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TrauMAP - Integrating Anatomical and Physiological Simulation (Dissertation Proposal)

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Abstract
In trauma, many injuries impact anatomical structures, which may in turn affect physiological processes - not only those processes within the structure, but also ones occurring in physical proximity to them. Our goal with this research is to model mechanical interactions of different body systems and their impingement on underlying physiological processes. We are particularly concerned with pathological situations in which body system functions that normally do not interact become dependent as a result of mechanical behavior. Towards that end, the proposed TRAUMAP system (Trauma Modeling of Anatomy and Physiology) consists of three modules: (1) a hypothesis generator for suggesting possible structural changes that result from the direct injuries sustained; (2) an information source for responding to operator querying about anatomical structures, physiological processes, and pathophysiological processes; and (3) a continuous system simulator for simulating and illustrating anatomical and physiological changes in three dimensions. Models that can capture such changes may serve as an infrastructure for more detailed modeling and benefit surgical planning, surgical training, and general medical education, enabling students to visualize better, in an interactive environment, certain basic anatomical and physiological dependencies.

Comments
TrauMAP
Integrating Anatomical and Physiological Simulation
(Ph.D. Dissertation Proposal)

MS-CIS-95-29

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1995
INTEGRATING ANATOMICAL AND PHYSIOLOGICAL SIMULATION

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Abstract

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1. Introduction

Anatomy is the study of the body structures. Physiology is the study of the essential and characteristic life processes, activities, and functions. Physiological processes are carried out within a physical space that may both influence and be influenced by the processes occurring within. This dissertation is about modeling anatomical structures, physiological processes, and some of their interdependencies as a result of mechanical interaction.

Trauma frequently involves structural changes to the body, such as fractures, hemorrhage, and ruptured organs, which may affect multiple body systems. Interaction among body systems occurs not only due to functional dependencies but also due to constraints of the physical space they share. When the physical interconnectivity of body systems changes, we need to reconsider the dependencies among them to predict the effects of injury. Such assessment and resulting behavior will depend crucially on physical proximity and contact forces.

For example, a flail chest is the condition in which segments of the ribcage become detached. During breathing, the flail section moves paradoxically to the rest of the ribcage because the net forces on that section are different from those acting on the intact sections. In a tension pneumothorax, accumulation of air within the intrapleural space results in pressing the mediastinum against the opposite lung. With the resulting increased pressure on the inferior vena cava in the mediastinum, the vein collapses and impedes venous return to the heart.

With a little knowledge about cardiopulmonary anatomy and physiology, it is straightforward for us to predict the resulting behaviors. Part of this understanding depends on our ability to reason about the interaction of adjacent physical structures within an enclosed environment and the processes that change those structures. While we can quickly grasp the essential mechanisms that result in the behavior, we would be more hard-pressed to describe the particular effects in detail. Identifying the particular causes, effects, and associations, are critical for our understanding of physiological mechanisms, both in physiological research and teaching.

The computer has the potential for elucidating that detail and presenting it in a visually-intuitive way for us, insofar as we can describe it. However, the computer does not implicitly share the insights we have about consequences of adjacency and physical change. Biomedical researchers have been using analog and digital computers to study physiological systems for some time now [18, 32, 37, 42]. Computer models are used as
research tools for advancing physiological and clinical insight, models for indirect estimation of physiological parameters, models for control and therapy of on-line systems, and models for education and training [37]. Interest in biomedical research has grown recently in areas of Computer Science, specifically within the Artificial Intelligence community [49, 51].

We are interested particularly in the computer’s potential to impact medical education such as by simulating examples described above. The examples emphasize the critical relationship between the physical existence of an anatomical part with the functional role it plays. An accurate simulation of the body, then, requires an approach that integrates a realistic, three-dimensional structural model, deformable body dynamics, and physiological dynamics (mechanical, biochemical, and electrical)—a functional anatomy that explicitly links the anatomical structures with physiological behavior of the body. With new developments in computer hardware and graphics, and the success of flight simulators in pilot training, much talk has been made of creating virtual environments for medical training [19]. While people recognize the existing body of work in physiological modeling, we have not seen an application bridging that work with computer graphics modeling.

