A Comparative Study to Balance the Computational Complexity and Virtual Graphics in a Novel Surgical Simulator

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Abstract

Background: High-fidelity medical simulators are widely implanted in surgical education programs because they are risk-free to patients and affordable. Moreover, they have similar learning transference capabilities from theory to reality compared to traditional training on a cadaver sample. However, it is impossible to maintain high fidelity without adding additional computing load. Therefore, the compromise between fidelity and user experience in medical simulators is still important.

Objectives: This project seeks to identify the virtual graphics requirements, in terms of computational complexity, to maintain the real-time virtual interactions between the user (trainee) and the simulator (trainer). There are three tasks to achieve this objective. First, to build a realistic visual feedback system for a high-fidelity medical simulator. Second, to examine the relationships between computational complexity and user experience. Third, to evaluate the user experience of the medical simulator.

Methods: Using images obtained from cadavers and actual patients as references, the author produced realistic textures to enhance the immersion of the trainees. Industry-standard software like Autodesk Maya and Substance Painter are involved in creating muscle surface colors and accurate geometric shape of bones. After completing a minimally invasive spine surgery on a cadaver, nine senior surgeons repeated the identical operation on a newly developed high-fidelity simulation training platform containing visual, audible and haptic feedback to simulate a laparoscopy surgery. The surgeons then immediately filled out a questionnaire that assessed the visual feedback of the internal and external textures based on their previous experience. In addition to the texture, the surgeons judged the mesh quality based on the number of nodes, which were built from five additional muscle models that displayed the cross-section area penetrated by the same tool as in the simulator.

Results: Overall, visual feedback was considered good and achieved high satisfaction. Concerning the number of nodes, 45% of participants indicated that there was no difference between the five models. The remaining 55% participants considered that the first two highest quality models best matched their experience. The number of nodes and the frame rate revealed a positive linear correlation ($r^2 = 0.925$) and the number of nodes had an impact on perception ($p=0.02$).

Conclusions: The model quality improves the reality of the simulated surgery, however it slows the refresh rate because of the extra computational complexity. This unique methodology suggests how much visual feedback compromise is needed to maintain real-time interactions. Future studies will serve to objectify this threshold.

Résumé

Contexte: Les simulateurs médicaux haute-fidélité sont largement implantés dans les programmes de formation chirurgicale car ils sont sans risque pour les patients et abordables. En outre, il peut maximiser le transfert de l'apprentissage de la théorie à la réalité par rapport à la formation traditionnelle sur un échantillon de cadavre. Cependant, il est impossible de maintenir une haute-fidélité sans ajouter de charge de calcul supplémentaire. Par conséquent, le compromis entre fidélité et expérience d'utilisateur dans un simulateur médical est toujours important.

Objectifs: Construire un *feedback* visuel réaliste pour un simulateur médical haute-fidélité. Deuxièmement, pour examiner les relations entre la complexité informatique et l'expérience utilisateur. Troisièmement, pour évaluer l'expérience utilisateur du simulateur médical.

Méthodes: À l'aide d'images de cadavres et de patients réels comme références, l'auteur a produit des textures réalistes pour améliorer l'immersion des stagiaires. Des logiciels standard comme Autodesk Maya et Substance Painter participent à la création de couleurs de surface musculaire et à la forme géométrique précise des os. Après avoir effectué une chirurgie de la colonne vertébrale minimalement-invasive sur un cadavre, neuf chirurgiens seniors ont répété l'opération identique sur une plateforme de formation par simulation haute-fidélité nouvellement développée contenant des commentaires visuels, sonores et haptiques pour simuler une chirurgie laparoscopique. Les chirurgiens ont ensuite immédiatement rempli un questionnaire qui évaluait la rétroaction visuelle de la texture interne et externe en fonction de leur expérience antérieure. En plus de la texture, les chirurgiens ont evalué la qualité du maillage en fonction du nombre de

nœuds, qui ont été construits à partir de cinq modèles musculaires supplémentaires qui affichaient la zone de section transversale pénétrée par le même outil que dans le simulateur.

Résultats: Dans l'ensemble, les deux rétroactions visuelles ont été jugées bonnes et ont reçu un haut niveau de satisfaction. Pour le résultat de la qualité du maillage, 45% des participants ont indiqué qu'il n'y avait pas de différence entre cinq modèles. Les 55% de participants restants considéraient que les deux premiers modèles de la plus haute qualité correspondaient le mieux à leur expérience. Le nombre de nœuds et la fréquence d'images ont révélé une corrélation linéaire positive ($r^2 = 0.925$) et le nombre de nœuds a eu un impact sur la perception ($p = 0.02$).

Conclusions : La complexité du modèle améliore la réalité du modèle simulé, mais elle ralentit le taux de rafraîchissement en raison de la complexité de calcul supplémentaire. Cette méthodologie unique suggère combien de compromis de rétroaction visuelle est nécessaire pour maintenir les interactions en temps réel. De futures études serviront à objectiver ce seuil.

Acknowledgements

First, I wish to express my sincere appreciation to my supervisor, Professor Mark Driscoll who has outstanding achievements in many fields: his extraordinary leadership and academic ability helped me through those tough roads. Without his persistent help, the goal of this project would not have been realized. I thank him for the stipend he provided so that I can focus more on my research without any worries. He has a convincing ability to handle many affairs and can balance life and work well. He taught me to face life positively and optimistically. And he is more than just a supervisor. He is more like a mentor and a good friend. He not only guides my graduate studies but also helps me plan my future career. I can never ask for a better supervisor during my graduate studies.

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Preface and Contribution of Authors

The thesis constructed in a manuscript-based style that is currently under review by the editorial board of Simulation in Healthcare. This study will help replicate a spinal microscope surgery into a novel medical simulator.

The candidate participated and contributed the research designs, conduct the questionnaires, data collection, analysis of results and drafting of manuscript.

CAE healthcare assisted the technology of creating realism visual feedback, and development of the simulator. Depuy Synthes provided the prototypes of experimental surgery and allowed surgeons to participate in this project.

Mr. Trevor Cotter and Mr. Khaled EI-Monajjed assisted in experiment set-up and questionnaire collection.

Professor Mark Driscoll was important in implementing and coordinating this large team project. He aided in the FEA theory coordination and research aspect of this applied project. Further he assisted in building the questionnaire that evaluated the visual feedback of the simulator. He also provided knowledge on statistical analyses.

Chapter 1

1. Thesis Introduction:

High-fidelity surgical simulation is becoming a universal pursuit in the field of simulation for this century. The extensive data from simulators can help surgeons to evaluate their performance in terms of generating and transferring surgeon skills [1]. Even though some studies confirmed that a low-fidelity simulator is enough to improve user's performance, the fidelity of simulator is still important [2]. In particular, during high-risk procedures, the fidelity level of the simulator should be maximized to replicate exactly each step as accurately as possible to minimize patient risk. A major component of simulator fidelity is the graphical representation, the so-called visual feedback, which should contain a bridge between theory and reality [3].

Building high-fidelity virtual reality simulations typically creates significant computer complexity, so a high-performance computer is required to produce real-time visual feedback and sustainable haptic output. Both features are important to provide the necessary immersion [3]. However, even today's most powerful commercial personal computers are still unable to simultaneously produce real-time output and accurate physical behavior for a high-fidelity simulator. This is because most simulators use finite element methods to present accurate physical behavior via constitutive models in the continuum mechanical method rather than surface models. The volumetric models in such simulators present the geometrical shape of the soft tissue and mathematical result of the finite element method provide realistic force output and topological changes. Since the nodes construct boundaries of the volumetric mesh, those mentioned results will be closer to reality as the number of nodes increases. However, too many nodes may hinder real-time interaction under load input. Therefore, understanding the relationship between number of nodes and visual feedback can avoid this conflict.

For real-time interaction, computers need to generate a frequency of at least 30 Hz, also known as 30 frames per second, to prevent degrading user performance by reducing the response time between user input and graphical output [4]. Thus, when the computer complexity prevents the real-time interaction, the compromise between complexity and visual feedback could help the simulator maintain the real-time interaction. This complexity is not only limited to number of nodes, but also reflects the texture embedded in the volumetric model. But few literature studies have examined the relationship among computational complexity, node number, visual feedback and frame rate. And at the same time, the current literature fails to quantify high and low fidelity because they define the levels based on their own interest. Therefore, this study has three objectives:

Objective 1

To establish realistic visual feedback for a high-fidelity medical simulator;

Objective 2

To examine how computer complexity affects the user experience; and

Objective 3

To build a questionnaire to analyze those relationships.

To better understand these relationships, a comparative questionnaire was utilized to find reference points that satisfy the interactive experiences and visual feedback. A group of senior surgeons evaluated the simulator after performing the identical surgery procedure on a cadaver.

This novel approach allows surgeons to compare a side-by-side scenario that provides the best opportunity to evaluate the simulator's visual feedback based on their experience with the same real-life surgery on a cadaver. It also provides a unique perspective to expand the definition of high fidelity, namely the number of nodes. The number of nodes not only describes the computational complexity but also indicates the level of potential fidelity.

Chapter 2

2. Literature Review:

2.1 Medical Simulation

The endoscopic operation technique, based on its advantages in avoiding damaging healthy tissue and reducing recovery time after operation, is gradually replacing traditional open surgery. However, the endoscopic technique increases the difficulties of operations because of the use of small perforation holes and relatively complicated optical and surgical instruments that require surgeons to practice those special skills of the surgery with extensive training [5]. Thus, medical simulators, the innovatory evolution of the surgical education process, gradually improve and dominate the traditional training system [6, 7]. The medical simulator has proven that it is a valid educational method for clinical knowledge and technical ability [8]. The development of this new technology dates back to developments in aviation and military simulators, both of which are seeking a safer and cheaper way to train novices. In 1904, Edwin Link invented the first aviation simulator known as the "blue box" [9]. It contained only essential mechanical, electrical and pneumatic systems, but nowadays, civilian aviation simulators include high-fidelity full-size control panels, radar, and display windows to express reality [10]. Therefore, pilots must first practice their skills on a simulator before attempting to operate a real aircraft. The reasons behind this process are self-evident, as the simulator is not only risk-free, saving time and money, but also easily transfers skills [11]. Similarly, surgeons have the same desires when learning new operations.

Traditionally, surgeons must practice on animals, cadavers, and sometimes even patients. They follow the “see one, do one, teach one” method first announced by Halsted in 1890, which is still in using today [12]. Namely, with this technique, novice surgeons watch the procedure for the first time, then perform it under supervision and finally become experts and teach the procedure to the next novices. This is a time-based training system that requires a decent amount practice before operating on real patients. Whether we use this or another system, medical simulators can be assigned to different steps of the learning process and help residents to practice and provide feedback. They develop their clinical capabilities without compromising patient safety [1]. Moreover, most medical simulators are suited for users at all levels, who can then practice the skills and knowledge without having to worry about making mistakes that harm patients [4]. In addition, simulators can implement iterative processes to maximize learning transfer [13].

