human tissue modeling, soft-tissue modeling, spring-mass model, finite element method, virtual and augmented reality in medicine.

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MODELING OF HUMAN TISSUE FOR MEDICAL PURPOSES

The paper describes the possibilities offered for medicine by modeling of human tissue using virtual and augmented reality. It also presents three proposals of breast modeling for the use in clinical practice. These proposals are the result of arrangements of medical and computer scientists team (the authors) and will be pursued and implemented in the near future. There is included also a brief description of the most popular methods for modeling of human tissue: spring-mass model and finite element method. Moreover the paper attempts to estimate the benefits of the developed models.

1. INTRODUCTION

Human tissue models using virtual and augmented reality may be used at different stages of treatment of diseases of the modeled organ, as long as they faithfully represent respectively its shape and properties. Therefore, there are ongoing researches for the best methods for mapping human tissue onto mathematical description. Here we confine our discussion to the mammary gland – an external organ that is easily accessible, a relatively simple and well-described by imaging studies.

Biomechanical modeling opens many areas of medical activities, ranging from medical image analysis [7, 28, 32] and ending with surgical simulation [19, 21, 26], up to new possibilities. However, implementation of tissue modeling methods must often combine an expectation of a high accuracy of model and a requirement of real-time calculations [29, 30]. Simplified models only to linear formulations [11, 34] do not always lead to satisfactory results. Therefore, nonlinear models have been introduced [12, 28] to overcome the limitations of linear solutions. Such models are becoming widely used [7, 20, 21, 26, 27, 32].

Development of methods for modeling human tissue is facilitated by special frameworks dedicated to the creation of new algorithms and simulators. Such tools allow researchers to focus on the essence of the problem. An example of such a development platform is the open source SOFA framework [2, 10].

2. APPLICATIONS

Modeling of human tissue allows in general to exploit the possibilities of virtual and augmented reality in relation to medicine and may set new directions for its development. In particular it will lead to improvement of procedures as well at the stage of surgeons training, as during the patients treatment, and consequently it will increase the socially expected effectiveness of treatment.

The main field of use of virtual and augmented reality in medicine is undoubtedly the education of future doctors and retraining of specialists already practicing, often enforced by the law [15]. An example of the use of virtual reality in medical education are surgical simulators which allow to train in both standard operating procedures and unusual situations behavior [5, 6, 9, 13, 24]. They may also be useful in developing and testing new surgical techniques. As an example of the use of augmented reality in medical education may serve systems that enrich the transmitted surgery image by computer graphics indicating or pointing out the various important objects, e.g. hidden under the tissue, so students can better understand the broadcasted course of surgery. Equally important are the possibility of using modern technology in public education for prevention.

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Indisputably the most important element of successful treatment is correct diagnosis. Virtual and augmented reality seems to be promising also here. It can help a physician with the analysis of examinations results in different ways. Virtual reality allows, for example, to generate for test in a controlled manner some stimuli, which in neurological diseases are a source of illness. The augmented reality enables the measurement and visualization of motor skills associated with orthopedic disorders (e.g. motion capture used to plot the phase characteristics and evaluation of varus knees [16]). Intelligent support for imaging and overlaying of images of various examinations may also be useful in surgery and radiotherapy.

Virtual and augmented reality can also support the healing process after diagnosis. Treatment of anxiety disorders as phobias (e.g. glossophobia) and obsessive-compulsive disorders (e.g. obsessively washing hands), where controlled exposure through systematic desensitization is used, may be an example of applications of virtual reality in therapy. Extinction of reaction to negative stimuli is in this case not based on the patient's imagination or real situation, but by virtual reality exposure [1, 22, 31]. Virtual reality seems to be useful in systems for remote surgery too [6, 24]. Augmented reality is also invaluable for remote surgery, where communication between members of the operating team during the surgery and between the surgeon and radiation oncologist after its completion can be supported by the mechanism of virtual marking of parts of the operated organ [18].

Back to full fitness after a successful treatment may also be aided by virtual and augmented reality. Virtual reality devices have been used for a long time in the motor system rehabilitation which requires multiple repeated exercises from a patient [6]. Similarly, augmented reality systems embedded in the patient's environment (clothes, glasses, cell phone) can monitor the work of the cured organ and warn against exceeding the acceptable norms during recovery, and recall the recommended exercises.

