Validation Study of a Wave Equation Model of Soft Tissue for a New Virtual Reality Laparoscopy Training System

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Abstract. Despite the benefits of laparoscopic procedures for the patients, this technique comes with a number of environmental limitations for the surgeon, which therefore require distinctive psychomotor skills. VR training systems aim to improve these skills. For effective transference of skills from these training systems, it is important to mimic the surgical environment; including the soft tissue models. This study introduces a novel two dimensional wave equation model to mimic the interactions between soft tissue and laparoscopic tools. This model accounts for mechanical and material properties of the soft tissue. This study also proposes a new face validation technique, for an objective analysis of the developed model as a viable soft tissue model. The statistical analyses and computational cost support the use of wave equation as a replacement for present models. In the future, this model will be applied to a novel VR surgical training system for an enhanced training experience.

Keywords: soft tissue model · surgical training · two dimensional wave equation · finite element analysis (FEA) · computer based models · virtual reality (VR) training

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1 Introduction

The medical industry is motivated by innovation in procedures, devices, and drugs. Laparoscopic surgeries, an innovation from the recent decades, are gaining popularity due to the benefits for patients. Some benefits of this procedure are: shorter recovery period, reduced blood loss, and less scarring, which are all results of the smaller incisions used in these surgeries [1,2]. The smaller incisions result in various environmental constraints that hinder the performance of inexperienced surgeons; some examples of these are: 2-dimensional view of operating area, limited hand-eye coordination, increased tremor due to long, inflexible tools and restricted movement [3,4].

1.1 Need for Laparoscopic Surgery Training

The environmental constraints in laparoscopic surgeries can result in some serious complications; for example: bleeding, infection, visceral injury or death. These complications are directly related to the amount of practice or experience of the surgeon; for example there is a higher likelihood of complications in the surgeon's first ten procedures [5]. Moreover, the smaller incisions entail distinctive psychomotor skills that vary significantly from those used in open surgeries; therefore requiring intensive and repetitive training to acquire the required skills and reduce the likelihood of complications [6,7].

1.2 Present Surgical Training Systems

The significance of training in laparoscopic surgeries has brought about extensive research towards the development of training systems for teaching hospitals [4]. The conventional training systems are either live patients or cadaveric humans. However, these systems come with various legal, ethical and cost issues, resulting in teaching hospitals' move towards the use of inanimate training systems [4], [8].

Inanimate training systems are popular due to their adaptability to the needs of the user, and the system's capability of repetitive training without risking the lives of patients [8-10].There are two major inanimate training systems: synthetic material and virtual reality (VR) models. The VR training system is being extensively researched in this area due to its promise of realistic simulations and user interactions [4], [8], [10].

In the following sections, the authors include their observations of previous works in the field of VR training systems and the soft tissue models used. Subsequently, the authors introduce their novel soft tissue model, and a novel face validity test that aims to provide objective results. Lastly, statistical analyses are performed, followed by a discussion of the results.

2 Previous Works

In recent years, VR training systems have been extensively researched and developed for use in surgical training; inspired by the flight simulators used for training pilots [10,11]. These systems aim to provide medical students or young surgeons essential laparoscopic skills while limiting the risks on patients. Another application of these systems is surgical planning with patient specific data [12,13].

VR surgical training systems range in price from US$5,000 to US$200,000 [14]. These systems provide skills, which span from basic skills to complete laparoscopic procedures [14,15]. Some commercially available training systems include: MIST VR, SIMENDO simulator, LAP Mentor, and LapSim. These training systems are designed to refine the user's dexterity within the constrained environment of a laparoscopic procedure, while removing the risks associated with on-patient training [3], [16]. VR training systems are popular due to their promise of intensive and repetitive training without risking the lives of patients, while providing objective performance assessment to the user [3], [4], [10].

2.1 Soft Tissue Models in Present VR Training Systems

There are various components of the VR training system that work together to create the ideal system for effective training in a surgical task or procedure. This paper highlights one such component; the visual representation of soft tissues within the VR environment. The models of soft tissue are important because they represent the environment of a laparoscopic procedure and how laparoscopic tools' manipulations would affect the soft tissue; therefore accurate representation of this environment would allow the users to transfer the skills acquired from the training system to the operation room (OR) [8], [17], [18]. Not only the realism of this model is important, but also the rate at which the manipulations take place; for this application, the soft tissue models should be transformable in real-time [18,19]. Researchers, also, have to take into consideration the effects of the computational cost on the user's ability to interact with the environment [10].

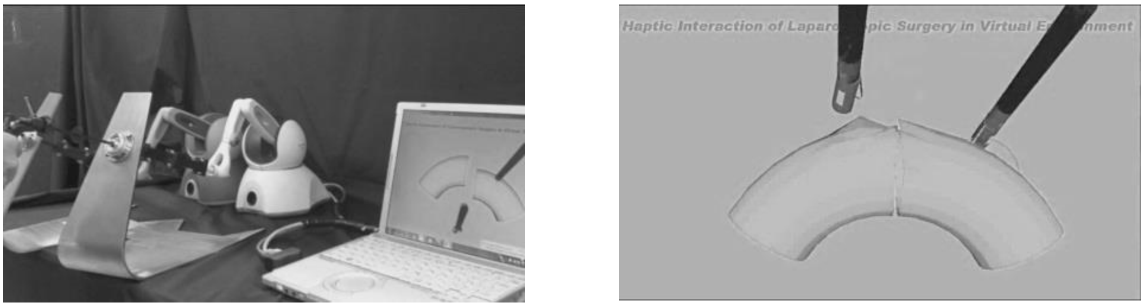
VR training systems, today, use mass-spring model, finite element models, or mesh-free models to model soft tissue in the environment. These models demonstrate the obstacles associated with modeling soft tissue in VR as a result of the need for balance between accuracy and computational cost.