In summary, the advantages of medical simulators are that they avoid risks to patients and learners, reduce undesired interference, can create tasks and programs on demand, can repeatedly practice skill, can customize training for individuals, and improve retention rates and accuracy. The simulators also enhance the transition of training from classroom to actual situations, and have the potential to become a standard assessment tool for assessing student performance and diagnosing educational outcomes [14].

There is plenty of research that provides evidence to prove the educational advantages of simulators [1]. The most important evidence is that the simulator can provide accurate informative feedback [15]. The feedback can be evaluated by the user and the instructor who monitors the surgeon’s progress towards becoming well acquainted with the surgery. To be specific, as an example one of the types of feedback may be the time that the participants spend on a task. It can also help surgeons to track whether their surgical trajectory is close to the ideal one [13, 16, 17].

Therefore, the user of simulators regards educational feedback as the fundamental feature. Another aspect is repetitive exercise. The repetition can help the learner to correct mistakes, reduce reaction time and maintain the familiar skills [18, 19, 20]. Studies also found that the surgeons can achieve higher learning efficacy if they are submitted to a range of difficulty which is an essential component of a simulator [21]. Another aspect is training groups. Unlike the traditional education scenario, the simulator can satisfy the multiple learning strategies in large and small groups, as well as individual independent learning [22]. Also, when the range of actual patients is limited, simulators can be used to display rare, low-frequency patient problems for educational purposes [23]. Medical simulators can then provide a controlled environment, which means that simulators can force the learner or trainee to rely more on themselves than on external pressure [24]. Moreover, for personalized learning speed, simulators can be modified based on individual learning needs. This is possible because medical simulations break down complex tasks into small parts that can accept different learning rates [25]. Some studies have found that simulators can provide realistic situations and improve the learner's response to critical incidents [26].

However, medical simulators can produce problematical results as well. For example, the surgery on a simulator may be easier than in a real environment. This may cause trainees to harm the first patient [27]. Moreover, if the trainee is trained on the simulator without supervision, the simulator may develop bad habits or negatively train an element of the surgery that increases the patient's risk. To avoid such consequences, it is important to choose the right simulator type and fidelity [28].

In fact, the range of the simulators is wide. The following list shows the categories that currently exist. Based on different function, the simulator categories are part-task trainers, simulated environments, computer-based systems, integrated simulators, virtual reality and haptic system, precision placement, complex manipulation, simple manipulation, simulated patients etc. At this stage, low-fidelity simulators are still widely used, mainly because they are economical and easy-to-use for basic skills training [4].

Computer-based simulators can generate real-time interactions between medical instruments and user. They also contain realistic soft tissue models that are anatomically and physiologically accurate [29]. Thus, the users can fully immerse themselves in computer-generated images, haptic sensations and audio feedback. With computer-based simulators, the users can experience model deformation and penetration caused by surgical instruments in real time. Figure 1 is an example of a fully developed computer-based system [30]. Because of these benefits from computer-based simulators, the candidate's team is targeting to develop a computer-based system simulator that can replicate a novel spine surgery with high fidelity.

Figure 1 NeuroTouch simulator components*: a) stereoscope/ visual feedback, b) haptic systems, c) power supplies and amplifiers for haptic systems, d) high-performance computer*

2.2 Soft Tissue Modelling

From the perspective of medical simulators, the training system should provide 1) realistic mechanical behavior and 2) allow trainees to interact with the system [31]. The modelling methodology of soft tissue can influence neurosurgery, plastic surgery, musculoskeletal surgery, heart surgery, abdominal surgery, minimally invasive surgery, etc. [32]. Therefore, in order to achieve the first requirement: realistic mechanical behavior, it is important to understand the mechanics of human soft tissue. In general, soft tissue exhibits very complicated properties such as non-linearity, viscoelasticity, anisotropy and incompressibility [33, 34, 35]. So, when the simulator enables deformation, cutting and needle insertion into soft tissue, huge amounts of data need to be processed. However, for the most advanced computers to date, it is still problematic to efficiently process this computational information in real-time. In 2005, Meier, Lopez, and Monserrat compared the mainstream methods, which revealed that the mass-spring model and finite element method are the best methods to imitate soft tissue behavior for medical simulators, but when considering speed, robustness, physiological reality, and topological flexibility, these two methods are not significantly better than one another [36]. At same time, they highlighted that perhaps future computational industry improvements could enable the volumetric-based mechanical methods to be faster than spring-mass models.

Right now, no matter which behavior the simulator replicates, realistic behavior and real-time capability are a trade-off, which means one aspect's improvement is based on the other's decline [31]. Therefore, many researchers leverage different optimizations methods to solve this problem. For the deformable model, it can be divided into following basic categories: the heuristic modeling methodology, continuum-mechanical methodology, and others.

2.2.1 Heuristic Modeling methodology

a) Deformation:

Despite recent advances, the computational capability is not able to adequately produce real-time rendering for actual behavior of soft tissue. Therefore, multiple approaches are required to simplify the mechanical behavior. Examples are methods like geometrically based method, mass-spring model, chainmail algorithm and so on, to represent the deformation [31].

2.2.1.1 Geometrically based method:

The geometrically based method, like free-form deformation, is excellent in terms of in computational speed. This approach is used to deform the soft tissue by adding a parametric parallelepip lattice and control points; such control points may then be manipulated in a free-form manner as shown in Figure 2. By moving the control points to desired place, a trivariate tensor product called the Bernstein polynomial will define the deformation [37].

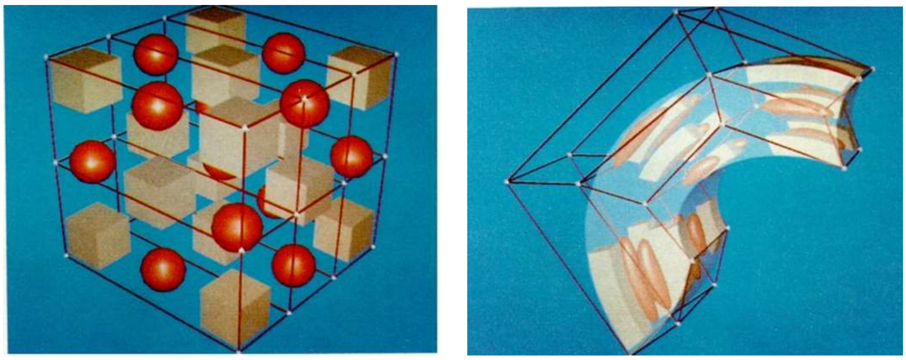

Figure 2 Free-form model deformation*: the left displays the undisplaced position of the object, and the right shows the control points in deformed position.*

The geometrical model is fast in terms of response time; however the deformation is based on control points that cannot accurately represent mechanical behavior especially for the purpose of medical practice.

2.2.1.2 Mass-spring model:

To avoid the defect of geometrically based method, mass-spring models are implemented into the calculation of soft-tissue deformation, see the Figure 3. This method is based on the principle of dynamics which calculates the deformation of soft tissue by using the mechanics of motion, in which each mass point, hence not continuous, is joined by spring forces that are connected to this point [38 – 41]. Therefore, by modifying the spring stiffness constants, use of penalty forces and compound mechanical dampers, mechanical properties like heterogeneity, incompressibility and time-dependence may be achieved [42 – 45]. But generally, a mass-spring system is still not accurate enough to represent the actual physical solution [40]. This is because the elastic springs heavily influence the deformation behavior of the model and may cause artificial anisotropy and heterogeneity [46]. At the same time, the internal forces produced by the position of the mass point do not fundamentally obey the constitutive laws governing the mechanical behavior of soft tissues [31]. Due to this mass-spring approach is reaching its limit of showing realistic behavior, it will be replaced by higher realistic mechanical properties with real-time computational efficiency [36]. Therefore, the mass-spring approach is considered limiting to this regard.

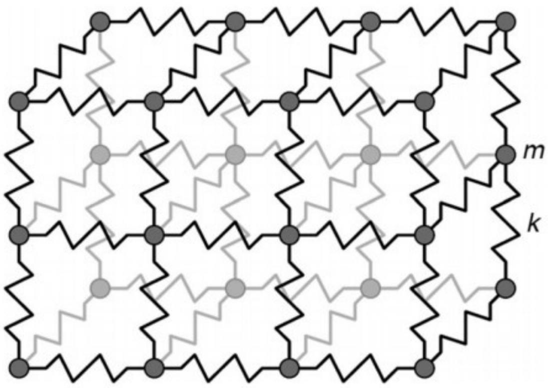

Figure 3 Mass-spring system*: each circle contributes a mass point and links by structural springs which are controlled by stiffness.*

The state of the mass-spring system is defined by the position x_i and velocity v_i of the mass point. The force f_i acting on the mass point has a linear relationship with the displacement, which generates between two mass points *i* and *j*

$$f_i = k_s(|x_{ij}| - l_{ij})\frac{x_{ij}}{|x_{ij}|} \tag{1}$$

where x_{ij} is the distance between two mass points, k_s is the spring's stiffness and l_{ij} is the unstretched spring length. Then, the motion of entire mass model can be calculated by using Newton's second law

$$f(x, v) = M\ddot{x} \tag{2}$$

where M is a 3N × 3N diagonal mass matrix. After assigning the external force, the mass-spring system can predict the deformation of the model [40].

Overall, the heuristic modeling methodology sacrifices mechanical behavior compared with the continuum-mechanics methods. Also, the deformation result could be invalid if the boundary conditions and topology are changed in the simulator compared to those to which they were optimized for [31]. Thus, the continuum-mechanics will be introduced in the following paragraph to provide a better physical accuracy compare with heuristic modeling.

2.2.2 Continuum-Mechanical Methodology:

a) Deformation:

The continuum-mechanical methodology considers soft tissue following continuum mechanics of solid and constitutive laws to display the accurate mechanical behaviors like deformation [31]. Depending on whether or not this model utilizing the object mesh, this continuum-mechanical methodology has two categories: mesh-based approach (finite element method (FEM), boundary element method (BEM)), and meshless approach (total Lagrangian explicit dynamics (MTLED), smoothed particle hydrodynamics (SPH)). This review will focus on the more popular FEM.

2.2.2.1 Finite element method (FEM):

In the FEM approach, the object mesh is divided into a finite number of element components, which in 2D are triangular or quadrilateral elements or in 3D are tetrahedral or hexahedral elements (see Figure 4 [47]). Each element uses constitutive laws that represent the mechanical behavior under the element domain, then the elements are assembled into the large scale matrix that determines the entire soft tissue model [40]. With this approach, the critical material properties of soft tissue, like Young's modulus and Poisson's ratio, can be integrated into the constitutive laws from experimental measurements. Therefore, this approach achieves high physical accuracy but at the same time produces massive computational complexity that causes problematic real-time interaction for the medical simulator [41]. For determining the results of state variables under deformation, there are two formulations which are updated Lagrangian formulation and total Lagrangian formulation [48]. The total Lagrangian formulation is less computationally complex since all variables are referred to the initial system configuration. Contrarily, the updated Lagrangian formulation requires a recalculation of spatial derivatives because all variables are referred to the end of the previous time step [49].