We propose to develop a first principles approach for supporting 3-D visualization of anatomical and physiological interaction in the domain of penetrating trauma. We plan to accomplish this by integrating physically-based modeling methods for simulating anatomical parts with traditional physiological simulation. The TRAUMAP system (Trauma Modeling of Anatomy and Physiology) proposed consists of three modules: (1) a hypothesis generator for suggesting possible structural changes that result from the direct injuries sustained; (2) an information source for responding to operator querying about anatomical structures, physiological processes, and pathophysiological processes; and (3) a continuous system simulator for simulating and illustrating in three dimensions anatomical and physiological changes. We argue that this fundamental knowledge and presentation can be useful for illustrating medical concepts and conditions involving anatomical and physiological dependencies. We also see that such an approach ultimately may serve as an infrastructure for surgical planning and training.

Outline of this Document

We begin describing our research plan in Section 2 by describing the problems we face, the requirements for the project, the objectives of the study, and the specific tasks we propose to undertake. Section 3 reviews some approaches from the literature to anatomical and

Introduction
physiological modeling. In Section 4, we outline our design and the methods we expect to employ, as well as detailing preliminary results. We conclude in Section 5 with a summary of critical themes.
2. Objectives and Tasks

While the debate rages over exactly how many words a picture ‘paints,’\(^1\) it is obvious that pictures or diagrams can be effective in conveying certain concepts, particularly those which involve some reasoning about physical space. The computer affords a unique opportunity through visualization beyond static images for us to create and interact within virtual environments. We believe that a virtual environment can be useful to demonstrate concepts in addition to its obvious value for enabling interactive exploration of difficult-to-reproduce scenarios.

The fact that the computer can present realistic looking images or animations does not imply that the computer has access to the knowledge of how the objects behave. In creating our virtual environment, we are concerned with linking physiological variables and parameters with anatomical structures in such a way that this combined object description can be applicable more generally, not just in specific, predetermined situations. Part of this involves developing methods to simulate physical laws so that the objects that populate the environment are exposed to and affected by them naturally. For example, a straightforward physical law dictates that objects cannot interpenetrate. If one object exerts a force on an adjacent object we need to model how that second object reacts to that force, its impact both on the object structure (anatomical deformation) and behavior (underlying physiological effect).

In our virtual environment, we represent anatomical organs and physiological systems. Activity consists of anatomical, physiological, and pathophysiological changes. Characterizing these changes in a principled and generalizable way will be an important step toward fully-interactive simulation for education, such as environments for virtual surgery. At the core of a surgical simulator must be a modeling approach that captures accurate body system behaviors and presents them in a visually-plausible way. For the most part, the body is composed of fluids, soft tissue, and bones; such a core will require algorithms for modeling fluids, deformable objects, and rigid structures. Most importantly, it will require methods to manage their interaction.

Before knowing how objects interact we need to know how individual objects behave. From this knowledge we may predict how changes from one object can affect another. There are at least two facets to object behavior, namely how the structure of the object can

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\(^1\)Preliminary research indicates around 1,000.
change (based on its material properties and forces applied to it), and which processes, if any, are occurring within. In most cases, aspects of the processes occurring within depend on the physical object structure. For example, fluid flow through a vessel requires that no cross-sectional area of the vessel becomes too small to permit passage of the fluid. The problems faced in this pursuit are choosing, developing, and integrating methods for anatomical object and physiological process behaviors.