Mass-spring model is the most commonly used soft tissue model in VR surgical training systems [20]. This is because of its low computational cost, which makes it the ideal model for real-time manipulations. This model uses the Kelvin-Voigt model and therefore implements springs and dashpots to model the viscoelastic behavior of the soft tissue [19].

A more accurate representation of the soft tissue in VR is the finite element model but the constraint of this model is its computational cost, which makes it less than ideal for real-time manipulations [19,20]. On the other hand, mesh-free models are specifically designed to meet the requirements for real time manipulation in a surgical training device. In this model, the nodes are not connected in a mesh, therefore permitting the cutting and reconnecting of the model [19].

The present VR training system at BART LAB uses a simplified spring-mass model [21]; therefore this study aims to go beyond and enhance the user interface through the development of novel soft tissue models.

2.2 VR Training System at BART LAB



(a) (b)

Fig. 1. The (a) physical and (b) graphical interface of our VR training system

Inspired by da Vinci Skill Simulator by Intuitive Surgical, at our lab, a researcher has developed a surgical training device. The Skill Simulator is a supplementary product available with the da Vinci robotic surgical system and provides training to users. The system has a realistic virtual environment but lacks a human interaction aspect. Therefore the BART LAB VR training system focuses on the human-robot interface [21,22]. The BART LAB training system is displayed in Figure 1 (a); it includes two Phantom OMNI devices and a tool holder to mimic the physical setup of a laparoscopic procedure. On the other hand, Figure 1(b) demonstrates the VR environment of the training system.

2.3 Limitations of Present Soft Tissue Models

VR training systems are gaining popularity among teaching hospitals due to their promise of greater patient safety, but they are still are not widely used due to their limitations. As discussed in the earlier subsection, soft tissue models play an important role in the success of a VR training system and its ability to teach the distinctive psychomotor skills that are required for laparoscopic procedures. A limitation of these models is their ability to simulate, realistically, the interactions between internal organs and laparoscopic tools [8].

The soft tissue models used in VR training systems are either simplified or are computationally expensive. These models propose a need for a novel soft tissue model that can mimic mechanical, material, and visual properties, while maintaining the need for real-time manipulations. This paper presents a novel soft tissue model, using a two dimensional wave equation to improve the realism of the training system and consequently increasing the transference of skills acquired on the training system.

3 Approach

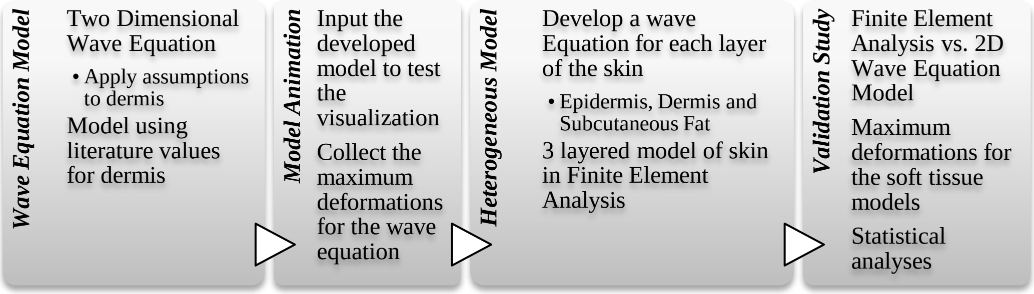


Fig. 2. Approach of this study: (1) to develop a novel model of a computer based soft tissue and (2) to perform a validation study on the novel model.

The computer used for the development of the novel computer based soft tissue model and validation study has the following specifications: Intel Core 2 Duo 2.66 GHz processor, NVIDIA GeForce 9400 GT graphics card, 4 GB RAM and a 160 GB hard disk. An overview of the approach of this study can be seen in Figure 2, which is discussed in further detail in the next two sections (Section 4 and 5).

4 Modeling Soft Tissue Using Two-Dimensional Wave Equation

Engineers study vibrations in elastic, flexible threads and membranes using wave equations; a type of partial differential equation. This study aims to use this equation to model the interactions between laparoscopic tools and soft tissue in a laparoscopic surgery for virtual reality training systems. Equation 1 is the two dimensional wave equation, which is used to model vibrations in membranes; in this equation u(x,y,t) is the displacement function, T is the tension per unit length, and ρ is the density of the membrane. Equation 1 is based on Newton's Second Law.

$$\frac{\delta^2 u}{\delta t^2} = c^2\left(\frac{\delta^2 u}{\delta x^2}+\frac{\delta^2 u}{\delta y^2}\right);\ c^2 = \frac{T}{\rho} \qquad (1)$$

Using initial and border conditions, Kreyszig et al. present a solution for the two dimensional wave equation, as seen in Equation 2. This solution is developed using double Fourier series and therefore B_{mn} (Equation 3), is the Euler formula of the Fourier coefficients, f(x,y), which is also the function representing the initial displacement. The solution is developed to model a drum membrane's response to being hit by a drumstick [23]. In Equations 2-3 the variables are defined as follows: B_{mn} is the Euler formula, B_{mn}^* is the relationship that takes into consideration the initial velocity, a and b are the boundary conditions, and λ_{mn} is the eigenvalue of this equation.

$$u_{mn}(x,y,t) = (B_{mn}\cos\lambda_{mn}t + B_{mn}^*\sin\lambda_{mn}t)\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}, \qquad (2)$$

$$where\ m = 1,\ 2,\ 3\ldots, n = 1,\ 2,\ 3\ldots, and\ \lambda_{mn} = c\pi\sqrt{\frac{m^2}{a^2}+\frac{n^2}{b^2}}$$

$$B_{mn} = \frac{4}{ab}\int_0^b\int_0^a f(x,y)\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\,dx\,dy \qquad (3)$$

Structural and mechanical engineers use wave equations to study the effects of vibrations on various structures; for example beams, rods, cables and plates. These studies idealize the structures as they are considered homogeneous and isotropic materials, which are composed of continuous chains of mass and spring [24]. Engineers can therefore use this model to determine the feasibility and strength of a structure; for example to observe the response of buildings in earthquakes [25]. Despite these applications of the wave equation in engineering, the authors have not encountered any previous applications of this model to mimic the behavior of soft tissue in virtual reality surgical training systems.