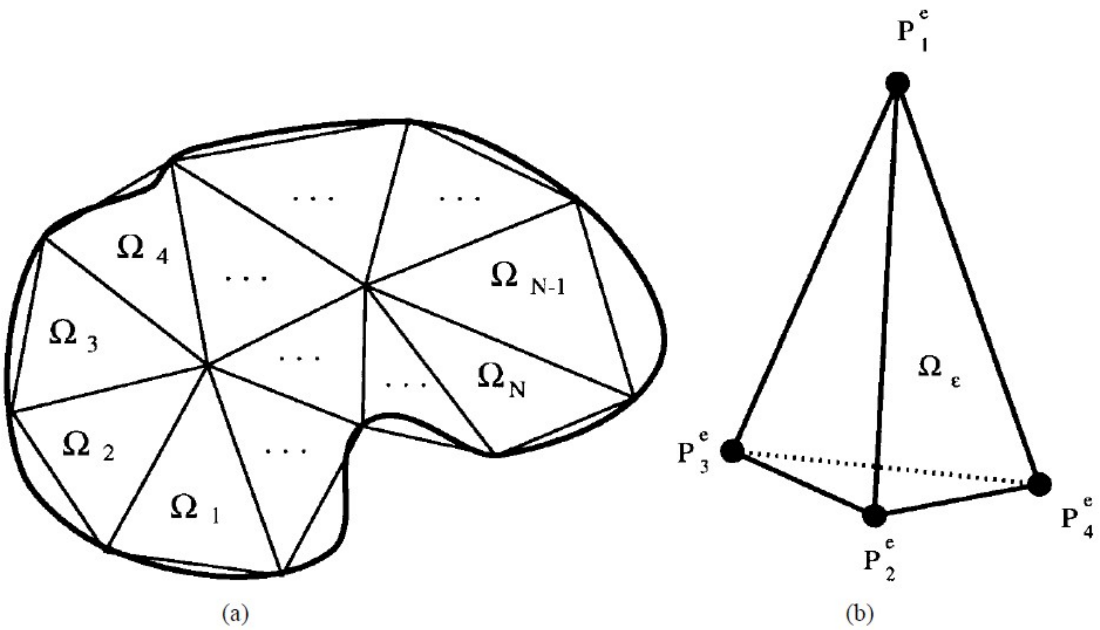

Figure 4 FEM example*: left: Discretization of the domain into finite elements (2D illustration), right: the volumetric mesh consists with tetrahedral finite elements.*

In order to achieve real-time interaction in the medical simulator, linear elasticity is most often considered for the mechanical properties of the soft tissue [46, 50 – 52]. Under this condition, the stress and strain follow the linear relationship:

$$\sigma = C\varepsilon \tag{3}$$

where C is the material property matrix, which is constant throughout the simulator. Then, the strain can be written as a formula that relates to the shape functions B and the displacements u

$$\varepsilon = Bu. \tag{4}$$

Therefore, the strain energy W_{strian} of a soft tissue model is [50]

$$W_{strian} = \frac{1}{2}\int_{\Omega} \varepsilon^T \sigma \, dx = \frac{1}{2}\int_{\Omega} u^T B^T C B u \, dx \tag{5}$$

where Ω is the spatial domain of the soft tissue model, consisting of points at position x with $x \in \Omega$. A number of finite elements W_{strain}^{e} consist the sum of the strain energy

$$W_{strain}^{e} = \frac{1}{2}\int_{\Omega} \varepsilon^{T}\sigma\, dx = \frac{1}{2}\int_{\Omega} u^{T}B^{T}CBu\, dx. \tag{6}$$

After applying an external force f^{e}, the equilibrium state will be achieved by minimizing the total potential energy. Thus, each element can be written as

$$\int_{\Omega} B^{eT}CB^{e}u^{e}\, dx = f^{e}. \tag{7}$$

This equation can be reduced into the following form because of the constants inside the integral sign

$$K^{e}u^{e} = f^{e} \tag{8}$$

where K^{e} is known as the stiffness matrix which is represented by

$$K^{e} = \int_{\Omega} B^{eT}CB^{e}\, dx = B^{eT}CB^{e}V^{e} \tag{9}$$

where V^{e} is the volume of one element. Then the overall soft-tissue model should contain the equation of the equilibrium state

$$Ku = f. \tag{10}$$

The size of the stiffness matrix is 3N × 3N, u is the displacement matrix of size 3N × 1, and f is the global force matrix of size 3N × 1, where N is the number of mesh vertices (or nodes). But as mentioned above, the soft tissue expresses anisotropy, viscoelasticity and compressibility. For FEM, the anisotropic property is achieved by modifying the strain energy density function to produce the directional-dependent behavior [53]. For example, for a transversely isotropic material, the strain energy density W_{aniso} will be expressed as

$$W_{aniso} = W_{strain}\,(I_{1}, I_{2}, I_{3}, I_{4}, I_{5}) \tag{11}$$

where I_1, I_2, and I_3 are the three invariants of the right Cauchy-Green deformation tensor C; I_4 and I_5 are the two invariants from existing anisotropic directions. Then the viscoelasticity of the soft tissue is achieved by using a time-dependent strain energy function. This function is expressed by a convolution integral [53]:

$$\widehat{W}_{\text{strain}} = \int_0^t \alpha(t - t') \frac{\partial W_{strain}}{\partial t'} dt'. \tag{12}$$

The compressibility is solved in continuum-mechanical methodology by combining volumetric and isochoric strain energy functions [54].

b) Cutting:

Besides the deformation, the finite element method currently contains the latest approach to model the cutting mechanism [55]. At beginning, the cutting behavior is expressed by using the element removal method, which was introduced in 1997 [50]. This method introduced collision detection to determine whether the surgical instrument is contacting the model and deletes the elements that are touched by the instrument. The element removal method is suitable for replicating the puncture effect but cannot accurately simulate the cutting behavior.

The element splitting method introduced by Bielser *et al.* improves the cutting effect [56, 57]. In this method, the tetrahedral elements of the volumetric mesh are split in two along the cutting path, and the flat, long and distorted tetrahedrons replicate the cutting scratches, which are usually irregular [58]. However, this is a complicated method with slow processing speed, which fails to achieve real-time interaction [55]. To avoid ill-shaped element cuts from the previously mentioned two methods, the element duplication method adds the extra elements in their original shapes. Although the duplication method is a good trade-off between accuracy and robustness, the snapping of vertices or element refinement, or a combination of both is required to accurately represent the cuts. Snapping of vertices is a cutting mechanism that does not contain any subdivision. This procedure has three steps: 1. Identify the face that needs to be dissected and repositioned. 2. Reposition the nodes from the face so that they can follow the scalpel path. 3. Dissect the nodes along the scalpel path [59]. A 2D example is shown in Figure 5.

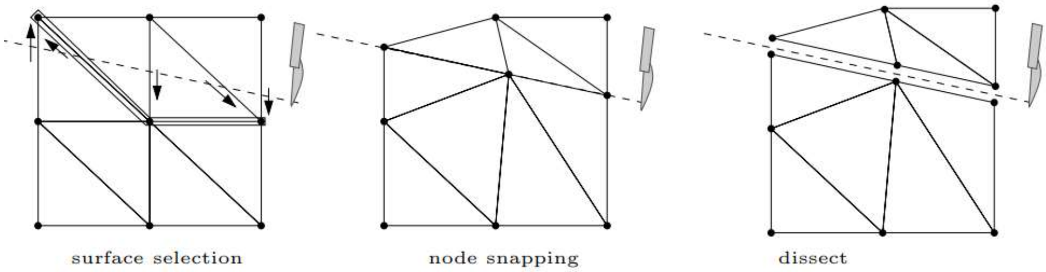

Figure 5 Snapping vertices process*: three steps in performing a cut, shown in 2D.*

In 1999, Bielser et al. presented a method that refines the element locally along the cut to accurately represent cutting, which achieved a generated vertex on each edge, and a vertex on each triangle, see Figure 6 [60]. Steinemann et al. proposed a combination of snapping of vertices and element refinement to better replicate the cutting mechanism. If a vertex of an intersected edge is close to the cutting surface, the vertex will move onto the cutting surface. If the cutting surface intersects on an edge, the edge will split [61].

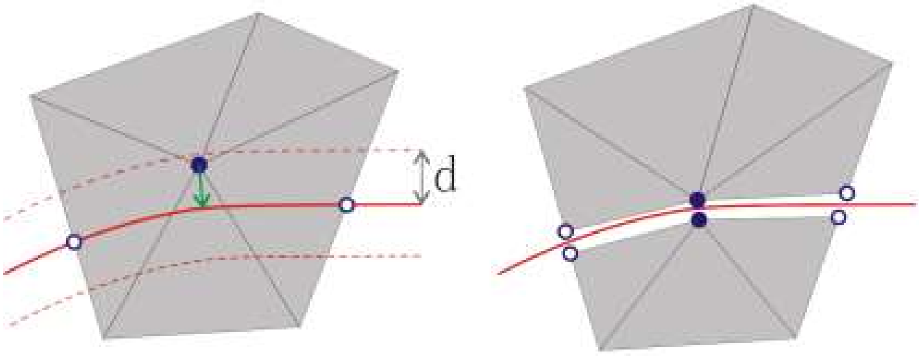

Figure 6 2D example of element refinement method*: the red line is the cutting procedure and creates new vertices on the edges.*

The following Figure 7 summarizes the current state-of-the-art in simulation of cuts in deformable soft tissue for the 2D cases [58].

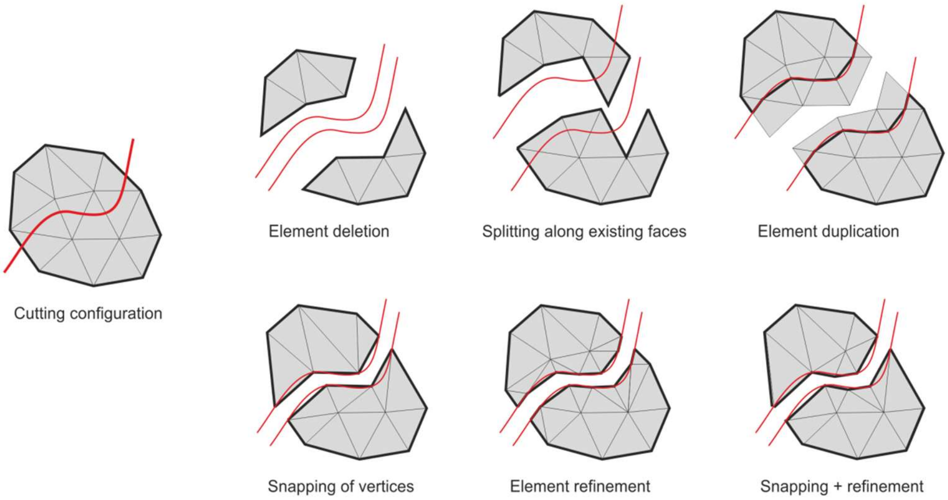

Figure 7 Illustration of different methods for incorporating cuts into a tetrahedral mesh (a triangle mesh in 2D). The red cutting path separates the object into two disconnected parts, which are illustratively displaced to make the discontinuity visible. The surface of the object (bold black line) is given by the set of surface faces of the tetrahedral elements, except for the approach that is based on element duplication, where a separate surface mesh is maintained.