We distinguish these facets by referring to the dynamics of physical shape and material modeling as anatomical modeling, whereas modeling the processes that cause the change we consider to be physiological modeling. More specifically, we focus our physiological modeling on the modeling of mechanical behavior, as opposed to related biochemical or electrical physiological processes. To model anatomical changes, we need to know such information as geometric descriptions of anatomical parts, relationships among them, material properties, and points of attachment. For physiological knowledge, we need to know such information as time-varying behavior descriptions, physiological variables, parameters, and associations among behaviors, conditions, and parts.

Conventional physiological modeling describes systems as lumped-parameter or distributed-parameter models [5]. A lumped-parameter model, described in ordinary differential equations, expresses the cumulative effect over an element. In contrast, distributed-parameter models, described in partial differential equations, express the possible variation in individual segments of an element. For example, a lumped resistance would be a single value (or variable) representing the resistance encountered along the full length of an element. A distributed resistance would be an array of values representing individual effects of segments along the element. Such detail, however, may be more difficult (if at all possible) to observe clinically. Most physiological models of interest to us have been described in lumped-parameter form. This is consistent with clinical physiological instruction and observable physiological behavior (e.g., body surface pressure, chest wall volume change, etc.).

The knowledge about relating physiological behaviors to anatomical parts involves knowing how physiological variables affect physical changes (to anatomical structures), and vice versa. For example, if a patient is lying with her lower extremities elevated (Trendelenburg position), as during a pelvic laparoscopy procedure, she may experience more difficulty breathing because the pressure from the abdominal contents exert more force against the diaphragm.

Lastly, we need a mechanism to ‘set the scene,’ in other words to present the clinical data appropriate for the circumstance being modeled. For modeling penetrating injuries, we

Objectives and Tasks
particularly need to know which spaces have been penetrated to know how the normal
topological configuration of the body has changed. Ultimately, such information could be
accessible from medical imaging results and/or tools for reasoning about the potential for
injury given the presenting evidence.

2.1. Objective

The primary objective for this research is to develop an application that integrates three-
dimensional anatomical models that are sensitive to physical forces with conventional
physiological models that describe behavior. Such an application reflects the two
interrelated aspects of physical objects in our world: 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. The aspects are interrelated because changes to one can
affect the other.

This integration should involve well-founded methodologies for describing anatomical and
physiological changes in a composable and natural way. It should be composable to
facilitate efficient development and future expansion, and ‘natural’ in the sense that the
modules interface with each other as they do in the real world being simulated. When we
look to specific applications of this knowledge, such as in a surgical simulator, we may use
it in an abstracted or abbreviated form. However, at first we should be concerned with
constructing the foundation.

Three components we want to address for this simulated environment are:

- **Defining the Injury Scenario.** This involves collecting and assessing
  physical findings, particularly wounds, to determine *direct* injuries. This
  information will not lead to definitive diagnoses, rather its role will be to
  suggest to the user possible damage which might be investigated further by
  modeling the consequence of these injuries.

- **Defining the Players.** We need to know anatomical, physiological,
  and pathophysiological knowledge to support rendering anatomical
  structures, describing relationships among structures, and simulating
  physiological behavior and effects on anatomical structures. This
  knowledge also includes baseline information about relationships and values
  for typical individuals, and interpretation of clinical findings in terms of
  anatomical and physiological involvement (e.g., defining terms that relate
  ‘jugular vein distention’ to the physical structures involved). We propose to
  use this knowledge in two ways: (1) for performing dynamic simulation that

*Objectives and Tasks*
drives a three-dimensional illustration of behavior; and (2) for enabling operators or other applications to access the knowledge for their purposes, particularly knowledge about anatomical relationships.

- **Environmental Factors.** This involves simulating physical laws in our environment.

We propose to demonstrate certain aspects of normal physiological and pathophysiological behavior that involve anatomical changes. This may have an impact for a human operator learning about these relationships, to support simulations for surgery, and for computer programs that may exploit such knowledge for reasoning, such as decision support tools.