4.1 2D Wave Equation of Dermis

The skin is a viscoelastic, non-homogeneous and anisotropic material. The mechanical and material behaviors of the skin are substantially dependent on the collagen and elastic fibers of the dermis; therefore this is the layer of the skin discussed thoroughly, in this paper [26-28]. In this section, the development of the two dimensional wave equation of dermis is discussed because of the role this tissue plays in the mechanical behavior of skin [26]. Other layers of the skin that are observed in this study are the epidermis and the subcutaneous fat. The three layers are used to develop a heterogeneous material, much like the skin, to model the soft tissue.

Assumptions of Wave Equation. There are five key assumptions that are applied to the 2D wave equation to get the solution in Equation (2). These assumptions are applied to the dermis, to demonstrate limited effects on the mechanical properties of the tissue.

1. Mass of dermis per unit area is constant
2. The dermis is flexible therefore bends without resistance.
3. The dermis is stretched and fixed throughout its boundary; as it is held in place by bones and connective tissues. This stretching results in a uniform tension, T, per unit length, which is constant during motion.
4. The deformation of the membrane is small compared to the size of the dermis, which is plausible since the area of deformation is smaller than the dermis that covers the entire body.
5. The membrane is thin; this is the rationale for modeling a single layer of skin, the dermis, using this equation. Multiple two dimensional wave equations are used to model all of the layers of the skin to show how they would interact to create a specific manipulation or deformation.

Literature Values for the Wave Equation Model. Here we look at the literature values of the mechanical and material properties of the dermis, listed in Table 1, which are required for the development of a wave equation model of the dermis. These properties will define the boundary and initial conditions of the soft tissue. As mentioned in the assumptions, multiple two dimensional wave equations are developed for the layers of the skin therefore a similar list is compiled for the epidermis and subcutaneous fat.

Table 1. Mechanical and material properties of dermis, a layer of the skin.

Properties of Dermis	Values
Area of Dermis	$60mm \times 60mm = 3600mm^2$
Thickness of Dermis	$1mm$ [29]
Volume of Dermis	$60mm \times 60mm \times 1mm = 3600mm^3$
Weight of Dermis	$1.8 \times 10^{-8} \frac{g}{mm^2}$ [27]
	$\therefore Weight = \left(1.8 \times 10^{-8} \frac{g}{mm^2}\right) \times 3600mm^2 = 6.48 \times 10^{-5}g$
Density of Dermis	$\rho = \frac{m}{v} = \frac{6.48 \times 10^{-5}g}{3600mm^3} = 1.8 \times 10^{-8} \frac{g}{mm^3} = 18 \frac{g}{m^3}$
Prestress (along the fibers)	0.024 MPa [28]
Prestress (across the fibers)	0.0093 MPa [28]
Prestress[1]	$F = \sqrt{0.024^2 + 0.0093^2} = 2.57 \times 10^{-2}MPa$
Tension	$T = (2.57 \times 10^{-2})(60 \times 10^{-3}) = 1.54 \times 10^{-3} \frac{N}{m}$

Applying Properties of Dermis to the 2D Wave Equation. This study proposes a simple 2D wave equation model to mimic a simple interaction between soft tissue and laparoscopic tools. Therefore the 2D wave equation is used to model the deformations the soft tissue experiences when a laparoscopic tool pushes down on it and after the tool is removed, the tissue's return to its original form.

The size of the soft tissue is $60\,mm \times 60\,mm \times thickness\ of\ dermis$. This size is based on the diameter of the tool, $5-8\,mm$, which would have a deformation in an area no larger than that suggested above. Using the 2D wave equation solution, from Kreyszig et al. [23], and the literature values for the dermis, the authors have developed a wave equation model of the soft tissue as seen in Equation 5 whereas Equation 4 is the Euler formula of the solution. The expression of B_{mn}^{*} is zeroed out by the assumption that there is no initial velocity. The solution of the Euler formula of f(x,y) is found using a symbolic math toolbox and is plugged into the 2D wave equation solution (Equation 5).

$$B_{1,1} = \frac{4}{0.06 \times 0.06} \int_0^{0.06} \int_0^{0.06} (5x(1-x) \times y(1-y)) \times \sin\frac{\pi x}{0.06} \sin\frac{\pi x}{0.06}\, dxdy = 6.11 \times 10^{-6} \qquad (4)$$