2.2.3 Summary

Overall, soft tissue manipulation is one of the most important tasks in medical simulation. The two most popular ways are mass-spring modeling and finite element modeling. When soft tissue undergoes small deformations, it can be simplified as linearly elastic and Hooke's law can be applied if one is using a mass-spring model [62 – 65]. Additionally, users have to choose a surface mesh for real-time interaction constrained by insufficient computer processing power, thereby avoiding the massive data produced by volume-based models. However, the mass-spring model is a heuristic approach which omits the constitutive behavior of the modeled tissue. Moreover, most biomechanical models should be treated as volume meshes due to the physical behavior of soft tissue [66]. Therefore, finite element modeling, which is based on continuum mechanics, more accurately captures the behavior of the tissue. But a large amount of data brings new challenges to the simulator. The surgical simulator must not only consider its physical tolerances, but also its interactive speed. If real-time interaction cannot be guaranteed, the medical doctor cannot achieve the desired learning results when using the simulator. Therefore, maintaining real-time properties becomes a significantly important component of simulations. In this research, mass-spring and finite element methods are the two major solutions to represent soft tissue in medical simulators [67].

2.3 Frame Rate on Human Performance

In the medical simulator system described in this thesis, the user receives the visual feedback from two monitors. Each monitor has constant refresh rate that displays frames with fluctuanting rates. In computer graphics, frame rate is described as how many images, so called frames, that appear on a display per second. While the corresponding term refresh rate refers to the capability of a hardware to display the images for instance head-mounted display, monitor etc. [68]. In general, refresh rate is a hardware determined constant. On the contrary, the frame rate fluctuates greatly due to the complexity of the scene and computer capability. When the frame rate is less than refresh rate, a duplication method appears to stretch each frame to fit the refresh rate of the display. For example, when a 60 Hz display device only has a 4 Hz frame rate input, the individual frame will duplicate 15 times before any further changes [69]. However, this method could be problematic. When the frame rate and refresh rate are unsynchronized, a lag occurs. The lag is a temporal discrepancy between the data stream from the tracker (e.g., input device such as a mouse or a haptic device) and the actual resulting graphic. Once the lag appears between user's action and rendering result, the user will feel distracted [70, 71]. Eventually, human performance in the visual environment will become degraded. On the other hand, a human requires at least 20Hz – known as the Critical fusion frequency to provide a reasonable contiguous-looking series of images. There are two vital components that affect the interactive frame rates: polygon numbers and viewpoints [72]. For example, a realistic-looking model contains more than millions of polygons, which usually exceeds the workstation's capability; in the viewpoint area, the visibility of different parts of the model will influence the frame rate as well [73].

Since changing the scenario details in a computing system will directly affect the frame rate, the frame rate is almost always irregular. Watson completed a study to examine the frame rate variation on virtual simulation. In that study, there is a range of frame rates will not significantly affect task performance in a virtual environment. However, there is much less tolerance in closed-loop tasks, which are defined as: the task receives feedback on the correctness of the movement and performs further movement to correct errors such as placement on a pedestal [70]. In addition, the background knowledge seems to have influence on the relationship between human performance and frame rate. The experienced subjects can maintain performance at lower frame rate than inexperienced subjects [74].

To understand how the number of nodes influences frame rate, it's important know the mathematical theory behind it. A tetrahedral volumetric mesh is used to represent the physical and geometrical body of a soft tissue. One tetrahedral element has four nodes with six edges that are generated by an interpolation shape function [75]. Also, as discussed previously in the soft tissue modelling, the greater the number of nodes there are, the more the stiffness matrix requires computational processing unit (CPU) to determine the geometrical shape of the model.

Of course, the accuracy of the geometry alone is not enough to trigger the surgeon into immersion in any arbitrary environment. The texture filling the gaps between the geometrical shape and real-life realism will help create the immersion by enhancing the surface appearance of the model into realistic looking images. In its definition, the texture means a “multidimensional image that is scanned into the system utilized for increasing the model’s surface details” [76]. Usually, the texture is a 2D array that will be mapped onto a surface in the 3D model. This process is called as texture mapping. It is the process of using the texture coordinate (*u, v*) of the fragment to look up the material color of the texture image [77]. The texture coordinate *u, v* has a range from 0 to 1 in the horizontal and vertical directions that corresponds to a location in the texture image. The fragment is a tiny piece that is rasterized from the model to display the pixel color on the screen. The coordinates of each fragment are determined by interpolating the vertex coordinates, and the graphics card interpolates the texture coordinates. Each fragment contributes to one pixel on the screen.

To better understand the complexity of the simulator, the mathematical theory behind the mapping process is investigated. The fundamental graphics system is called the graphics pipeline. This simplified graphics pipeline describes each step of the rendering process from a 3D mathematical model to each frame that is displayed on the 2D screen (Figure 8). The texture data which stores the information of the texture will send information to the graphics card to compute the final color based on the incoming light and viewpoint.

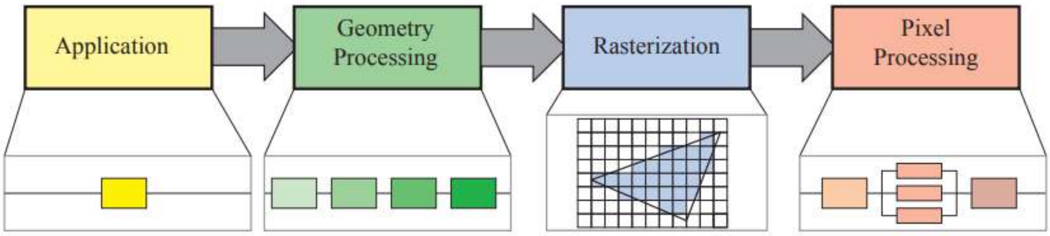

Figure 8 Simplified rendering pipeline for computer graphics. *This process describes a 3D mesh rasterized into fragments. Each fragment combines with texture data will contribute into pixel of the monitor.*

For a high-fidelity simulator, user's input passes through this pipeline and results appear from the simulator to the screen. The running speed of the pipeline becomes the crucial parameter that influences the experience. In the field of modern computer graphics, a shader can replace parts or entire functions of the pipeline.

In the case of our simulator, surgeons tend to practice the performance of the surgery on a muscle model, which will represent the accurate physical behavior like deformation and puncture. At the same time, real-time interactions maximize the learning transfer from the simulator to reality. Initially, the muscle model, constructed by millions of vertices, sends the vertex data into the CPU to determine the location of each vertex in the screen space. Then the (x, y, z) position in the object's local frame of reference is found; for example, it is (1.5, 80, 12). Then this position uses an orthographic projection to change the (x, y, z) position into a two-element vector (u, v). Now the values obtained are in the form of (0.5, 0.75). Thereafter, these texture coordinates are used to find the color at this location to form the texture image. Since the resolution of the muscle texture is, say, 256×256, the color of position (0.5, 0.75) is related to the pixel of position (128, 192) in the texture image. Therefore, the pixel (128, 192) is found in the texture image and has color, say, (0.8, 0.8, 0.7), and this color will display on the screen. See the following Figure 9 to better understand the process.

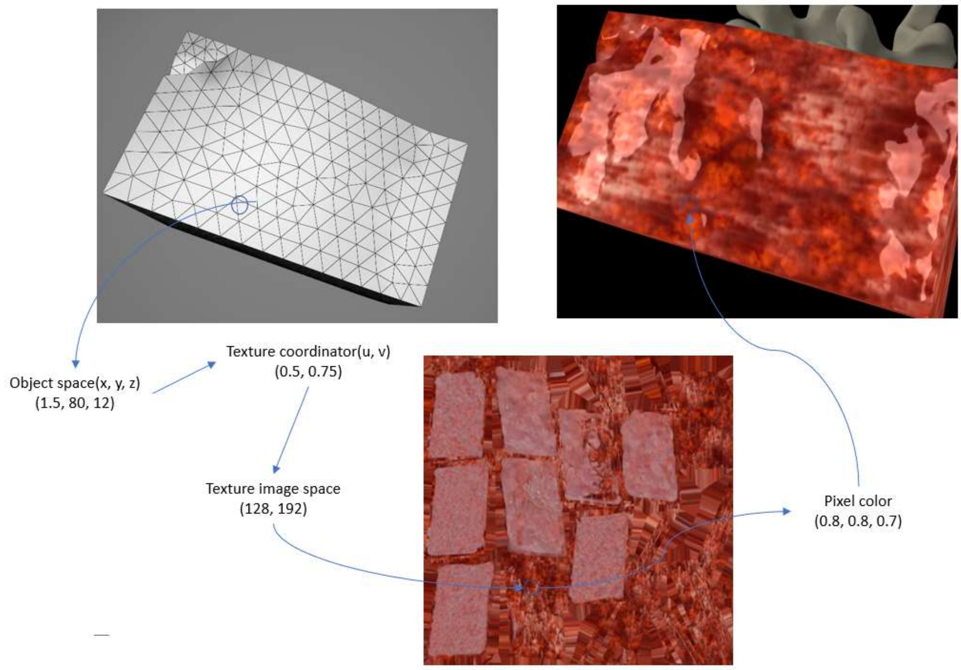

Figure 9 An example of rendering process*: the computational calculation process of one pixel on the screen.*

2.4 Simulator Fidelity

In order to describe a simulator, the term "fidelity" used all the time. In definition, the fidelity in modeling or simulation is *"The degree to which a model or simulation reproduces the state and behaviour of a real-world object or perception of a real-world object, feature, condition or standard in a measurable or perceivable manner"* [78]. But why is fidelity so important? This is because it represents the cost of the simulator and the potential learning transfer from training on the simulator, which various articles have investigated the relationship between fidelity and training effectiveness. From the perspective of cost, generally, increasing the fidelity of a simulator will lead to a cost increase [79]. In regard to the training effectiveness, Norman, Dore and Grierson [80] confirmed an improvement of simulator fidelity and performance than the no-intervention group from a group of 24 different types of simulators. Also, high-fidelity simulators have improved student satisfaction and self-confidence [81]. Lasater verified this statement by testing nursing students with high-fidelity simulation during their training program, then comparing the results without using the high-fidelity simulator, which implied that the simulation can support developing clinical judgement [82]. But, the high fidelity has limits, in which Scerbo indicated that high-fidelity simulators may not always be equivalent to high performance but rather sometimes hinders the learning process [83]. Norman, Dore and Grierson had similar results that high fidelity simulators did not have significant optimization of learning that low fidelity simulators had [80]. But those experiment has bias, as Smink, Yule and Ashely agreed [84]. Although the high-fidelity simulator provided limited improvements in additional adjustments, this does not mean that simulation fidelity is not important. They clarified that simulators still required at least moderate fidelity to produce nontechnical skill learning [84]. However, simulators for high-risk surgery should maximize fidelity to replicate the procedure as closely as possible for training the required motor skills [27].