3. EXAMPLES

A bit more precisely we will discuss three examples of breast modeling in surgical procedures. These examples, which we intend to pursue and implement in the near future, show the possible use of virtual and augmented reality in various stages of surgical treatment of breast cancer, ranging from training of doctors, through oncological treatment (radiotherapy) and recovery after mastectomy. The implementation of each of the proposed below solutions should lead to an increase in the effectiveness of training surgeons in general, and in particular to increase the effectiveness of breast-conserving surgery by improving communication between specialists leading the successive stages of treatment, and ultimately to increase the welfare of patients by improving the aesthetics of the reconstructed breast.

A major difficulty in the process of training and implementation of new surgical techniques is the spatial arrangement of vascular, nerve and bone structures, so traditional methods of learning and procedures for introduction of surgical techniques, such as exercises on models and preparation and assistance during the operation, appear to be insufficient. Supplementing them by the method of spatial training on virtual models leads us to the first application: real-time simulator of breast-conserving surgery and oncoplastic breast surgery operation, which should increase in general the efficiency of surgeons training. Realism of today's simulators leaves much to be desired [17], hence beyond the development of appropriate models and algorithms, interface device selection is very important.

Treatment is often a multistep process that requires the cooperation of many specialists. For example, surgical oncologist, pathologist, clinical oncologist, radiation oncologist, therapist and clinical psychologist participate in the treatment of breast cancer. Therefore the communication between them is ery important. During breast conserving surgery a surgeon cuts out the tumor with a certain nvironment. During the boost radiotherapy radiation oncologist evaluates the location of the tumor bed n the basis of imaging examinations and surgical scars. Location of the scar is not determined by the ocation of the removed tumor. This fact combined with the easiness of deformation of the breast reduces ne accuracy of X-rays irradiation. Hence the second application is an intelligent adaptable breast opography projector, which will allow a surgeon to describe the location of the removed tissue for later se by the radiation oncologist. It is worth noting that the substitute of this method in the form of foil laid n the breast to its contouring and marking the location of the tumor is successfully applied in practice by o-author – surgical oncologist [25].

It is difficult to separate the effectiveness of treatment from the patient's mental status. This is particularly evident in the treatment of breast cancer by mastectomy. Despite successful surgery, patients may fall into depression. Only the guarantee of breast reconstruction at the appropriate aesthetic level, taking into account the body symmetry, allows to avoid the discomfort associated with mastectomy. Therefore, the third application is a virtual fitting tool of the silicone implant to the breast after mastectomy. It will allow a surgeon to choose the optimal size of the implant from the aesthetic point of view. There are various tools of this type, from simple Flash applications [3] to sophisticated 3D modeling systems [4, 8, 14, 23, 33], but unfortunately, they are characterized by a simplified data acquisition of the geometry and especially the physical properties of the real human torso.

4. MODELING

Mathematical models of the tissue allow identification of the biological processes in organisms and form the basis for their simulation. We present two commonly used modeling methods – spring-mass model and finite element method (FEM). The former method is dedicated for solutions where the speed of calculations is more important than the accurate behavior of tissues. It allows simulation of very complex models in real time. The latter method offers a much greater accuracy, but for the larger models is computationally very expensive.

The spring-mass model describes the mechanical properties of tissue by a grid of points connected by weightless elastic springs and optional dampers (Fig. 1). Each point has specific parameters such as weight and position, and its movements are set in accordance with Newton's laws of motion by differential equation:

$$M\frac{\partial^2 x}{\partial t^2} + C\frac{\partial x}{\partial t} + Kx = F \ , \qquad (1)$$

where M – mass matrix, C – damping matrix, K – stiffness matrix, x – vector of points coordinates describing the object. This equation allows the calculation of new coordinates for each point. Springs tend to keep the system in balance – maintain a safe distance between the points of the masses. The forces acting on each point are dependent on the distance between points adjacent to that point and the external forces acting on the system (e.g. gravity).