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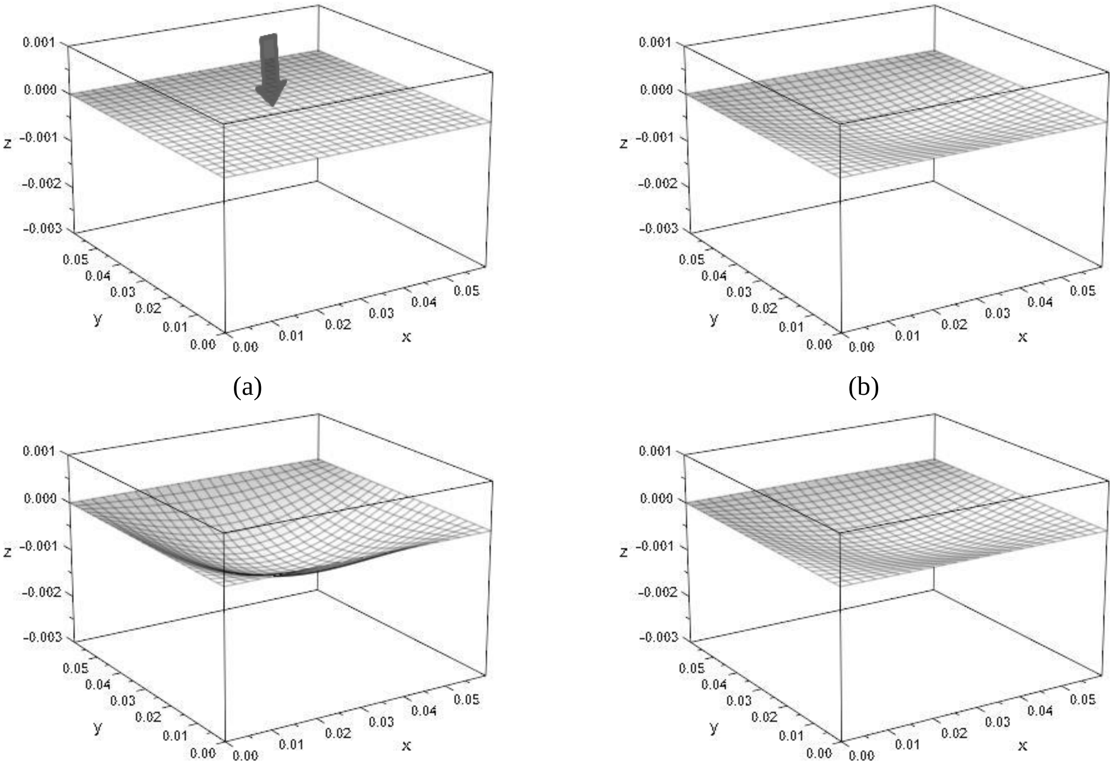
[1] Prestress is the variable T from Equation 1, and takes into account the effects of the natural forces, for example the result of connective tissue and bones holding the skin in place.

$$u_{mn}(x,y,t) = \left((6.11 \times 10^{-6}) \cos(0.686t)\right) \times \sin\frac{\pi x}{0.06} \sin\frac{\pi y}{0.06} \tag{5}$$

Animation of Wave Equation Model of Dermis.



(a) (b)

(c) (d)

Fig. 3. Here are screenshots from the animation of the two dimensional wave equation of the dermis. The first three images (figures a-c) depict the model's response to the tissue being pushed down by a laparoscopic tool. In figure a, the arrow demonstrates the direction of the virtual force causing the deformation. On the other hand, the last image (figure d) represents the model's return to its original shape after the tool and applied force are removed. The unit along x, y, and z axes is meters, therefore resulting in the small values for the deformation over time.

The authors have developed an animated model of the dermis in a symbolic math toolbox, using the 2D wave equation solution in Equation 5. This animation aims to verify the model as a representation of an interaction between the soft tissue and a laparoscopic tool, as discussed in the previous subsection. The resulting animation is demonstrated in Figure 3; through multiple screenshots. As can be seen from the images, the model starts out by reacting to a push to create a deformation, and following the deformation, the model starts to return back to its original shape.

5 Validation Study of Novel Soft Tissue Model

Presently, validation studies of novel soft tissue models in VR surgical training systems are assessed with face validation. Face validity, is performed on many VR surgical training systems and provides a subjective analysis of the realism of the soft tissue model in the system. These studies collect the opinions of users of the system through questionnaires and Lickert scores of 1-5 [30-32].

5.1 Validation Study Design

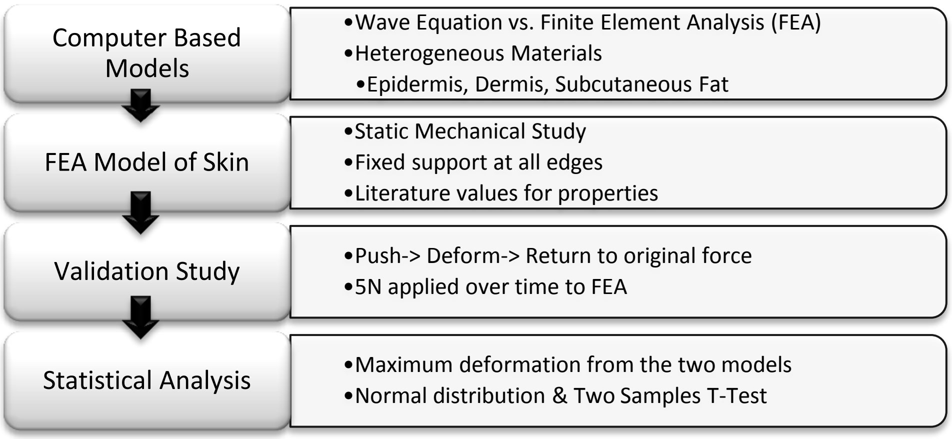


Fig. 4. Flowchart representing the process of the face validation study

The flowchart in Figure 4 shows an overview of the novel validation study that is performed in this study. As discussed earlier, the wave equation is developed for three layers of the skin; epidermis, dermis and subcutaneous fat. Therefore when developing a finite element analysis (FEA) model, the authors use a heterogeneous material to compare between the two models, at each layer. The authors have chosen FEA model because it is the most accurate computer based model for mimicking soft tissue behavior.