The low-fidelity simulators have a few studies working on its validation of educational purposes [2]. Kinney's study established that low fidelity simulation was an instant learning improvement tool but there was no significant enhancement in four months compared to the training method using only lectures. However, in the research by Ryan et al. they manifested the most efficient way of simulation-based education was the progressive method, which constructed a low to mid to high fidelity approach [85].

A study published by Hyun *et al.* [86] investigated the fidelity influence in laparoscopic surgical training, which is one of the major applications of minimally invasive surgery. In that study, the fidelity level is distinguished by whether it has force feedback, or the soft tissue model undergoes linear or nonlinear mechanical behavior. The highest fidelity in their simulator is the nonlinear approximation model with accurate physical behavior; the medium fidelity contains the linear approximation model, and the lowest fidelity was a model without force feedback. Then they selected a series of performance matrices to evaluate their surgery performance: performance time $\tilde{T}$, push accuracy $\tilde{P}$, cut accuracy $\tilde{C}$ and tool control $\tilde{O}$. Those components can be defined as a linear equation,

$$Performance = s_1\tilde{T} + s_2\tilde{P} + s_3\tilde{C} + s_4\tilde{O} \tag{13}$$

where $s_1 - s_4$ are the weights, which defined by an expert laparoscopic surgeon in a successful surgery. Push accuracy and cut accuracy were given the highest weighting because these were tasks where tool coordination and depth perception was important. From their results, the haptic feedback is a crucial feature for improving the performance. Further, an effective simulator should provide both graphical and haptic feedback. However, the results also indicate that linear elasticity does not produce significant differences for these tasks compared with nonlinear elastic models.

A review article from Norman *et al.* identifies the minimal relationship between simulation fidelity and transfer of learning [80]. They conclude from 24 studies that the both high and low fidelity simulators improved the surgeon's performance, but the difference between those two are not significant. In one of the studies made by Matsumoto *et al.* [87], which educated the surgeon to practice ureteroscopic skills and stone extraction, the high-fidelity simulator contains a bench model which was made by Limbs and Things (Figure 10). In reverse, the low-fidelity simulator only consists of a coffee cup and plastic straw (Figure 10). Another example, Kinney denoted their definition of low fidelity was an anatomical model used for case studies [2]. Therefore, it is easy to conclude that every simulator considers its own interest in a measurable form, and the fidelity level does not have a clear dimensional definition for high or low [88].

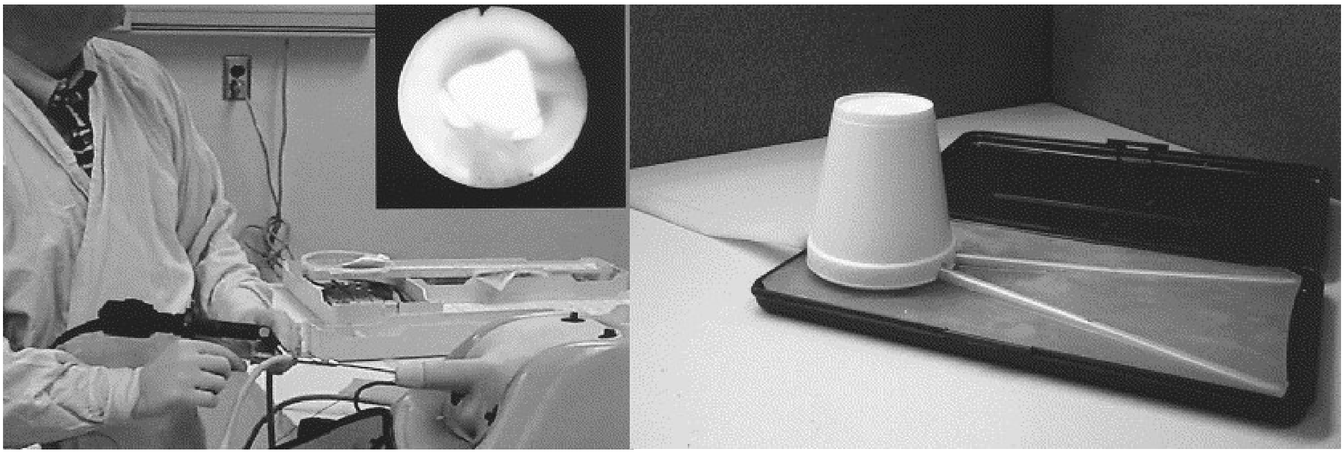

Figure 10 A comparison between low and high-fidelity simulators: *high fidelity simulator of ureteroscopy which contains the bench model with visual feedback (left). The low fidelity simulator contains a coffee cup and two straws to mimic simple tasks of the ureteroscopy (right).*

From Seropian's work [89], simulation fidelity can be categorised into three levels: low, moderate, and high. The low fidelity simulation means frequent static imagery and is vaguely defined for the purposes of introduction and psychomotor practices. The moderate or so-called medium fidelity simulation has the characteristics of the existing low fidelity simulation but also adds additional sound features and more complex components. The high fidelity simulation should comprise both realism in appearance and interaction. However, in a comparison study by Brydges et al., the low fidelity simulation did not contain a physical bench model even though it has advanced haptic and communication cues [85]. The mid-fidelity simulation referred to an inanimate plastic arm (Nasco Health Care, Model LF01121U). This model did not provide the communication cues but included physical interaction. The high fidelity simulation comprised both physical model and cues; an example could be a SimMan simulator (Laedal Medical, Model 211-00050). Cant and Cooper generated a different explanation of the medium to high fidelity simulation [8]. They indicated the medium to high fidelity simulation required a realistic environment and interacted with actual medical equipment and supplies. In the high fidelity field, Issenberg et al. assigned four categories in terms of functionality: realistic, three-dimensional procedural simulators, interactive simulators, and virtual reality simulators [1].

Although the method to measure fidelity is under debate, the fidelity can be categorised into three areas: physical, functional and psychological. As early as 1954, Miller announced this classification for the first time [90]. However, Maran considers that fidelity has two aspects: engineering and psychological. He said engineering fidelity was called physical, but functional was the same as psychological fidelity [14]. Another naming system is from Lathan et al, where in their article the psychological fidelity is called cognitive [91]. No matter how terminology is named, the physical or engineering fidelity is used to describe how the simulator looks like compared with reality. This means that this section covers all the external components, such as visual displays, controls, audio, and the physical model that drives each of these variables [92]. However, the psychological or cognitive fidelity is focusing on another perspective that describes the effects of the simulation on the trainee (i.e. communication, situation awareness) [3].

The psychological fidelity describes the degree that a user can engage psychologically and cognitively in the simulation [93]. For instance, in an aviation simulation, people are required to pay constant attention to avoid any risks, thus producing a demanding environment that resembles actual stress and workload [94]. The surgeon is also in a high-stress profession, where high stress could undermine performance [95]. Therefore, simulations with similar stress levels to the actual situation can transfer the training benefit for novel tasks [96]. Usually, the psychological fidelity can be improved by increasing the realism of clinical environment in the simulator: for instance, the time pressure, noise, and exposure to violent and distressing events were utilized in simulation [97, 98].

Physical fidelity can be decomposed into audiovisual fidelity, equipment fidelity and motion fidelity [99]. In 1982, Baum et al. completed a study that investigates the impact of both physical and functional fidelities in a training simulator. They found out in terms of simple mechanical adjustment tasks, physical fidelity had a significant effect on learning transfer, but had no major effect for function and the interaction between those two [100]. A similar result from Ilanit et al. shows that physical fidelity has a greater influence on training [13]. In this study, they set up their simulator to practice a procedural task. The training time was the measure used to evaluate trainee's performance. In summary, they demonstrated that the group exposed only to the virtual aspect of physical fidelity had a relatively similar time compared to the real-world training group. Moreover, it was shown that the group exposed only to the cognitive aspect of fidelity had significantly longer times than the previous two groups: the virtual aspect and real-world groups. For recent simulators, developing computer technology concentrates on achieving high physical fidelity in both visual and haptic rendering [101]. This means the high-fidelity simulators are extremely realistic and can provide a high level of interactivity and realism for the learner [102]. The benefits are obvious: shorter learning time and more learning transfer. But while the computer industry has achieved an unprecedented fidelity level, a high level of fidelity simulator may not always be cost-effective. As the realism increases, the extra computational load slows down the frame rate per second (FPS). Ideally, the minimum visual and haptic frame rates that do not affect the experience are 30 Hz and 1kHz, respectively [66, 103].

The results from the previous paragraph indicate that the role of physical and psychological fidelity in medical simulators is different. To practice simple skills, whether in a high or low fidelity simulator, the psychological fidelity affects the performance of surgeons more. However, precise surgical skills require high physical fidelity to make the learning transfer from simulation to reality [1, 3, 104].

In conclusion, determining the degree of physical and psychological fidelity should consider technical feasibility, cost and training needs. Thus, an important compromise should be made among those features. In other words, it is important to design which feature should be more realistic than others. There is no simple taxonomy for the fidelity degree and does not necessarily follow the principle “more is better”.

Chapter 3

3. Article Manuscript

3.1 Rationale for Study

This project aims to create a realistic virtual environment for a high-fidelity medical simulator that can help surgeons to maximize their learning transfer. Mainly, this is accomplished by using a unique methodology to understand the relationship between the computational complexity and user experience under well-designed circumstances.

3.2 Study

A comparative side-by-side cadaver and surgical simulator study exploring the balance between computational complexity and virtual graphics in a novel surgical spine simulator.

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3.2.1 Abstract:

Introduction

High-fidelity medical simulators are becoming widely leveraged in surgical education programs. They can maximize the transfer of learning from theory to reality. However, it is impossible to maintain high-fidelity without adding additional computing complexity. Therefore, the compromise between fidelity and computing in a medical simulator is essential. The purpose of this study was to identify the graphical requirements, in terms of number of nodes, to maintain a real-time high-fidelity simulation training platform (frame rate > 30 Hz).

Methods

After completing a minimally invasive spine surgery on cadavers, senior surgeons (n=9) repeated the same procedure on a developed simulation training platform containing visual, audible, and haptic feedback with 30Hz. The surgeons then immediately completed a questionnaire assessing the visual fidelity of the models and then contrasted this experience with the five other models of varying quality via image comparison. Then the simulator's frame rate or calculation speed was evaluated for each model and compared.

Results

Overall, 55% of surgeons responded that the two highest quality models best matched their experience compared to the cadaver. The remaining 45% considered the five models to be indistinguishable. The number of nodes and the frame rate revealed a positive linear correlation ($r^2 = 0.925$) and the number of nodes had impact on perception (p=0.02).