### 2.2. Thesis Claim and Contributions

This thesis is about modeling the interaction of anatomical parts and underlying physiological processes. The purpose is to encode the relationship between an anatomical part and the physiological processes occurring within, and to demonstrate resulting behavior from the interaction of individual body part behaviors.

We claim that our integration of three-dimensional, physically-based anatomical modeling with lumped-parameter physiological models provides a natural and clinically-useful way for modeling interactions among physically-adjacent parts and physiological systems due to the application of forces. For example, certain physiological variables (pressure gradients) are translated as forces in the anatomical models, and certain physiological parameters are sensitive to object deformation (such as the constriction of a vessel increasing the flow resistance). The integration rests on developing an accurate three-dimensional interpretation for physiological variables that are expressed as scalar quantities as well as a means for interpreting the impact of three-dimensional forces on scalar physiological parameters, such as flow resistance.

We will model behaviors by encoding object deformations and physiological processes in differential equations, in addition to defining physical laws such as propagation of forces through physical contact. These laws will result in inter-object influences.

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\(^2\)We mean by ‘clinically-useful’ that our scalar physiological variables are clinically observable and relevant, as opposed to more involved methods that rely on difficult-to-measure properties such as specific tissue segment displacement.

*Objectives and Tasks*
We expect this approach will be useful to

**Enhance the illustration of medical concepts** that entail spatial reasoning, in that it provides a three dimensional environment for visualizing and predicting anatomical and physiological changes. By describing the physiological mechanisms and the spatial constraints in which they operate, we may also investigate the consequences of multiple, interacting diseases;

**Provide an extendible 3-D modeling environment** in which conventional (lumped-parameter) physiological models can be integrated for more realistic modeling and ultimately for *predicting* physiological response; and

**Encode fundamental anatomical knowledge** and physical relationships that could facilitate access to that knowledge for other computer programs, such as programs applied to medical diagnosis and care. Some amount of attention ([9, 10, 38]) has been drawn recently to the idea of reusing medical knowledge across applications. Anatomical knowledge may be a good candidate because most medical applications encode some anatomical relationships.

We see at least three aspects that our application must address:

1. **Defining the scene**, particularly insofar as knowing the approximate conditions of objects and topological relationships among them. Our specific means enables the operator to place wounds on the body and any known bullets within. We then calculate potential direct injuries resulting from hypothesized penetration paths. Without such a component, the program would have less knowledge about motivating topological changes. This component also assists with visualizing anatomical structures along possible penetration paths.

2. **Organizing knowledge** of anatomical parts, relationships, and which physiological processes occur within anatomical parts or across body systems. This component represents TRAUMAP’s knowledge. It could be useful to answer questions about object or process properties. For

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*Objectives and Tasks* 8
example, it could suggest which sites for chest compressions during CPR\(^3\) would be most appropriate, and indicate possible results of improper hand placement. In addition, it may be easier to make abstractions automatically from the more detailed knowledge when circumstances do not require such precision.

3. Creating models for how anatomical parts and physiological variables change (dynamic simulation). Having our behavioral knowledge expressed in differential equations, we apply numerical methods to solve the equations and simulate the resulting behavior. Without this component, we would be limited in our ability to predict changes to body systems and visualize those changes accurately.\(^4\) To illustrate changes to anatomical structures that reflect inter-object effects, this module must incorporate the environmental factors mentioned before.

This third aspect, dynamic simulation, is the main contribution of this thesis and hence we intend to focus our efforts here. In particular, we need to address four principal issues in building this part of our application:

a. Developing physiological models appropriate for the physical spaces in which they apply. We need to verify that the physiological variables have correct physical interpretations for the situations we are simulating. For example, in our respiratory mechanics models, we use pressure differences as generalized forces and volumes as generalized displacements.\(^5\) This formulation depends on the pressures being applied to the same area;

b. Linking the results of our physiological modeling with our anatomical modeling and vice versa. This will involve giving 3-D interpretations to our scalar pressure gradient and volume variables and relating structural changes

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\(^3\) Cardiopulmonary Resuscitation, a method used to provide circulating blood and oxygen to a patient whose heart has stopped beating.

