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Integrating Anatomy and Physiology for Behavior Modeling

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Abstract

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Integrating Anatomy and Physiology for Behavior Modeling*

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Abstract. In producing realistic, animatable models of the human body, we see much to be gained from developing a *functional anatomy* that links the anatomical and physiological behavior of the body through fundamental causal principles. This paper describes our current Finite Element Method implementation of a simplified lung and chest cavity during normal quiet breathing and then disturbed by a simple pneumothorax. The lung model interacts with the model of the chest cavity through applied forces. The models are modular, and a second lung and more complex chest wall model can be added without disturbing the model of the other lung. During inhalation, a breathing force (corresponding to exertion of the diaphragm and chest wall muscles) is applied, causing the chest cavity to expand. When this force is removed (at the start of exhalation), the stretched lung recoils, applying pressure forces to the chest wall which cause the chest cavity to contract. To simulate a simple pneumothorax, the intrapleural pressure is set to atmospheric pressure, which removes pressure forces holding the lung close to the chest cavity and results in the lung returning to its unstretched shape.

1 Introduction

For some time now, we at the Center for Human Modeling and Simulation at the University of Pennsylvania have been developing human behavior models for virtual agents in simulated worlds. One underlying philosophy has been that producing realistic behavior involves both presenting our agents with accurate visual graphics and endowing them with structural and functional constraints of the body, as they interact with their world.

To produce analogous realism in our virtual agents' bodies, we recognize the critical relationship between the physical existence of an anatomical part with the functional role(s) it plays. This has led us to to couple our quantitative deformable model techniques [6] with models of the physiological mechanisms that produce physical changes. This allows us to design models that reflect the fact that anatomical parts have two intrinsic, interrelated existences: they are physical objects that obey physical laws, and they are part of physiological systems, so their behavior contributes to the overall functioning of the body. They are interrelated because changes to one can affect the other, both as part of the same system and as a result of physical adjacency.

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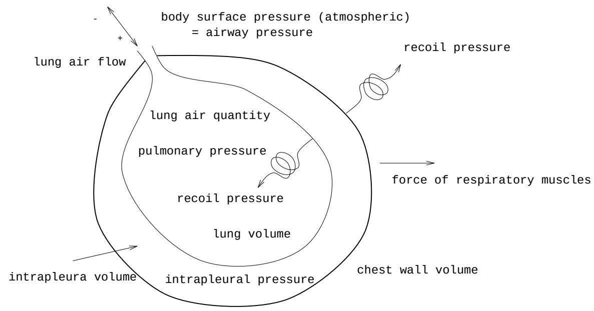


Figure 1: Qualitative, idealized lung model

1.1 The Effort

For several years we have been working to provide computer-based decision support in aid of the initial definitive management of multiple trauma [2, 9, 12]. Because trauma disrupts physiological processes through anatomy, we see much to be gained from creating a *functional anatomy* that will aid in visualizing and predicting the results of penetrating trauma to the human torso. A functional anatomy links the anatomical and physiological behavior of the body using fundamental, causal principles. Another area of medicine that can gain from models of functional anatomy is the emerging field of Virtual Surgery. To date, however, many efforts have concentrated on providing realistic images and dynamics (e.g., Noar [7] on techniques used in endoscopic simulators), neglecting functional issues. The consequence is that a necessary characteristic for virtual surgical simulators [10], *reactivity*, that organs must react appropriately to manipulation or cutting, such as by bleeding or leaking fluid, cannot be achieved.

We chose first to model the respiratory mechanism since it involves physiological change, such as pressures and flows, that depends on gross anatomical deformations. Ultimately, with models for other physiological systems [8], we want to demonstrate their interaction due to the physical space they share.

We currently express physiological dynamics in both a quantitative and qualitative framework. This provides us with a mixed quantitative/qualitative description of physiological behavior, which may be more appropriate for explanation than a purely quantitative model. Our system consists of two integrated levels of abstraction: (i) geometric and physics-based modeling of anatomy (shape extraction, motion, deformations, and graphical rendering); and (ii) simulation of physiological mechanisms that behave in accordance with physical laws and physiological processes.