Conclusions

The model quality affects the fidelity by adding computational complexity as it may slow the refresh rate. Feedback marginally favouring of the higher number of nodes was observed, and future studies may serve to objectify this threshold.

3.2.2 Introduction

Medical simulation, an innovative method in surgical education, aims to replace traditional training systems currently in use. The potential of this training system lies within its ability for residents to develop and refine surgical skills while eliminating ethical and cost issues associated with cadavers or animals [1]. In the field of medical simulation, high visual fidelity is becoming an essential target. In simulation, fidelity, *"the degree to which a model or simulation reproduces that state and behaviour of a real-world object or perception of a real-world object, feature, condition or standard in a measurable or perceivable manner"* [2], is often referred to qualitatively with most research groups failing to quantify high and low fidelity [3]. However, for the purpose of this study, high fidelity is defined as containing a concrete benchtop with some form of visual display and interactive haptic output [4 – 6]. Few studies discuss which parameters researchers should consider while developing the visual component of a virtual reality simulators. Often, these studies emphasize the importance of realism to trigger the same psychological and physical immersion as would be experienced in surgery. Although the criteria for sufficient fidelity in simulation for educational purposes is poorly defined, currently most researchers tend to pursue standards of high fidelity [7]. High-fidelity simulators can lead to student satisfaction, self-confidence, and the ability to transfer the acquired skills to a surgical setting [6, 8].

To accurately represent soft-tissue in the medical simulation, surface and volumetric models are used to visualize the geometry of the tissues as based on the demand of computer efficiency or physical accuracy. To build geometrically-identical tissues, surface models are more advantageous due to the minimal number of nodes, but often lead to invalid physical deformations [9]. Moreover, considering the geometric deformations to tissues undergoing cutting and penetration process in the simulation, a volumetric model is more relevant for our high-fidelity simulation platform, due to physically its requirement for delivering precise data matrices and geometrically accurate representation. With the rapid development of the computational industry, increased computational power reduces the burden of calculation time of the volumetric model and optimizes the graphics for simulation display. In general, there are two ways to augment of the visual feedback in virtual reality: (1) adding complexity to the objects and (2) mapping textures on the surface of the objects. The first method adds nodes to the model for increased force feedback accuracy and realistic graphical representation of the topological changes under usual surgical manipulations (such as deformations, cutting, and penetration) [10]. Even though the extra polygons of the model improve the geometric and physical details, the complexity increases the computational time per frame or frame rate. When this frame rate per second (FPS) becomes less than 20 Hz, discontinuous and lagging graphic feedback affects the user experience, which is related to the rate at which the brain processes visual data [11]. However, real-time simulators aim to provide feedback at 30 Hz as a requirement during the design phase to match the required frame rate [7, 12].

Various simulation platforms simulate soft tissue models generated by the finite element method [13]. The generated volumetric model provides physical accuracy but may hinder the interaction in real time simulation. The ability to provide real-time interaction is important for the educational value of the simulation platform, effectively allowing for surgeons to efficiently practice the surgical procedure. This also affects the ability of the simulator to accurately evaluate operational performance [14]. Besides the graphical accuracy, the tissues' response (both visually and topographically) when undergoing loading input by the surgeon is also essential to the simulation.

Technological developments allow for faster calculation, but the visual realism and user experience may still be compromised [15]. It is also unclear how and which quality parameter should be modified when the computational cost exceeds the computing allowance. Therefore, the goal of this work is to determine the relationship between frame rate, number of nodes and visual feedback by comparing surgeons' feedback on a novel surgical simulator immediately after having performed an identical cadaver surgery.

3.2.3 Methods

The surgical simulator under consideration is a physics-based simulator of a minimally invasive spine single level fusion. The geometry of the surgical scenes in the simulator are reconstructed from patient specific data. This medical simulation was run on a high-performance gaming laptop (i7-8750H) with Windows 10 operating system. The rendered images were displayed on two flat panel monitors to match the interface in the operating room: one built-in monitor and another external touch screen monitor which produced 120Hz and 60Hz refresh rate,

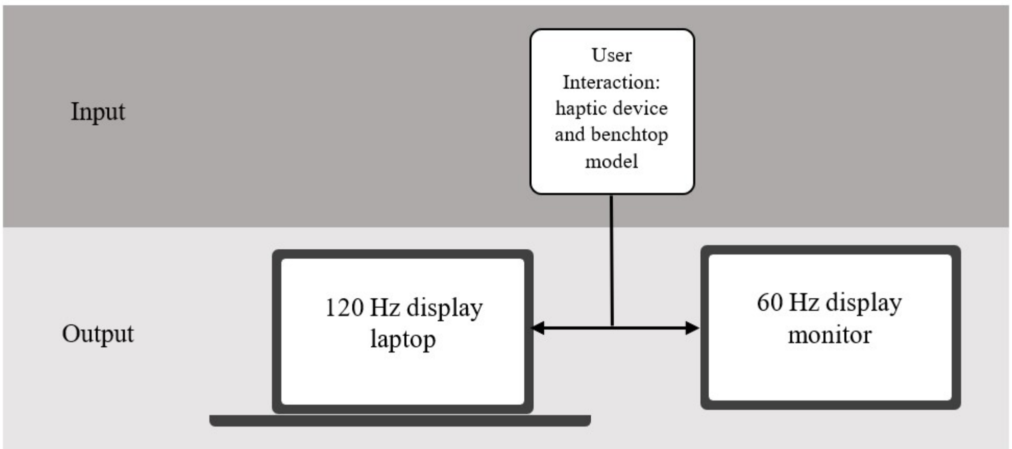


Figure 1 The platform set-up. *Left is the laptop that runs the 120Hz display, the haptic device and benchtop model are in the middle, and right is the external touch-screen running the 60Hz display. The surgeon operates the haptic device based on the visual feedback from both monitors*

respectively. Haptic feedback was provided from a six-degree freedom ENTACT W3D device (Figure 1).

In the simulator, an experiment was performed to access the volumetric models that reproduce the physical behaviour of physiological volumes (e.g. the behaviour of muscle). A total of six artificial muscle models were generated using a tetrahedral mesh with incremental element size starting from 3mm up to 8mm. Due to the frame rate requirement, the mesh model containing the element size that produces the 30Hz was embedded into the training platform to provide complete visual and haptic feedback for the participants.

Next, a texturing technique using diffuse and normal mapping methods was added to the muscle models to maximize the realism for participants. To examine the visual feedback associated with actual surgery experience, internal and external textures were chosen because they are major visual components during the simulated minimally invasive surgery which uses an endoscopic viewpoint. The external texture reflected the superficial area of the muscle that produce the specular effect of biological fluid during surgery. The internal muscle texture represented the deep muscle tissue under cutting and penetration. These texturing treatments were based on videos and images collected during cadaver experiments and were implemented using the industrial graphical painting software *Autodesk Maya* (2019, San Rafael, United States) and *Substance Painting* (2019.3.1, San Jose, United States). Therefore, the applied texture provided the fidelity required to maintain an immersive experience while using the medical simulator. To determine whether the texturing treatments (diffuse and normal mapping) affected the computational complexity, each model was run through an additional trial to compare the frame rates. As shown in Figure 2, the solid colour replaces the diffuse and normal maps, and the other functions such as collision detection and deformation remain the same.

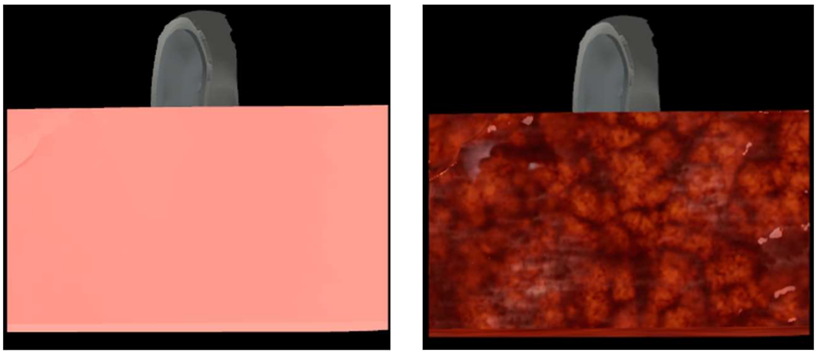


Figure 2 The example of solid colour treatment: *left is solid colour treatment and the right is full texture treatment.*

Images were used to compare the visual fidelity of different computational complexities; those images were recorded visual feedback for other generated muscle models that under the same operation. Since the mesh should be deformed and penetrated by the instrument, the leftover cross-sectional area of the mesh was selected as visual feedback to compare the influence of number of nodes. Following collision detection between the instrument and tetrahedral mesh, the contacted element would be removed, leaving the rest of the mesh to express the real penetration in the platform. Images of these mesh were used in a questionnaire for surgeons to evaluate the visual feedback. Nine senior surgeons participated in the questionnaire. They completed a minimally invasive spine surgery on a cadaver, then immediately repeated the identical procedure on the surgical trainer/simulator. The surgeons then completed a questionnaire comparing these models in terms of visual satisfaction contrasted with the cadaver surgery (questionnaire in Appendix A). This questionnaire contained a point scale from 0 to 5, representing "not applicate, very poor, poor, moderate, good, excellent," respectively. The questions were:

1. How do you rate your overall impression of the visual graphics compared to real surgery?
2. How close is the internal impression of the model in the demo to reality?
3. How close is the external impression of the model in the demo to reality?

4. Which image is best suitable for your experience?

To complete any required statistical analysis, as in the case of Question 4, the score of each image is ranked from 5 to 1 based upon the number of nodes used (large to small). Should the participants determine image to be equal in quality, a score of 3 was allocated. The null hypothesis of the number of nodes has no impact on visual feedback was evaluated by processing the data and leveraging the one sample sign test statistical method. A p value of less than 0.05 was deemed to provide statistical significance.

3.2.4 Results

1. The relationship between number of nodes and FPS. Although the element size is the fundamental parameter to determine the model shape, it is impossible to define a uniform element size for each face. Therefore, the number of nodes provides a better representation for the computational complexity of the model. A quadratic function relating the average element size and number of nodes was found $NON = 3170.9S^2 - 45458S + 245385$ with $r^2 = 0.9828$ where NON and S mean number of nodes and element size (Figure 3). The frame rate corresponding to each number of nodes were collected during the simulated operation (Table 1). To account for the time the surgeon spends on the simulator's module, every muscle mode is run through the simulation for five minutes to collect the average frame rate. The frame rate remained stable with little change during the simulated operation. Based on the frame rate results a positive and linear correlation was found with respect to the number of nodes $FPS = -0.0004NON + 77.952$ with $r^2 = 0.925$, where NON means number of nodes (Figure 4). In terms of frame rate, the smallest two element size models were below the 30 Hz range, which is the minimum requirement to prevent losing real-time interaction [7, 12].