5.2 FEA Model Setup: Heterogeneous Material

The setup of the FEA model is essential to developing a comparable model and therefore an effective validation study. As can be seen in Figure 4, the FEA model of skin has fixed support at all edges. Also, the literature values for the mechanical and material properties of the dermis are incorporated into this model, which are: density, damping factor, Young's modulus, Poisson's ratio, and tensile yield strength [26], [28], [33]. Figure 5 is an exploded view of the developed heterogeneous material, which shows the three layers of the skin, observed throughout this research. A static mechanical study is performed, in which a total force of 5N is applied at increments of 0.05N/s and this force is removed at the same increment, over a time period of 100 seconds. Maximum deformations of the skin and each of its layers is collected over time to see changes in the heterogeneous material and how they compare to those observed in the wave equation model.

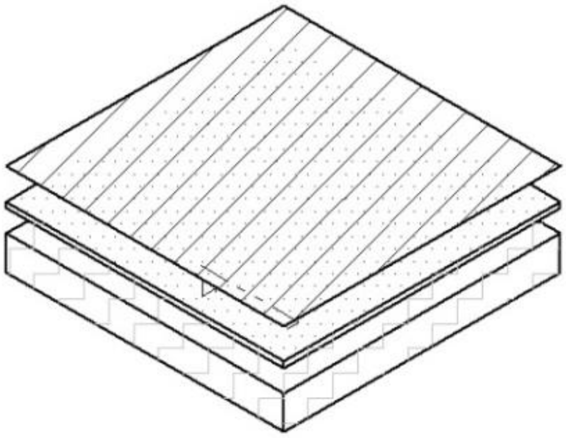


Fig. 5. Here, the hatched layer is the epidermis, the dotted layer is the dermis and the layer with the zigzag pattern represents the subcutaneous fat.

6 Results of Validation Study

Maximum deformations of the two models at hand, FEA and wave equation, allow for a comparison of mechanical and material properties of the two tissue models. In Figure 6, there is a comparison of the two models of dermis; therefore it shows the resulting deformation and then the tissue returning to its original shape.

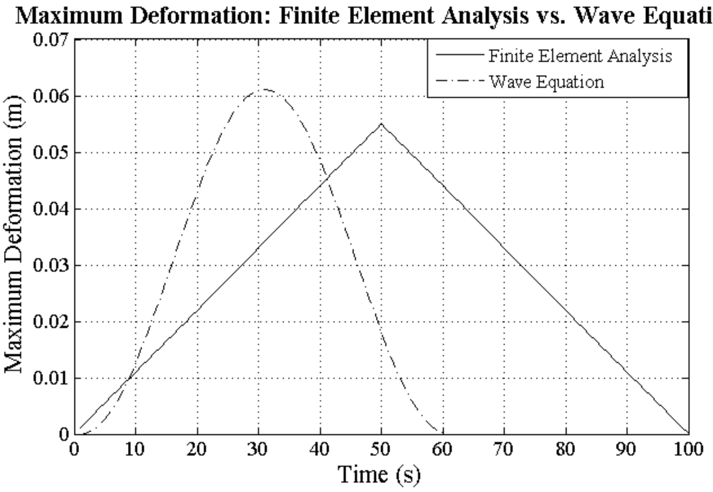
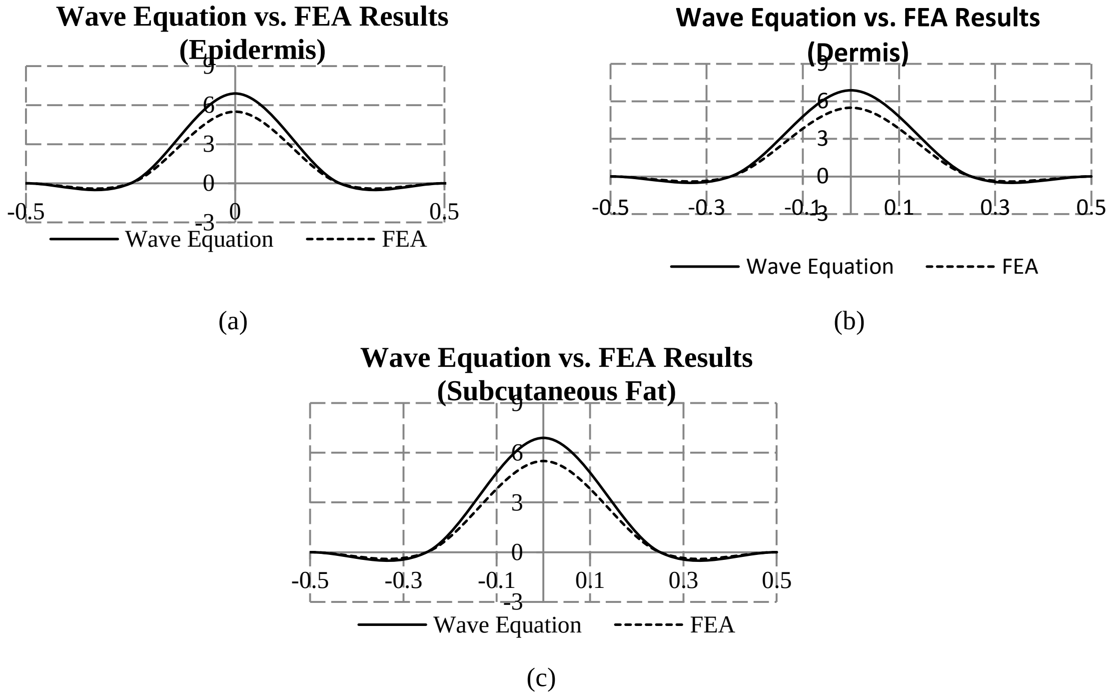


Fig. 6. Graphical representation to display a comparison of maximum deformations between the FEA and wave equation models

7 Statistical Analysis

To evaluate the results from the two models, FEA and wave equation, the authors use two methods of statistical analysis: normal distribution and two sample t-test. For the two analyses, the maximum deformation data from the two models, for each layer of the skin, are used. These two studies help identify the similarities and differences between the models as they are used to model the same soft tissue; the three layers of the skin.