\(^4\) Calling any modeling ‘accurate’ is extremely dangerous because the word implies different resolutions to different people. When we use ‘accurate’ we imply for the purpose of demonstrating general medical concepts visually, concepts such as respiratory mechanics. We explicitly say ‘general’ because we do not model specific biomechanical properties of tissue, at the same time we need to certain level of detail to suggest visual plausibility.

\(^5\) Generalized forces and generalized displacements are part of a reformulation of Newton’s Law \((f = ma)\), called the Euler equation in which forces and displacements are expressed in q-space where q is the degrees-of-freedom of the object (or a superset that includes the object’s parameters).
(as a result of 3-D forces) to their impact on physiological quantities (variables and parameters);

c. Choosing the appropriate set of equations that reflect the topology of the body systems; and,

d. Verifying that our models make valid, qualitative predictions (numerically and visually) about resulting physiological behavior.

If we were only interested in visualizing a certain set of different pathological consequences, we could build a system that coupled pre-computed tables of physiological values with pre-determined animated sequences. By making the knowledge explicit, though, we create the potential for a far greater degree of user interaction and exploration.

Since we are interested in viewing how objects interact, one might suggest simply defining a network of ‘causal’ connections between events. However, we are interested in describing system behavior in a manner that may facilitate a deeper understanding of the mechanisms involved. As Coiera [12] interprets the comments of others, the act of simply representing causal connections between events does not necessarily mean one has captured any deep knowledge of the system or its behaviors. We are included in this category too, to some extent. Our descriptions in terms of differential equations in themselves do not necessarily capture causal relations.

The utility of dynamic simulation can go beyond its value in driving the visualization. Davis [17] indicates how his approach of integrating a simulator with a declarative system description represents an important advance because the same description can be used:

(i) as a basis for the troubleshooting module, (ii) as a database of facts about connectivity, part identity, etc., (iii) as a body of code than can be run to simulate the device, and (iv) as the basis for a display program for observing the device.

These statements inspired us to involve both equations and equation annotations as important system features.

2.3. Proposed Work

This section defines the tasks and modules involved in demonstrating the specific aims. It is arranged by three application themes, which we summarize as follows:

- **Penetration Path Assessment**: Given the weapon category (stab or gunshot), external wound number and locations, internal bullet number and locations, and some clinical findings, present which organs were likely to have been injured and propose a
set of possible resulting topological configurations, indexed by penetration path hypothesis. In other words, derive a list of which new physical connections or disconnections may exist between existing anatomical spaces.

- **Static Anatomical and Physiological Knowledge**: Provide a means to view (in three dimensions, when appropriate) TRAUMAP’s knowledge about anatomical organs, systems, physiology, and pathophysiology. This module could be used to answer questions about properties at a particular ‘frozen moment’ of the system, such as adjacency and topological concerns.

- **Dynamic Simulation**: Enable the simulation of certain normal physiological behavior and some pathophysiology that occurs in penetrating trauma. The operator will interact with the simulation by manipulating parameters or objects in the environment.

2.3.1. Penetration Path Assessment

With penetrating injuries such as gunshot and stab wounds, the location of the wounds and the hypothesized trajectories offer significant information about the extent of direct injury. Health care professionals who assess these clinical findings are told to “visualize” likely trajectories, given whatever information is available about a wound, the scenario (perhaps where the victim was in relation to the assailant), and the person’s anatomical knowledge. With a three-dimensional anatomical representation, the computer can assist the user in the visualization, offering a concrete mental image of internal structures to discriminate better among trajectory hypotheses. Since we are interested in using this module to indicate possible direct damage, our method focuses on suggesting which organs may have been involved by considering the space of possible trajectories instead of trying to recreate the trajectory explicitly. Even though this will result in hypothesizing more organ involvement than a single trajectory formulation, we feel the conservative approach is more appropriate clinically. In the clinical setting, we feel it is more appropriate for such an application to identify possible injuries that should receive diagnostic attention than to rule out anatomical possibilities based on a trajectory hypothesis.