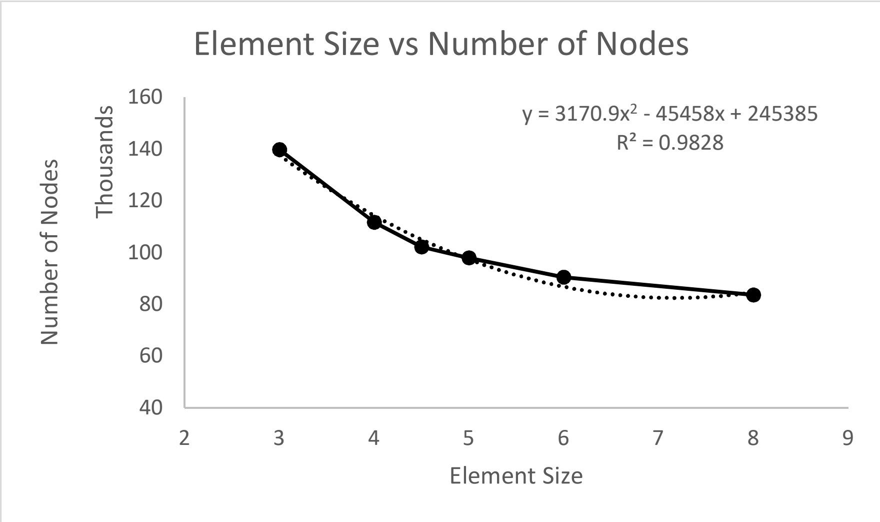


Figure 3 Recording of the relationship between average element size and number of nodes.

Table 1 Model performance in the simulation platform.

Element Size (mm)	Number of Nodes	FPS(Average)	FPS (Solid Colour)
3	139788	21	30
4	111744	28	40
4.5	102216	31	41
5	97896	37	42
6	90426	42	53
8	83622	43	58

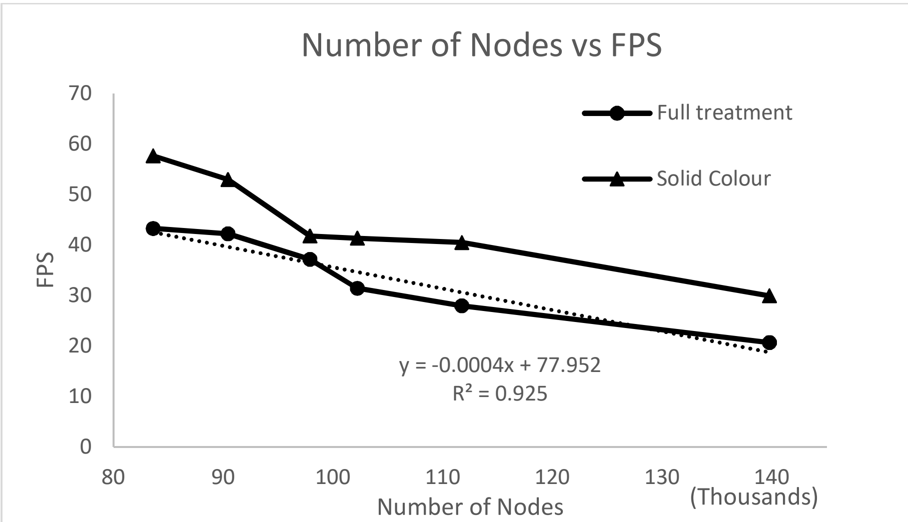


Figure 4 Comparison of average frame rate between different surface treatment with different number of nodes

2. The effects of surface treatment on computational complexity. After replacing the texture produced using diffuse and normal mapping, with a solid colour on the models, an improved and linear frame rate was observed for all sized meshes (Figure 4). As a result, it is concluded that surface treatment accounts for universal delays due to computational complexity. The relationship in Figure 3 allows an estimation to be determined for the added computational complexity by the textures.

Table 2 Visual feedback questionnaire.

Participant	Q1	Q2	Q3	Q4
1	5	3	3	Same/3
2	4	3	4	Same/3
3	4	3	4	No.2/4
4	4	3	5	Same/3
5	4	4	3	No.1/2/4.5
6	4	3	4	No.2/4
7	4	3	3	No.1/5
8	3	4	3	No.1/5
9	3	3	4	Same/3
Mean	3.89	3.22	3.67	3.83

3. Evaluation of the visual feedback by senior surgeons. To summarize the results from the questionnaire, the mean score for overall impression (Question 1) was 3.89 ±0.6 (range: 3-5), a score which represented a good satisfaction with the overall visual graphics. Both internal and external models were considered over moderate satisfaction as well, but the trends support the external expressions were scored slightly better than the internal expressions (Table 2). The mean score for internal impression was 3.22 ±0.44 (range: 3-4), and for external impression was 3.67 ±0.71 (range: 3-5). For question 4, best suitable image for user's experience, five of the surgeon participants reported that either the first or the second smallest element sizes best suited their experience in the operating room compared to the cadaver trial they had just completed. The remaining four participants indicated no difference among the five element size models. Therefore, the data supports the use of a high number of nodes to enhance the details on the muscle model during regular surgical manipulations (p=0.025).

3.2.5 Discussion

Based on the present study, with respect to fidelity, the number of nodes provided important information. It visually affects the level of realism in displaying the cross-sectional area after surgical tool penetration. Also, from the simulation point of view, the larger the number of nodes there is, the more accurate the physical behaviour would be [16]. Due to the nature of this simulation platform, the surgeon would spend significantly more time looking at and working with the internal texture. Thus, the internal texture including the cross-section area have a greater impact on visual feedback than the external effects. A high number of nodes reflects a more representative visual appearance, but at the same time this property decreases the response time of the computer. Both of the smallest element sizes failed to produce 30 Hz frame rate, which is required for real-time manipulations [12]. Similarly, in a real-time game engine, adding higher mesh resolution enhances the apparent geometric detail of fracture [17].

When comparing each model's mesh performance with respect to the texture treatment, an unusual frame rate drop was observed after the number of nodes was increased past 97,896, an average of 5 Hz decrease was observed. Further investigation needs to be performed to understand how textures influence computational complexity.

After comparing the surgeons' satisfaction for the images provided in the questionnaire, the best model appears to be the one with the largest number of nodes, which means this larger number produces a more realistic muscle cross section. However, even if this platform runs on one of the most advanced computers at the time of the experiment, it is still difficult to produce a realistic representation of the surgical area without sacrificing the interactive experience. Since the simulation should maximize transference of surgical skills, which needs a high degree of realism and fidelity, an interactive simulation platform without real-time feedback is not feasible [18]. Although researchers continue to debate on the importance of fidelity for a surgical simulation towards transference of learning, high-fidelity simulation provides more confidence in the simulation experience for the surgeons [19]. For the satisfaction of the visual feedback, most participants still indicate the smallest element size is most suitable for the realistic experience. This result proves that the training simulator platform still needs an accurate visual mesh to model the surgery, especially the cross-section, which is influenced mainly by internal texture and number of nodes. For a volumetric model, more nodes can improve the smoothness of the tissue during cutting surface and prevent sharp edges associated with the significantly higher element size [20]. The mesh size could potentially increase the accuracy of haptic fidelity, which is associated with the contact information collected from the models [21]. However, the difference is small: 44% of the participants accepted the mesh with the lower number of nodes with no a significant difference between models. Since the frame rate linearly correlates to the number of nodes, an estimate can be determined for any given number of nodes. After considering both the frame rate and visual feedback results, a balance is required where the model with a larger number of nodes is rated best for producing realistic visual feedback and real-time interaction. In the future, by matching the minimum frame rate requirement, it is possible to produce desired realism in the visual feedback using this relationship. Similar studies, such as Ullrich's work, demonstrated the same linear relationship between number of nodes and computational time per frame [22].

Two limitations appeared during the experiment. First, the sample size of the questionnaire is fairly small comparing with ideal sample size (n>30). Nevertheless, participants in the questionnaire were senior surgeons with broad experience in an operating room therefore providing the required insight. Given the unique set-up of this experiment, using an immediate comparison to a cadaver surgery provides the author's confidence in the reported results. However, the methodology of this experiment aims to add to a quantifiable value for fidelity, which may be utilized by researchers to validate the visual framework of future surgical simulators. The second limitation is that the participants were unable to use the simulator with the different models and frame rates due to time constraints. While similar studies examined the effect of frame rates, it would still be valuable to test with senior surgeons in the context of this study and its parameters.

Because no standard has been established for determining fidelity, describing fidelity in the context of a surgical simulator is still based on physical and psychological perception [6]. However, it is often vague and differently defined based on the trainer's needs. For example, the simulation platform in this study is considered to have high fidelity because it contains virtual environment (computer display), haptic feedback, and benchtop model for interaction. Therefore, it is feasible to consider adding the frame rate or the capability of frame rate productions to quantifying the fidelity of the simulator. On one hand, frame rate is a critical parameter, which heavily influences the cost of a training platform and enhances the immersion to connect the virtual and real-life experience. On the other hand, it is a quantifiable parameter providing a method determine whether this platform meets the needs of the surgical method like head-mounted display or continuously accurate haptic output [23].

3.2.6 Conclusion

In summary, the relationship between model complexity and simulation frame rate time were examined in this study. Nine senior surgeons provided an opinion based on experience compared with the procedure on a cadaver within a short period of time. This unique methodology produced a final compromise when graphical requirement exceeded the computational budget. A new approach to determine simulation fidelity is suggested in this study. Future work will focus on implementing a dynamic platform that allows various number of nodes to be modelled in a desired region to maximize visual performance with a given computational power while investing in optimization.

3.2.7 Appendix A

Visual Feedback Survey

Q1 How do you rate your overall impression of the **visual** graphics compared to real surgery?

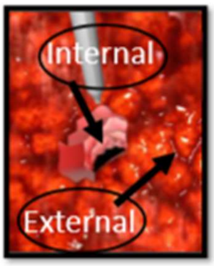
Not Applicable | Very Poorly | Poor | Moderate | Good | Excellent

Q2 How close is the **internal** impression of the model in the demo to reality?

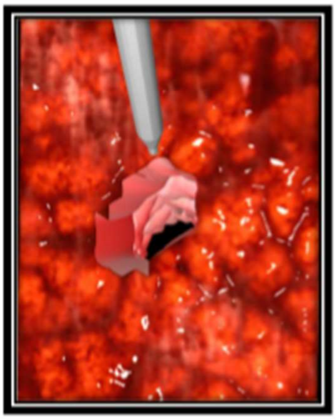
Not Applicable | Very Poorly | Poor | Moderate | Good | Excellent

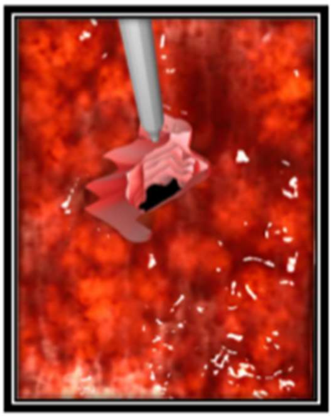
Q3 How close is the **external** impression of the model in the demo to reality?

