format, each element is connected to six of its neighbours. These are, top, bottom, right, left, front, and back. When the object is manipulated, each element is tested to see if it violated certain distance thresholds it shares with its neighbours. If the distances are exceeded, the element is moved in the desired direction. If not, then the object does not move. These rules are applied to element/elements, which is/are within the influence of manipulation and then propagates to its/their neighbours. So, local deformations are generated only if distance thresholds were exceeded. Links between elements are initially set slack, so movements only occur if the distances were violated. Elasticity or deformation constrains can be modelled by setting different distance values for different object types. For example, by giving rigid objects small variations, while deformable objects are given high values.

The major advantage of this approach is that it takes benefit of all the high resolution volumetric data generated by scanners and applies simple calculations on elements to generate the required deformation results. A range of material types can be modelled using this approach, such as rigid, deformable, plastic, and elastic (Gibson, 1997). Chainmail method is also relatively easy to implement compared to other approaches.

A knee arthroscopy simulator was developed using such approach (Gibson et al, 1998). This simulator was modelled using a volumetric object representation as explained in §2.1.1.

2.2.4 3D linear elasticity. Because of the elastic and deformable nature of soft tissue, linear elasticity (Landau and Lifschitz, 1986) is also a common algorithm used to model deformations and cuts. Considering an object composed of a number of tetrahedral elements in a domain Ω, the elasticity theory problem solution can be defined by the solution of the linear system (Cotin et al, 1999)

$$\mathbf{K}\,\mathbf{u} = \mathbf{f} \tag{1}$$

Where **K** is the stiffness matrix and is symmetric, positive, definite, and sparse; **u** is the unknown displacement field and **f** is the external force. The size of this matrix **K** is $3N \times 3N$ where N is the number of mesh vertices (nodes). In general, a set of external forces are applied to the surface of the solid while some mesh nodes are fixed, otherwise a translation would occur, not a deformation. In linear theory, the behaviour of deformable model is physically correct only for small displacements (approximately 10% of the total mesh size), and less realistic for larger deformations. Another feature of linear theory is that any mesh deformation can be computed from knowing a finite set of elementary deformations (Cotin et al, 1999). Also, because most soft tissue materials behave in a non-linear fashion, linear elasticity can not always be applied.

2.3 Tissue Cutting

In order to simulate cuts in a soft tissue, there are a number of routines, which can be applied. These include collision detection, subdivision, and relaxation.

2.3.1 Collision detection. What we mean by collision within the focus of this paper is the intersection between the soft tissue and the scalpel or the cutting tool. Collision detection algorithm computes two actions, firstly, finds the intersections between the swept or cutting plane and the active intersected tetrahedral (Four triangular sided entity, which forms 3D meshes) edges, and secondly finds the intersections between the scalpel tip path and the intersected faces. Bielser and Gross (2000) introduced two types, the surface collision detection and the volume collision detection. Surface collision detection algorithm finds boundary elements that collide with the cutting tool; an axis aligned bounding volume hierarchy over the surface is normally employed. On the other hand, volume collision detection finds those tetrahedrons inside the tissue, which are split or partially cut by the tool.

2.3.2 Subdivision. Because most volumetric meshes are represented as tetrahedral, there has to be a mechanism to split or cut these tetrahedral elements. Subdivision is the main procedure to do this splitting. Bielser and Gross (2000) had used tetrahedron cut-specific subdivision patterns. Here only edges and faces that are part of the cutting face are considered. Five topological patterns were suggested. Three of them represent partial cutting, while the other two model a complete tetrahedron split.