7.1 Normal Distribution Study



(a) (b)

(c)

Fig. 7. Normal distribution to compare the wave equation and FEA models of the three layers of skin.

Figure 7 looks at the normal distribution studies based on the collected data. The normal distributions are performed for the two models, wave equation and FEA. Therefore this study observes the behavior of each layer as a result of interaction with laparoscopic tools. The graphs in Figure 7 suggest high variability between the two models. The calculations for this statistical analysis are performed in Microsoft Excel.

7.2 Two Sample T-Test

Table 2 shows a list of important results from the two sample t-test. In Microsoft Excel t-test is performed, while assuming equal variance, with a significance level of: $\alpha = 0.05$. Therefore the null hypothesis is that the means are equal for the two models, whereas the alternative hypothesis is that the means are not equal. The expected result is the acceptance of the null hypothesis because the models represent the same soft tissue. This is determined using the two relationships, displayed in Table 2: $p - value > 0.05$ and $t\ stat < t\ critical$. If they are true, the null hypothesis can not be rejected.

Table 2. Two sample t-test results for epidermis, dermis and subcutaneous fat.

	T-test Results	$p - value > \mathbf{0.05}$	$t\ stat < t\ critical$
Epidermis			
P (Two Tail)	0.364		
t Stat	-0.912	True	True
t Critical Value	1.975		
Dermis			
P (Two Tail)	0.395		
t Stat	0.911	True	True
t Critical Value	1.975		
Fat			
P (Two Tail)	0.363		
t Stat	0.853	True	True
t Critical Value	1.975		

8 Discussion

In this validation study, two computer based models of soft tissue are compared to justify the use of a novel model in VR surgical training systems. Aforementioned, the authors compare the behavior of two computer based models of soft tissue, the wave equation models with respect to FEA models.

Two statistical analyses are used to verify wave equation as a valid model of soft tissue. The normal distribution study results demonstrate high variability for models at each of the layers of the skin, therefore suggesting high correlation, which is expected as the study looks at two different models of the same tissue that makes up skin. A two sample t-test is performed to verify the results from the normal distribution study. This is determined using the relationships between the p-value and the significance value, and the t-stat and t critical values. This study shows that the null hypothesis, the means of the samples are equal, can not be rejected. This analysis therefore further validates the use of wave equation as a model of soft tissue because it shows similarities between the means of the two models' maximum deformations. As can be seen from the sections above, the statistical analyses are performed for the three layers of the skin, therefore allowing an accurate observation of the behaviors of the different soft tissues of the skin and how they compare for the two models.

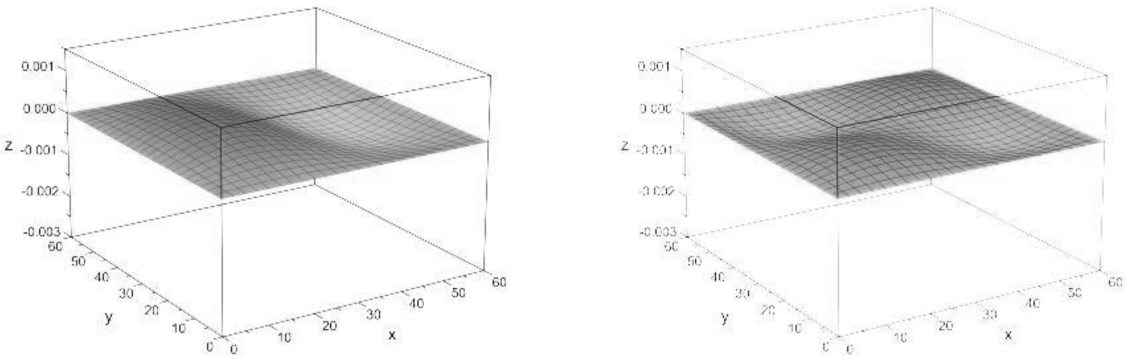
Another data used to compare the two models is the computational costs associated with the wave equation and FEA models. Both of the models are tested on the computer that is described in an earlier section. The wave equation model is solved in 6 seconds whereas the FEA model takes approximately 4 minutes.

The FEA is used to evaluate the novel soft tissue model as it is one of the most accurate computer based models available. Based on the statistical analyses and the computational cost of the two models, wave equation is considered a feasible alternative to presently used soft tissue models.

The validation study described in this study makes certain assumptions or simplifications, which, if addressed, can provide more accurate results. For example, the heterogeneous material is simplified as it does not take into consideration the effects of additional components, i.e. hair follicle, connective tissue and blood vessels, towards the mechanical behavior of the soft tissue. Along with that the thickness of these models are consistent throughout the model, but in biological tissue this property varies and is irregular. This simplification can be rectified using blocks of soft tissue with various thicknesses to create a single block of irregularly shaped tissue. Another improvement that could enhance the results from this study would be to solve the problem of shifting peaks between the two models' maximum deformation; as can be seen in Figure 6. This change could show more correlation between the two models as a result of similar forces and rate of reaction.