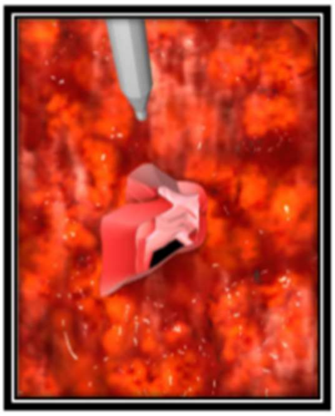
Not Applicable | Very Poorly | Poor | Moderate | Good | Excellent

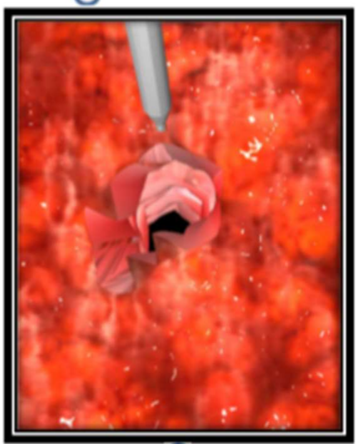


Q4 Which image is best suitable for your experience?









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4. Additional Materials

4.1 Summary

To maximize the visual immersion of a high-fidelity medical simulator, this thesis produced two ways to achieve this goal: the exact geometry of the real patient and realism texture. The accurate geometry can serve as a beacon, which helps surgeons tracking where the locations of their surgery tools. From this perspective the model includes skin, vertebral column, rib, femur, hipbone and sacrum (Figure 11).

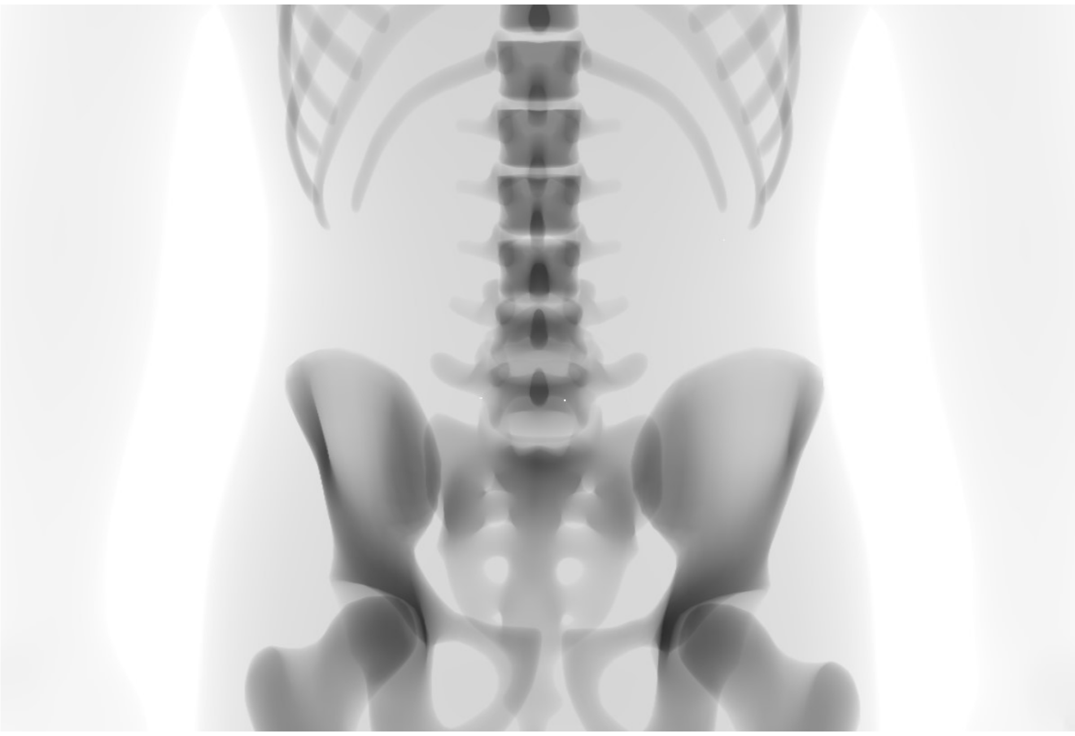

Figure 11 Model meshes displayed in intraoperative camera: *it guides surgeons during their experience of the medical simulator. The model mesh contains accurate geometrical shape of human skin, vertebral column, rib, femur, hipbone and sacrum.*

The texture method is aiming to produce the realism experience for surgeons in the simulator. Thus, the target is replicate the user experience by using the computer graphics. To achieve this goal, the author captured multiple images from cadaver experience and real surgery (Figure 12). Thus, based on the reference picture, the first prototype of the muscle texture is showing in Figure 13. However, as suggested by the surgeons, the first prototype is failing to present the ligament and body fluid of the real muscle model, which are important features for immersion. Thus, the second prototype matches those requirements. Besides the regular diffuse texture that represents the color, the normal map creates the irregular surface and replicates the effects of body fluid. The results are showing in Figure 14, which was highly satisfactory with nine senior surgeons.

Figure 12 The reference images to create realism for feedback. *The left image is captured from the cadaver experience and the right one is from the real surgery that displaying the cross-section area of the inside muscle tissue*

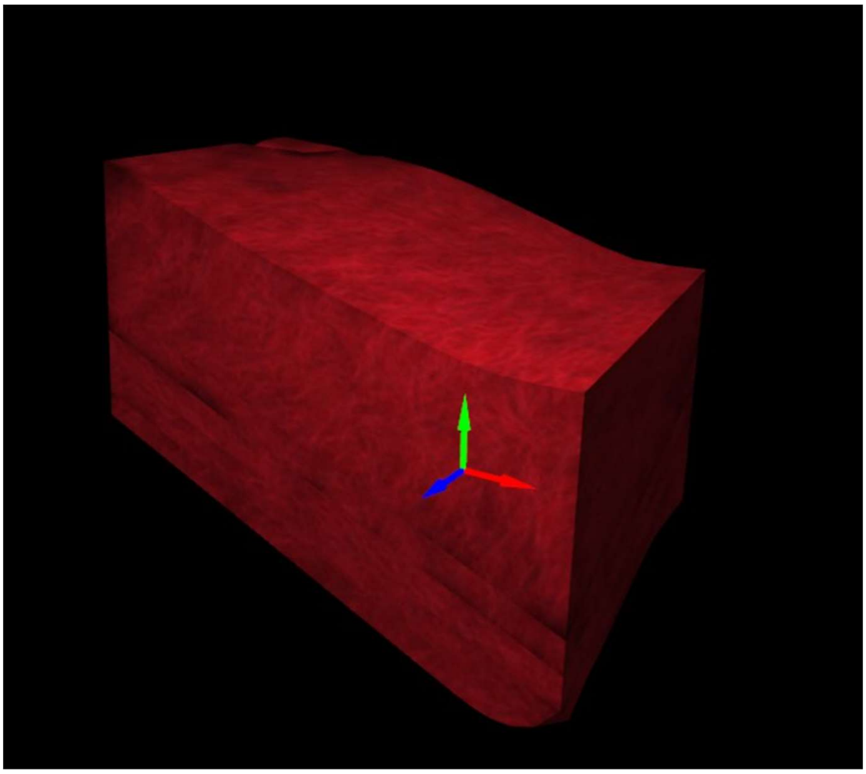

Figure 13 The first prototype of the muscle model*: it only replicates the muscle color and muscle layers.*

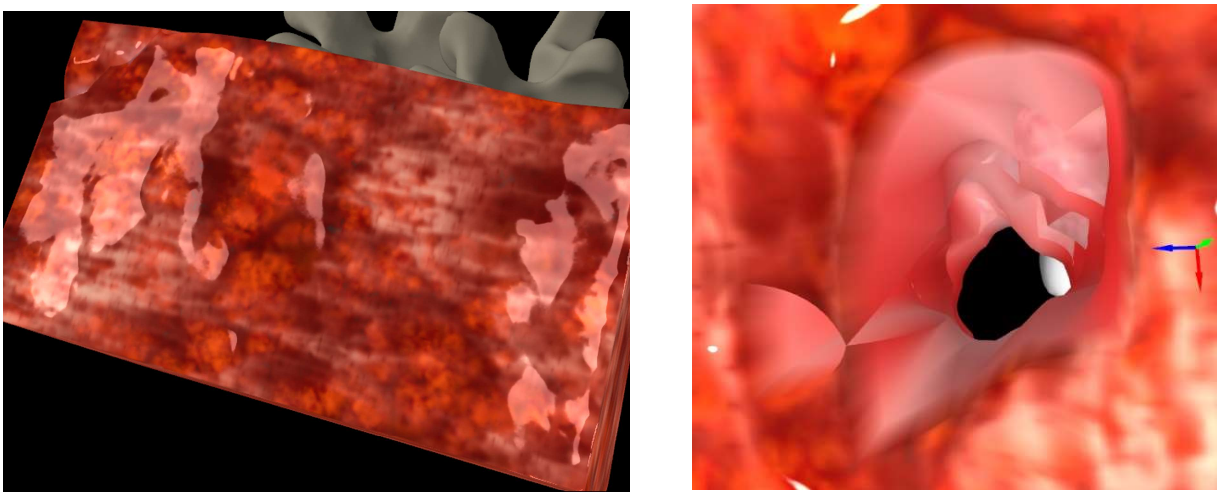

Figure 14 Optimized visual texture: *it replicates the color of the muscle and ligament on the left. And on the right displayed the internal muscle texture and specular effects from body fluid.*

The thesis describes the relationship between computational complexity and visual graphics. The number of nodes has impact on the visual feedback with $p = 0.025$. But the impact does not significant influence the visual feedback based on previous results from the surgical questionnaire.

In conclusion, this unique methodology provides evidence of the final compromise when graphics needs exceed the computational budget. And those results provide evidence on how to enhance the visual experience of high-fidelity simulators.

4.2 Future Direction

As mentioned in the methodology, the study involved nine senior surgeon participants. Despite their extensive experience with evaluation simulators, the number of surgeons was still insufficient to represent the entire surgery and residential community. In the future, it will become more valuable to collect more data from a larger sample size from multiple institutions to evaluate the graphics requirement of this medical simulator.

Moreover, this study is focusing on the external and internal textures created by the existing computer graphical technologies like diffuse mapping and normal mapping. Indeed, those techniques represent the visual feedback in a stabilized way, which means the texture will not change over time. Therefore, to optimize the texture in the future, dynamic visual feedback can take into consideration, which further improves the visual fidelity, but requires a computer with a higher calculation speed.

The graphics developed in this simulator need further development for wider applications. Although there is still controversy in the field of fidelity, a certain degree of fidelity is still important for end users. Future extensions of this project can focus on to investigations of how much graphics fidelity end users require. A system with different levels of fidelity can help the surgeons perform controlled experiments and summarize their performance based on well-designed indicators to determine the minimal graphics fidelity before performance degradation.

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