Bielser et al (1999) have used the same five possible topological representations to cut a tetrahedron. For each of the five cases, a set of actions needed to produce the new mesh are stored in a look-up table. Insertion of new mass-nodes and assignment of connectivity are some of the actions stored in the look-up table. By mirroring and rotating the five main possibilities, a combination of all possible cases can be produced and registered in the look-up table. Tetrahedral splitting was carried out by proposing a generic 1:17 tetrahedral split, where the current geometry of a surface cut is represented by replacing the reference edge and face midpoints by the current intersection points, which are computed by the collision detection algorithm. By referencing the edge mid-nodes twice and the face mid-nodes three times, a pre-split tetrahedron composed of five parts can be produced. Although, the generic subdivision method produces acceptable results, it has some limitations. This include; producing hanging nodes that have no connection to neighbouring tetrahedral, which may lead to cracks in the model. This problem can be solved by splitting adjacent tetrahedral accordingly, but this has a trade-off between accuracy and computational load. Also, because splitting the tetrahedral is carried out after completing the cut, this may produce some visual inaccuracies and discontinuities.

Progressive Minimal cutting is another effective procedure proposed by Mor and Kanade (2000), which generates a minimal set of new elements that follows the trajectory of the scalpel. Developers of this system argue that the cutting algorithms introduced so far do not split the intersected element until the cut has been completed, which causes lag into the cutting process. They have implemented a method based on progressive cutting, where the subdivision is based on the geometry of the original element. In a progressive cutting procedure, a temporary subdivision of each partially cut element is encountered. Any temporary face interactions are updated for each partially cut tetrahedron. Then, the modified topology of the partially cut tetrahedron is checked for any changes. If the topology has changed, then a new set of temporary tetrahedral overwrites the old set. If the topology has not changed, then the temporary tetrahedral are updated by applying the new positions of the new face intersections. As soon as the cutting edge leaves a tetrahedron and the cut is finished, the temporary elements are then deleted and a final subdivision procedure is applied again. Eleven different combinations of intersected edges, faces, and temporary face intersections were generated to model the possible cut combinations. Mor and Kanade (2000) suggest that cutting can be affected by three factors,

- Cutting should occur along a free form path traced by the cutting tool.
- There should be no time lag between the movement of the scalpel and the resulting cut.
- The generated number of elements by cuts should be as small as possible, as this will affect the update rate significantly.

2.3.3 Relaxation. Relaxation defines the procedural computation of the physical behaviour of tissue after cutting.

2.3.4 Examples of cutting implementations. Outlined below are some implementations that have used the aforementioned cutting approaches and other application specific techniques.

A progressive cutting routine was used by Mor and Kanade (2000) to cut through tetrahedral models of soft tissue. Developers of this system claim that such technique increased accuracy and applicability of their simulator. Zhang et al (2002) also employed progressive cutting to subdivide the surface and produce interior structures that follow the path of the cutting device. Bielser et al (2003) also used progressive cutting approach to subdivide tetrahedral meshes. They have used a state machine to track the topology of tetrahedral and then control their progressive subdivision.

A combination of finite element deformation with interactive cutting was implemented by Nienhuys and Stappen (2000, 2001). An iterative algorithm was used to simulate linear deformation and cuts of tetrahedral meshes at real time with no pre-computation. The separation between the topological and geometric aspects is maintained, which made cutting interactive and fast.

Virtual freeform incisions on Finite Element tetrahedral meshes can be produced as suggested by Mazura and Seifert (1997). In their implementation, the user specifies a series of 3D points and a corresponding depth on the surface. Each pair of the succeeding points then defines the incision as a freeform shape.

A multi-resolution based cutting approach was introduced to ensure the required speed and to support dynamic changes of the topology at real time (Ganovelli et al, 2000, 2001). The idea is that changes in structure are only applied to parts of the model, such as cuts or lacerations. This system is based on tetrahedral decomposition of the space.

Bro-Nielsen et al (1998) have used mass-spring models to achieve reasonable cut results. They have accomplished this by applying a set of operations to individual triangles. A linear mass-spring model was used to model arteries and other tabular models as the backbone of a structure, which based on connected contours.