This paper describes our ongoing effort [3] involving the procedures we have developed that graphically demonstrate organ geometry, physics, and physiological dynamics. It details our current implementation of a simplified lung during normal, quiet breathing, describing the quantitative results of our Finite Element Method implementation, based on techniques from [6].

Our qualitative formulation of the dynamics involved in quiet breathing is described in [3]. It makes use of the qualitative simulation paradigm QSIM [4]. Figure 1 shows the quantities we considered, assuming constant resistance and compliance.

2 Quantitative Lung Modeling

Our anatomical modeling is based on our physics–based framework [6, 11] for shape and nonrigid motion estimation and synthesis. This framework features a Lagrangian dynamics framework which will be used to describe the dynamics of our lung model. The geometry of the lung model will be chosen so that we may utilize these previously developed methods for deformable body mechanics.

When applying Lagrangian dynamics [6], we obtain second order equations of motion which take the general form

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{D}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{g}_{\mathbf{q}} + \mathbf{f}_{\mathbf{q}}, \tag{1}$$

where $\mathbf{q}$ are the generalized coordinates (the degrees of freedom) of the model, $\mathbf{M}$, $\mathbf{D}$, and $\mathbf{K}$ are the mass, damping, and stiffness matrices, respectively, $\mathbf{g}_{\mathbf{q}}$ are inertial forces, and $\mathbf{f}_{\mathbf{q}}$ are the generalized external forces. The vector $\mathbf{q}$ contains the information needed to specify the shape of the lung. If the equation of motion (1) is integrated over time, the dynamic deformation of the model is observed.

The shape and viscoelastic properties of the lungs are modeled by using isoparametric finite elements [13]. Because we currently lack detailed data on the elastic properties of the viscoelastic material of the lung, we use linear finite elements. However, our methodology is general and is also applicable to non-linear finite elements.

We incorporate the isoparametric finite elements into the Lagrange equations of motion (1). The finite elements are used to compute internal elastic forces that arise due to the deformation of the lung. This deformation is caused by applied forces that include pressure and collision forces.

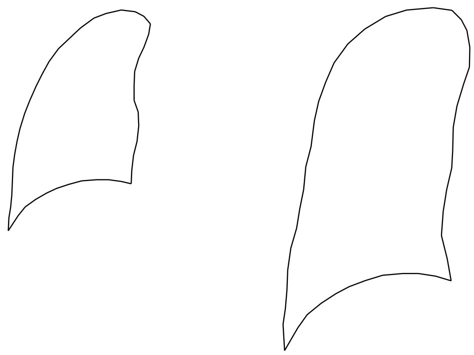
We can now use this model to create dynamic simulations of inhalation and exhalation, and also of a simple pneumothorax. Our model of the lung interacts with the surrounding chest cavity by applied forces. This type of representation of the lung lends itself to a modular approach, where this lung model could be incorporated into a larger model of human anatomy without changing the implementation. For instance, the addition of a second lung or heart would not require changes in the implementation of the first lung. The first lung need not "know" about the other lung or the heart directly. Their effects could be dealt with through applied forces.

2.1 Model Geometry

The following sections describe the lung model used in the dynamic simulation. While the model is two-dimensional, it observes the qualitative behaviors of a full lung model in three dimensions.