With some knowledge of clinical findings and their anatomical significance, the computer can also help to constrain the possible hypotheses. In addition, the computer can keep track of which organs should have been affected by trajectories in particular hypotheses.

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6Part of this is the assessment of mechanism of injury which may give clues about direct and indirect injury. Typical injuries that result from a particular type or location of a wound would give those injuries a high index of suspicion.
and as it is told about pertinent negatives,7 the computer can further reduce injury possibilities.

This module requires a user interface that allows the operator to place external wounds and bullets in the body, as well as report clinical findings. From the wound descriptions, we would compute the set of possible penetration path hypotheses. Each hypothesis would suggest which spaces have been penetrated, thereby indicating topological changes that may be important for behavior modeling. Briefly stated, the components are

- Placing external wounds and known bullet locations;
- Reporting types of wounds and pertinent clinical findings;
- Computing direct injury (which organs involved and spaces breached) as a result of penetration path hypotheses, resulting in sets of possible topological relations among anatomical spaces due to each hypothesis; and,
- Developing a method for assessing likelihood of injury based on evidence from direct path and clinical findings. This feature will not be an integral part of TRAUMAP, rather it will serve as an example of one type of reasoning the anatomical knowledge can support.

2.3.2. Static Anatomical and Physiological Knowledge

This component will provide the underlying knowledge for the system. This includes geometric data to support drawing and reasoning about object interaction, topological relationships to know which component is connected to which component, adjacency and inside/outside relationships, and which parts comprise which physiological system, anatomical and physiological parameters that are significant to the objects or processes being modeled, parameter relationships among anatomical and physiological parameters to associate mechanisms of change, and behavior models (or process descriptions) that relate parameters within processes (annotated equations).

Armed with this knowledge, we propose to implement the following functions:

- Develop a simple querying interface to the knowledge, one that can provide, for example, answers concerning adjacency and topological relationships in the body (as suggested in the CPR example before).

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7A pertinent negative is a clinical finding or test result that is significant because of its absence, e.g., a patient suspected of having a injury that would cause a left pneumothorax is discovered to have normal left lung sounds. Decreased lung sounds, the expected finding, is negative. The finding is pertinent as a contraindication of a pneumothorax.
• Allow arbitrary viewing perspective and navigation within and around body.

• Answer questions about physiology or pathophysiology, relating clinical findings (such as jugular vein distention) to physiological mechanisms and anatomical involvement.

2.3.3. Dynamic Simulation

The dynamic simulation module consists of the functions necessary for modeling both physical objects and processes involved, allowing the operator to set initial conditions. The tasks proposed are to:

• Develop volumetric, lumped-parameter models for solid and hollow anatomical organs, particularly those involved in cardiopulmonary physiology;

• Propose a method for linking scalar physiological variables such as pressure and volume with three-dimensional analogs;

• Use ordinary differential equations to model physiological processes such as fluid flow occurring within organs and responsive to shape changes; and,

• Integrate a method for propagation of forces between adjacent objects, when appropriate; and,

• Develop a method for representing the approximate physical space that blood occupies. We will integrate a particle system method for visualizing blood flow and represent the collection of blood as a deformable object so that we can calculate the effect of internal hemorrhage on surrounding tissue. This will be important for our simulation of a pericardial tamponade.