Cutting, tearing, and suturing can be simulated using the chainmail (Frisken-Gibson, 1999; Gibson et al, 1998). Cuts can be produced by breaking the connections between elements along the path of the virtual knife instrument. Intersection between the knife and the object are detected by scanning the knife space through the occupancy map and checking for collisions. Tearing happens when the distance between two elements is stretched beyond the allowable limit. When this limit is exceeded and cannot be compensated by the moving neighbours, then the connections are broken to simulate tearing. During suturing, elements along the path of the suturing instrument, which have missing links, are paired to their neighbours. These elements can be detected using the occupancy map within the vicinity of the suturing instrument.

Cotin et al (2000) have implemented real time deformations and cuts using linear elasticity. They have used three models do their simulations. The first model was built to make deformations, but no topological changes. The second was based on "tensor-mass" model, which allowed the simulation of deformations and cuts on small size meshes. A hybrid model based on the other two allowed the simulation of deformations and cuts on complex meshes.

Pflesser et al (1998, 2002) have developed a way of specifying, and modelling arbitrary shaped cut surfaces in volumetric models. These freeform cuts were represented within a voxel model together with partially volumetric effect. Using a grey-level gradient method allowed the calculation of accurate surface normals, which can be used to find sub-voxel localization of cut surfaces.

2.4 Task Specific Approaches

In this section we outline some systems, which have been built using approaches slightly different from the aforementioned techniques.

2.4.1 Karlsruhe endoscopic surgery simulator. Karlsruhe has developed an advanced endoscopic surgery simulator (Karlsruhe, 1997; Kuehnapfel et al, 1997) capable of producing highly realistic tissue behavior. In order to model such realistic behaviours, developers have adopted an approach, which is based on three different modelling elements. These are; the physical modelling, the geometric modelling, and the model interaction (Karlsruhe, 2001). To model the physical behaviour, a simple-element-system called "nodal net model" was employed. This model was implemented based on physical equations applied on discrete components. The result system with mass knots produces a system with differential equations, which can be solved in real time numerically. A B-Spline surface software was used in tissue (physical) modelling. Two methods were employed for pure data representation, a freeform surfaces method, and a direct output of polygonal nets. To connect the physical model with the geometric model, the mass knots were connected to the related control vertices of the polygonal net. Interaction involved three elements, collision detection, interaction management, and model modification. The deformable objects behaviour has to be dependant on the manipulation model hence instrument manipulations simulate actions such as, cutting, and grasping.

2.4.2 Endoscopic sinus surgery simulator. This endoscopic sinus surgery system was developed using the (NLM) Visible Male dataset (NLM, 2001) to model body tissue. The used dataset included MRI, CT, and colour cryoslice photographs. The rendered model has been developed through three stages, Segmentation, Surface Extraction, and Surface Simplification (Lockheedmartin, 2003).

Due to the high spatial resolution of the NLM cryoslice images and the difficulty in extracting details of such images, segmentation masks with unique colour for each image segment had to be produced. This permitted the developers to enhance the data by adjusting the segmentation masks. For surface extraction, developers had employed the marching cube algorithm from General Electric. For surface simplification process, an algorithm was used to reduce the high frequency in the polygonal mesh. In order to compute the surface structure in real-time, the polygons were classified into four groups, low, medium, high, and very high resolution. It has been noted that low and medium resolution polygons deliver acceptable results in real-time, so they were used for the proposed simulator. Textures were applied to the low fidelity data, and various anatomical structures were contorted, which have generated different pathological variants.

2.4.3 Gynaecology endoscopic simulator. Here we refer to the endoscopic simulator mentioned in §2.2.1. The modelling process of such system was divided into two stages, anatomical modelling and organ appearance modelling (Székely et al, 1999).

The Visible Human Female dataset from the National Library of Medicine (NLM, 2001) was selected to provide the data for constructing the simulator anatomical model. This choice has been made, because of the relatively high resolution and due to the consistency of the images provided. In order to produce 3D images from this standard 2D datasets, a segmentation system was used. Texturing was selected to model organ appearance, because it enhances realism and gives a cue to space perception. Also, texturing is crucial in modelling pathological tissue, which helps improve diagnostic skills. Organ specific base textures were produced using a texture analysis/synthesis procedure. A small texture sample is taken from a real image can be computed in any analysis stage. A 3D texture block is then modified until its second order statistics is close to the sampled texture. Organs then can be textured on the solid texture block.