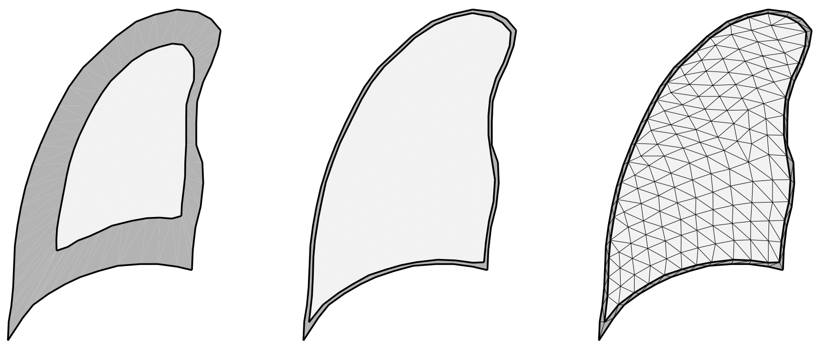
This lung model will react to external forces that include pressure forces (due to the difference in pressure between the lung and intrapleural space), and contact forces caused by the lung rubbing against the chest wall.

The lung is contained within the chest cavity. For this implementation, the chest cavity is given two degrees of freedom, which correspond to diaphragm and chest wall deformation. This simplified chest model is suitable currently, for the purpose of demonstration. However, because of the modularity of our lung model, we could add a more complex chest wall model without disturbing our model of the lung. This chest cavity model contains what is necessary for simulation of inhalation and exhalation. Figure 2 shows kinematic motion of the chest wall at the extremes–(a) at rest, and (b) fully inhaled.



(a) (b)

Figure 2: Geometry of the chest wall (a) at rest, and (b) after inhalation



(a) (b) (c)

Figure 3: Dynamic construction of lung model (a)-(b), and finite element mesh geometry (c)

Within this chest wall is the finite element mesh for the lung and intrapleural space. The initial model can be constructed by creating the lung in its unstretched shape shown in figure 3(a), and then setting the intrapleural pressure to its negative value (with respect to atmospheric pressure), resulting in the lung at rest in (b) (recall that the lung is stretched in its normal resting state due to the negative intrapleural pressure). In this (and all following) model diagrams, the lung is shaded with a light gray, and the intrapleural space with a darker gray. A diagram of the finite element mesh used is shown in figure 3(c).

2.2 Model Dynamics

During inhalation, the increase in size of the lung is due to pressure forces. As the chest cavity increases in volume, the difference in pressure between the lung and intrapleural space causes the lung to expand. For the applications in this paper, we make the simplifying assumption that the pressure changes occur instantaneously. This means the lung is always at atmospheric pressure, and the intrapleural space has one common pressure, P, which changes assuming PV is constant (where V is the intrapleural volume).

The forces that arise due to pressure differences occur at the boundaries of the intrapleural space, which is the only location where two adjacent elements will differ in pressure. For such an element, we can compute the pressure force at a node along an element edge as

$$f_{\text{pressure}} = \frac{P}{l}\mathbf{n} \tag{2}$$

where P is the pressure of an element, l is the length of the edge, and $\mathbf{n}$ is a normal pointing