With the functions so described, we expect to implement the following conditions: (a) normal, quiet breathing; (b) different types of pneumothoraces (open sucking chest wound and tension pneumothorax); (c) impaired descent of the diaphragm due to increased abdominal pressure; (d) hemorrhage (simplified\(^8\) modeling out of the body and into the pleural cavity, abdominal cavity, and pericardial sac); (e) perforated diaphragm with abdominal evisceration; and (f) flail chest. If time and condition permit, we also may implement some surgical intervention, (e.g., chest tubes or needle aspirations), assisted ventilation, and a perforated bowel.

\(^8\)The reason we specify 'simplified' is that we will not make a general model for visualizing fluids, only a means to represent roughly the space the fluid occupies.
2.4. Summary

This section has described our objectives for building a system to support simulation of anatomical and physiological changes. We have proposed to develop three components, one to generate hypotheses about the structural changes from direct injury, a second that encodes our anatomical and physiological knowledge, and a third that simulates the changes as a result of environmental forces (via inter-object constraints or operator interaction). With these objectives in mind, we next look to the literature to consider insights from related efforts.
3. Background

Interactive medical applications in Virtual Reality are relatively new, owing to new developments in computer hardware. Medical modeling, on the other hand, has an illustrious history within bioengineering [42]. More recently, interest has grown within Computer Science, specifically the Artificial Intelligence (AI) community [48, 51, 52].

This section reviews some approaches that relate anatomical and physiological knowledge. We discuss initially approaches that encode symbolic anatomical knowledge, generally for the purpose of supporting physiological simulation. Then we present a few quantitative, anatomical efforts (anatomical databases) that deal directly with images but less with their relationship to underlying physiological mechanisms. From this discussion we proceed to consider approaches aimed at surgical simulation and medical education that relate to Virtual Reality (see Emerson et al [21]9 for an extensive bibliography on the subject).

An exciting prospect for visual presentation involves potential uses for the data collected in the Visible Human Project [1]. The Visible Human Project is an endeavor to create a complete, anatomically detailed, three-dimensional representation of the male and female body, from CT, MR, and cryosection images. Part of the long-term goals for the Project is to develop basic research into representation of structures, particularly encoding the connection between structural-anatomical to functional-physiological knowledge. For our purposes, such data could provide static organ models and realistic-looking images to map onto them, using the real-time texture-mapping hardware.

3.1. Symbolic Anatomical Knowledge in AI

In this section, we review a few approaches we feel are representative of those that encode symbolic anatomical knowledge explicitly. Our purpose is to see the types of knowledge important for specific applications and discuss how the integrated quantitative and symbolic knowledge in TRAUMAP might assist these types of applications in addition to providing a means for visualizing anatomical changes.

LOCALIZE

The LOCALIZE system [23] is devoted exclusively to the anatomy of the peripheral nervous system. Nerves are represented anatomically by their position relative to the

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9This bibliography is available via anonymous ftp at ftp.u.washington.edu in the file /public/VirtualReality/HITL/papers/tech-reports/emerson-B-94-2.
nerves to which they connect. Based on positive and negative motor findings, the algorithms trace the findings along nerve pathways to derive a minimal set of damaged nerves. The system is impressive in its attention to the complex detail of the peripheral nervous system.

**AI/MM**

AI/MM [31] is a system for analyzing renal physiology. It does not engage in diagnosis or therapy per se, but rather is a tool for exploring physiological behavior that is consistent with known information and for exploring the effect of therapy. Although unstated in the description of AI/MM, it appears usable not only by clinicians but also by other programs.

AI/MM’s knowledge is expressed as “concepts” that correspond to anatomical objects, physiological processes, physiological substances, mechanisms (empirical observations and physical laws) and parameters. Each concept may have features, which may be other concepts. For example, an anatomical object may have subparts, parameters and physiological processes associated with it. Processes describe the substances involved and how parameters can change values. Change, as a result of introduced information, is propagated along anatomical connections, subject to the physiological constraints. AI/MM’s explicit use of anatomy distinguishes it from many other physiological simulations.