3. COMPARISION

Object modelling approaches each have distinct advantages and disadvantages. Pure volumetric representations are ideal for true volume modelling, because they preserve the original data from the scanned images, but they require huge storage space and powerful software and hardware to render. Surface representations are easy to render and do not need powerful computers, but are an artistic impression of the body rather than a faithful representation of real data.

We have seen that the deformation approaches mentioned complement each other in many ways. For example, FEM can produce realistic and accurate models, but they are slow when manipulated. On the other hand, Mass Spring modes are relatively fast, but they lack accuracy and do not generate realistic images. Few simulations were built using the Chainmail method, but it is a promising candidate for future volumetric simulations. 3D linear elasticity is only valid for small deformations, which can be used mainly to simulate deformations associated with cuts. Linear elasticity can not be used for the modelling of all soft tissue materials, because most of these materials have a non-linear behaviour.

It can be seen that the intended aim of the simulating system may suggest which deformation approach to use. If the purpose of the simulation system focuses only on the visual part and ignores the time required to render that model, then FEM will be the ideal candidate. But if our focus is to carry out deformations in real time, then Mass-Spring method will be adopted. If we wanted volumetric simulations with greater speed computations, then chainmail method with volumetric representations are recommended.

With regard to cutting, we have seen how effective progressive cutting technique is in simulating cuts on tetrahedral surfaces, which suggests that this approach is a promising one. But this technique was only applied to tetrahedral surfaces with no deformations involved. A way of applying this method with deformable models will be an advantage. Also, applying progressive cutting on volumetric models, such as those used by Pflesser et al (1998, 2002) will be beneficial. No single approach was claimed to be the ideal solution. A combination of such techniques, especially when deformation and cutting involved, may provide a common ground for a universal solution, but this will require some time and effort to apply and test. We have also learned that there is a trade-off between accuracy and speed in simulating cuts, using the aforementioned implementations. Individual systems tackled portions of the problem, not the whole. It is clear that simulating cut on tissue is still a research topic. Further investigations are required before we see a system that delivers such task with the required accuracy and at acceptable computational rates.

4. CURRENT LIMITATIONS AND FUTURE EXPECTATIONS

In the following section we will outline some of the current limitations of modelling techniques and in the next one we will highlight some of their future expectations.

5.1 Current Limitations

Despite all the satisfactory results obtained by using the aforementioned modelling approaches, there still many limitations, which keeps medical simulation a research subject. Some of these limitations include,

- Modelling techniques used and to what degree they can be employed are governed by the required degree of complexity and realism and their relation to computational speed, storage, and access.
- Few open surgery simulators exist. This is because this type of surgery involves many tissue types with different nature and characteristics that can not be easily modelled using today’s technology. Also, because this type of surgery is based on direct involvement of surgeons’ hands which are versatile and hard to mimic.
- Various modelling approaches lend themselves to particular application, because of their characteristics, particularly in terms of appearance and rendering speed.

In summery we can say that volumetric modelling approaches based on real data sets are good when it comes to realistically modelling the human organs, but there is a big trade-off between what looks real and how long it takes to display and manipulate. Also, there is no ideal modelling approach, for medical simulators. The type of simulator and its intended purpose and the required degree of fidelity play a major role in deciding which approach to use.

5.2 Future Expectations

The wide acceptance of simulators as tools for medical planning and training will require the defeat of some challenges, particularly in terms of model representation, deformation, and cutting, some of these challenges include,

- Develop further expertise and mechanism to address the problem of complexity and realism and their relation to computational speed and storage.
- Improvements in fidelity and accuracy of deformation, cutting, appearance, and haptic cues, particularly with respect to complex open surgery.

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