Despite the use of wave equation to model skin, in this study, the authors aim to develop an easily modifiable model which can be altered to fit the mechanical and material properties of various soft tissues. This feature would allow the manipulability of the model to meet the needs of the surgeon, medical residents or the specific laparoscopic procedure.

8.1 Additional 2D Wave Equation Models



(a) (b)

Fig. 8. Variations of the wave equation model of soft tissue and tools' interaction

Due to the success of the wave equation models in comparison to the FEA model of soft tissue, the authors propose two variations of the wave equation models as shown in Figure 8; Figure 8(a) is the deformation resulting when the tool collides at an angle whereas Figure 8(b) is when two tools interact with the tissue at the same time.

8.2 Future Application

The aim of the research team is to apply this model of soft tissue to a VR laparoscopic surgery training system. The user interface would also include: laparoscopic tools (i.e. needle holder and suture) and guidelines for correctly performing the task at hand. This system intends to not only provide realistic visual and mechanical representation of biological tissue in a VR environment but also to provide realistic haptic interaction during the training. The haptic interaction is offered through Phantom Omni. The training system will provide the user with intensive and repetitive training with objective assessment therefore limiting the risks of on-patient training.

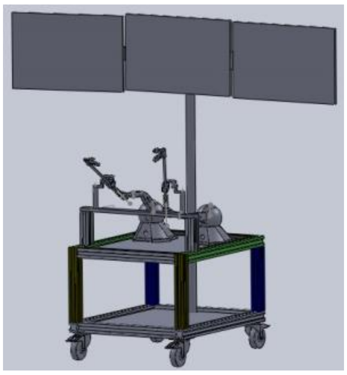


Fig. 9. Proposed, preliminary design of the telesurgical and surgical training system at BART LAB

To support the need for surgical training and provide the same level of healthcare nationwide, our team has designed a telesurgical and surgical training system, as shown in Figure 9, which is designed by our research group. This system aims to not only allow surgeons to provide their skills remotely but also encourage training of young surgeons or medical students.

9 Conclusion

Laparoscopic surgeries' popularity can be attributed to the advantages of this procedure for the patient. However, there are a number of limitations for the surgeons, which arise due to the smaller incisions used in this procedure. This paper, therefore, suggests a novel soft tissue model with the aim to provide an improved training experience on a novel VR training system; a system that shows promise for complementing with on-patient training. The new face validation study in this paper supports the use of the 2D wave equation as a soft tissue model. Along with that, the computational cost is significantly lower for the novel model with respect to one of the most accurate computer based models, the FEA model. In future studies, the researchers intend to apply this novel method to a new VR training system, which will allow the user to obtain intensive and repetitive training while obtaining an objective performance feedback.

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References

1. Basdogan, C., Ho, C.-H., Srinivasan, M.A.: Virtual environments for medical training: graphical and haptic simulation of laparoscopic common bile duct exploration. Mechatronics, IEEE/ASME Transactions on **6**(3), 269-285 (2001).
2. Nguyen, N.T., Goldman, C., Rosenquist, C.J., Arango, A., Cole, C.J., Lee, S.J., Wolfe, B.M.: Laparoscopic Versus Open Gastric Bypass: A Randomized Study of Outcomes, Quality of Life, and Costs. Annals of surgery **234**(3), 279-291 (2001).
3. Bashankaev, B., Baido, S., Wexner, S.D.: Review of available methods of simulation training to facilitate surgical education. Surgical endoscopy **25**(1), 28-35 (2011). doi:10.1007/s00464-010-1123-x
4. Roberts, K.E., Bell, R.L., Duffy, A.J.: Evolution of surgical skills training. World journal of gastroenterology : WJG **12**(20), 3219-3224 (2006).
5. Gallagher, A.G., McClure, N., J., M., K., R., P., S.N.: An Ergonomic Analysis of the Fulcrum Effect in the Acquisition of Endoscopic Skills. Endoscopy **30**(7), 617-620 (1998).
6. See, W.A., Cooper, C.S., Fisher, R.J.: Predictors of Laparoscopic Complications After Formal Training in Laparoscopic Surgery. JAMA **270**(2), 2689-2692 (1993).
7. Wherry, D.C., Rob, C.G., Marohn, M.R., Rich, N.M.: An external audit of laparoscopic cholecystectomy performed in medical treatment facilities of the department of Defense. Annals of surgery **220**(5), 626–634 (1998).
8. Munz, Y., Kumar, B.D., Moorthy, K., Bann, S., Darzi, A.: Laparoscopic virtual reality and box trainers: is one superior to the other? Surgical endoscopy **18**(3), 485-494 (2004). doi:10.1007/s00464-003-9043-7
9. Madan, A.K., Frantzides, C.T., Park, W.C., Tebbit, C.L., Kumari, N.V., O'Leary, P.J.: Predicting baseline laparoscopic surgery skills. Surgical endoscopy **19**, 101-104 (2005).
10. Kneebone, R.: Simulation in surgical training: educational issues and practical implications. Medical education **37**(3), 267-277 (2003).
11. Rosen, K.: The History of Simulation. In: Levine, A., DeMaria, S., Jr., Schwartz, A., Sim, A. (eds.) The Comprehensive Textbook of Healthcare Simulation. pp. 5-49. Springer New York, (2013)
12. Dimaio, S., Salcudean, S.: Needle insertion modeling and simulation. In: IEEE Transactions on Robotics and Automation 2003
13. Auer, L.M., Radetzky, A., Wimmer, C., Kleinszig, G., Schroecker, F., Auer, D.P., Delingette, H., Davies, B., Pretschner, D.P.: Visualization for Planning and Simulation of Minimally Invasive Neurosurgical Procedures. In: Taylor, C., Colchester, A. (eds.) Medical Image Computing and Computer-Assisted Intervention – MICCAI'99, vol. 1679. Lecture Notes in Computer Science, pp. 1199-1209. Springer Berlin Heidelberg, (1999)