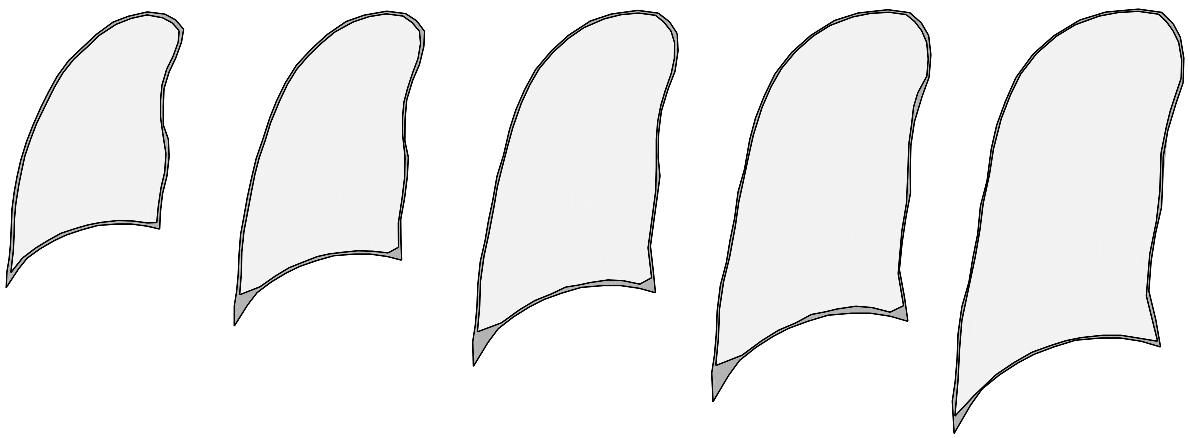


Figure 4: Inhalation of the lung

out of the element that is perpendicular to the edge. This is a 2-D analog of the $f = P/\text{area}$ relationship. When considering the sum of all pressure forces, the net contribution of force for each edge is related to the pressure gradient across the edge.

2.2.1 Chest Cavity Dynamics

The deformation of the chest cavity is performed by specifying its two degrees of freedom–diaphragm and chest wall shape. The pressure forces described above not only are applied to the lung, but also act on the chest wall. Using our Lagrangian dynamics framework, these applied forces are converted into generalized forces which directly control the shape of the chest cavity. During inhalation, a breathing force (corresponding to exertion of the diaphragm and chest wall muscles) is applied, causing the chest cavity to increase in size. Once this force is removed (at the start of exhalation), the stretched lung recoils, applying pressure forces to the chest wall, causing the chest cavity to decrease in volume.

The contact forces due to collision of the lung with the chest wall are implemented as in [5].

2.3 Simulations

The following are simulations using the dynamic lung model described above. These simulations run at interactive rates on a 100 MHz R4000 VGX SGI. Figure 4 shows a simulation showing the process of inhalation using our model. The behavior of this model agrees qualitatively with our qualitative physiological model.

To simulate a simple pneumothorax, we can set the intrapleural pressure to be equivalent to body surface pressure (atmospheric pressure) in our model. This will eliminate any pressure forces holding the lung close to the chest cavity. The resulting collapsing motion of the lung is shown in figure 5. The location of the injury is indicated by the gap in the chest wall. Notice how the lung returns to its unstretched shape, as shown in figure 2(a).

3 Conclusion

Our work involves the simulation, modeling, and visualization of anatomical and physiological mechanisms, considering in particular pathology related to penetrating injuries. Our intent is to provide a reusable anatomical knowledge base coupled directly with knowledge of the

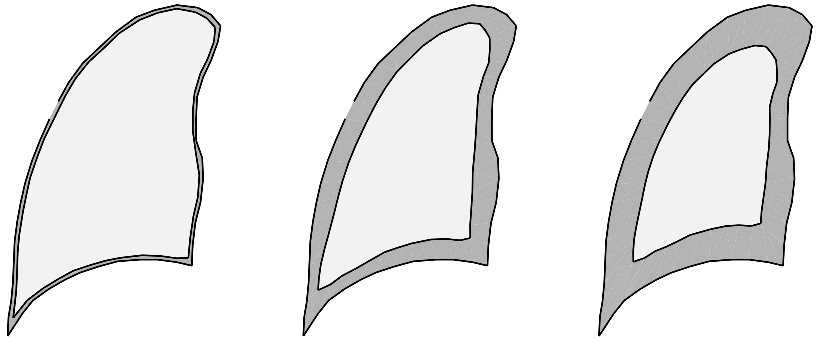


Figure 5: Simple pneumothorax of the lung

underlying physiology, or what we refer to as a *functional anatomy*. A functional anatomy links the anatomical and physiological behavior of the body through fundamental causal principles.

In this paper, we have examined one aspect of our project, the Finite Element Method implementation of a two-dimensional, idealized lung. This preliminary work will be used as the basis for our continuing physics-based three-dimensional modeling which we will apply to simulating normal respiratory physiology and related pathologies. It will also serve as a basis for considering the interaction of physiological systems due volume constraints.

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