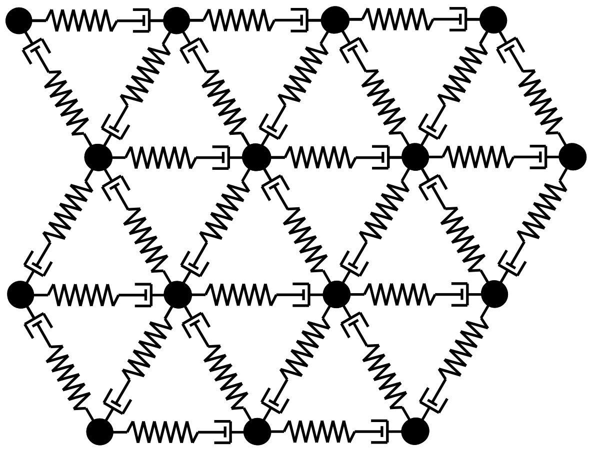

Fig. 1 A simple spring-mass-damper model of a flexible object 2D

The spring-mass model is widely used in surgical simulation. It is relatively easy to implement and does not require high computational power. Therefore the visualization and modification of the model in real time is enabled. Unfortunately, this model also introduces important limitations. Deformations are not accurate reproduced, this is only an approximation of the real behavior of tissues. In addition, delays are introduced due to the propagation of forces in the system. Any modifications to the model, such as removing of the grid points or cutting of the springs, force adjustment of the system parameters. It also has a tendency to oscillate, due to the iterative method for calculating the forces acting on grid points.

The finite element method relies on the division of modeled object into finite elements (Fig. 2) for replacing the analytical problem of object behavior expressed by differential equations by compact algebraic description. This method greatly simplifies the solution of the problem, and in many cases can generally find a satisfactory result. Accuracy of the method is determined by the precision of division on finite elements. Too much fragmented division leads to a decrease in performance of calculations. Therefore a final selection of the finite element mesh should be a compromise between accuracy and efficiency.

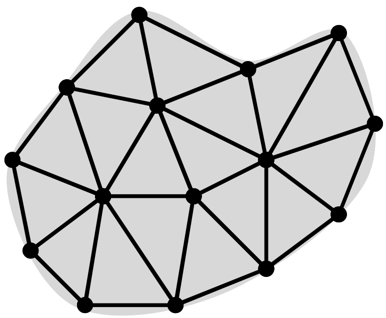

Fig. 2 A division of modeled object 2D into finite elements

The finite element method is based on continuum mechanics laws described by a system of differential equations. After discretization, each finite element is described by a set of nodes and interpolation functions. Then the calculations are carried out in order to receive a solution – the displacement vector for each node. Assuming a linear elasticity of material the system of equations takes the following form:

$$K\,U = F\,, \tag{2}$$

where F – external force, U – displacement vector, K – stiffness matrix of size $3n \times 3n$ (n – number of nodes), depending on the initial shape and material properties. As one can see the size of the grid has a significant impact on performance calculations. In order to simplify the calculation some condensation technique is used, that consists in solving the equation (2) only for the nodes on the surface of the material.

Model assuming linear elasticity is correct for the distortion of less than 10%. In the case of larger deformations more complex nonlinear equations are required. This introduces an additional decrease in performance of calculations. Nonlinear dependence can be achieved taking into account the kinetic energy and the effect of damping. Equation (2) takes the following form:

$$M\,\ddot{U} + D\,\dot{U} + K\,U = F\,, \tag{3}$$

where: $\ddot{U}$ – acceleration, $\dot{U}$ – speed, M - mass matrix of each node, D – damping matrix (other symbols as above). Models based on finite element method can be very accurate and are suitable for simulating large deformations. However a major drawback of this method, especially for nonlinear description, is the significant computation times that may be required to solve large models. Therefore in recent years there has been a growing number of works concerned with use of graphics processing units (GPUs) for tissue modeling.

5. CONCLUSIONS

Human organs, and mammary glands in particular, can be accurately modeled. Their models using irtual or augmented reality may be used at different stages of treatment of diseases of these organs. This s demonstrated by description of three applications of the breast model: simulator of breast-conserving urgery (BCS) and other oncoplastic breast surgery, a virtual implant fitted for breast reconstruction following a mastectomy, and intelligent topographic grid projection on the breast surface with auto-adaptation to its shape.

The importance of the described project is difficult to overestimate. The successful development of a breast model should allow one to create different medical applications. What is more, three virtual and augmented reality medical systems allow to use the created breast model in medical procedures. It will increase in general the efficiency of surgeons training, it will increase the psychological comfort of patients by improving the aesthetics of the reconstructed breast after mastectomy, and it will lead to increased effectiveness of breast conservation surgery.

American study from 1999 shows that medical errors committed in hospitals in the United States annually cause the death of about 44 000 patients [13]. Similar statistics concern other countries. Increase the effectiveness of training physicians and improving the treatment process should significantly reduce this number. Presented application after implementation should lead to increased effectiveness in the breast-conservative surgery, which in Poland concern approximately 30% (while in the U.S. and Western Europe about 70%) of all cases. In recent years the number of breast tumors diagnosed in Poland is approximately 15,000 and it is estimated that in 2020 will reach 20,000. Breast-conserving surgery in Poland concerns at the moment about 4,500 people per year and that number over the next decade will increase to 6,000.

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