14. Sutherland, L.M., Middleton, P.F., Anthony, A., Hamdorf, J., Cregan, P., Scott, D., Maddern, G.J.: Surgical simulation: a systematic review. Annals of surgery **243**(3), 291-300 (2006). doi:10.1097/01.sla.0000200839.93965.26
15. Ali, M.R., Mowery, Y., Kaplan, B., DeMaria, E.J.: Training the novice in laparoscopy. More challenge is better. Surgical endoscopy **16**(12), 1732-1736 (2002). doi:10.1007/s00464-002-8850-6
16. Carter, F.J., Schijven, M.P., Aggarwal, R., Grantcharov, T., Francis, N.K., Hanna, G.B., Jakimowicz, J.J., Work Group for, E., Implementation of, S., Skills Training, P.: Consensus guidelines for validation of virtual reality surgical simulators. Surgical endoscopy **19**(12), 1523-1532 (2005). doi:10.1007/s00464-005-0384-2
17. Seymour, N.E.: VR to OR: A Review of the Evidence that Virtual Reality Simulation Improves Operating Room Performance. World J Surg **32**, 7 (2008). doi:10.1007/s00268-007-9307-9
18. Niroomandi, S., Alfaro, I., Cueto, E., Chinesta, F.: Accounting for large deformations in real-time simulations of soft tissues based on reduced-order models. Computer methods and programs in biomedicine **105**(1), 1-12 (2012). doi:http://dx.doi.org/10.1016/j.cmpb.2010.06.012
19. Basdogan, C., De, S., Kim, J., Muniyandi, M., Kim, H., Srinivasan, M.A.: Haptics in minimally invasive surgical simulation and training. IEEE computer graphics and applications **24**(2), 56-64 (2004).
20. Brown, J., Sorkin, S., Latombe, J.C., Montgomery, K., Stephanides, M.: Algorithmic tools for real-time microsurgery simulation. Medical image analysis **6**(3), 289-300 (2002).
21. Itsarachaiyot, Y.: Haptic Interaction of Laparoscopic Surgery in Virtual Environment. Mahidol University (2012)
22. Itsarachaiyot, Y., Pochanakorn, R., Nillahoot, N., Suthakorn, J.: Force Acquisition on Surgical Instruments for Virtual Reality Surgical Training System. In: 2011 International Conference on Computer Control and Automation (ICCCA 2011), Jeju Island, South Korea, May 1-May 3 2011, pp. 173-176. IEEE
23. Kreyszig, E., Kreyszig, H., Norminton, E.J.: Partial Differential Equations (PDEs). In: Corliss, S. (ed.) Advanced Engineering Mathematics. pp. 540-585. John Wiley & Sons Inc., United States of America (2011)
24. Beards, C.: The vibration of continuous structures. In: Structural Vibration: Analysis and Damping. vol. 4, pp. 129-156. Butterworth-Heinemann, Burlington, MA, (1996)
25. Sánchez-Sesma, F.J., Palencia, V.J., Luzón, F.: Estimation of local site effects during earthquakes: An overview. ISET journal of Earthquake Technology **39**(3), 167-193 (2002).
26. Silver, F.H., Freeman, J.W., DeVore, D.: Viscoelastic properties of human skin and processed dermis. Skin research and technology : official journal of International Society for Bioengineering and the Skin **7**(1), 18-23 (2001).
27. MacLaughlin, J., Holick, M.F.: Aging decreases the capacity of human skin to produce vitamin D3. The Journal of clinical investigation **76**(4), 1536-1538 (1985). doi:10.1172/JCI112134
28. Hendriks, F.M.: Mechanical behaviour of human skin in vivo: a literature review. Koninklijke Philips Electronics N.V., Nat. Lab. Unclassified Report 1-46 (2001).
29. Silver, F.H., Seehra, G.P., Freeman, J.W., DeVore, D.: Viscoelastic properties of young and old human dermis: A proposed molecular mechanism for elastic energy storage in collagen and elastin. Journal of Applied Polymer Science **86**(8), 1978-1985 (2002). doi:10.1002/app.11119
30. McDougall, E.M.: Validation of surgical simulators. Journal of endourology / Endourological Society **21**(3), 244-247 (2007). doi:10.1089/end.2007.9985
31. Kenney, P.A., Wszolek, M.F., Gould, J.J., Libertino, J.A., Moinzadeh, A.: Face, Content, and Construct Validity of dV-Trainer, a Novel Virtual Reality Simulator for Robotic Surgery. Urology **73**(6), 1288-1292 (2009). doi:http://dx.doi.org/10.1016/j.urology.2008.12.044
32. Gavazzi, A., Bahsoun, A.N., Van Haute, W., Ahmed, K., Elhage, O., Jaye, P., Khan, M.S., Dasgupta, P.: Face, content and construct validity of a virtual reality simulator for robotic surgery (SEP Robot). Annals of the Royal College of Surgeons of England **93**(2), 152-156 (2011). doi:10.1308/003588411X12851639108358
33. Gibney, M.A., Arce, C.H., Byron, K.J., Hirsch, L.J.: Skin and subcutaneous adipose layer thickness in adults with diabetes at sites used for insulin injections: implications for needle length recommendations. Current medical research and opinion **26**(6), 1519-1530 (2010). doi:10.1185/03007995.2010.481203