AI/MM’s reasoning derives from a set of causal rules that express relationships between parameters which are either based on physical laws or empirical observations. Although the program treats them identically, the distinction does reflect which types of relation, namely the physical laws, might be useful for other domains. In contrast, the empirical relations will apply in specific domains or specific contexts within a domain. The user describes a clinical observation to the program, and it reports an analysis (at selectable levels of detail) of the expected physiological behavior.

**Naive Physiology**

Arana and Hunter [3] are developing what they call a “rich multi-functional knowledge base” for physiology. It describes anatomical parts, physiological processes, and materials, at various levels of detail and abstraction, such as a ventricle being a container. The abstraction is useful because it provides a means to describe compactly why a process

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10Kunz states that the program will suggest appropriate therapies and predict their effects, but he does not discuss how the program determines which are appropriate.
is important to the overall functioning of the body. Their objective is to describe “naive
physiology”—an encoding of the dynamics of medicine and the processes that keep the
body alive. The knowledge in their system is represented in such a way to perform simple
simulation, based on the physiological processes and anatomical connections, at least to the
extent that the program can recognize when processes affect normal physiology.

Their simulation language is based on rules for combining parameter values, which it
appears will be extended with some concept of time. Their anatomical representation
consists of part-whole relationships, at various levels of detail, and an indication of which
parts connect to other parts. A subsequent discussion with the author indicates that she will
also include inside/outside relationships, though how or if she uses them was not specified.

Discussion

These three efforts—LOCALIZE, AI/MM, and Naive Physiology\textsuperscript{11}—roughly portray
human anatomy from the same perspective. While LOCALIZE is considered as a modeler
of anatomy, it really does not model any spatial aspects of anatomy apart from physical
connection, since it focuses on the behavioral consequences of damage to the peripheral
nervous system. The description of nerves does not specify where they are located in the
body, only which nerve connects to other nerves or muscles. In AI/MM and Naive
Physiology, anatomy is described in terms of the parts of the body and their connections.
Yet these structural descriptions provide only one perspective for viewing anatomy—that
is, as the connections that are important for the chosen physiological processes. Nor is
there treatment for the spaces between instantiated anatomical organs.

Abstraction in itself is necessary to yield more efficient reasoning for particular tasks.
However, the assumptions should be accessible to an intelligent system, because the
abstractions supply only a partial picture of the real circumstance in which the body
operates. Forbus et al [25] argue convincingly for a representation that includes both a
symbolic representation and the underlying (quantitative) knowledge from which it has
been derived. An example they present deals with assumptions in a qualitative description
about gears that are supposed to mesh. Given a chain of gears, each gear can mesh with its
neighbors without necessarily meaning that the first and last gear in the chain will fit. Each
successive meshing will depend on the play between neighboring gears. The play might be
successively reduced through the chain, resulting in gears that from the same chain that

\textsuperscript{11}We refer the Arana and Hunter system as “Naive Physiology” pending a name being given to it.
cannot mesh. This example illustrates how any qualitative description depends on the contextual granularity assumed.

In work on anatomical localization for neurologic diagnosis, Banks and Weimer [5] divide the nervous system into hierarchical groups of cubes. Each cube indicates which objects are totally within it, partially in it, and which blood vessels are inside. Each anatomical object has which cube(s) it is in, which it is partially in, and which blood vessels supply it. They divide the body into twenty-seven cubes, and then each of those into twenty-seven, and so on, until the resolution is three millimeters on each side. The cubes are arranged hierarchically. While this may be sufficient for their purposes, it is probably also clear that it is most likely sufficient only for their purposes. Of concern is the algorithm that partitions the body hierarchically to achieve the 'right' abstractions in the smallest cube.

Davis [17] also advocates the explicit encoding of representational assumptions in his landmark work on the role of adjacency in diagnosing faulty systems. In Davis’ view, the concept of adjacency is central to troubleshooting: “devices interact because they are in some sense adjacent: electrically adjacent (wired together), physically adjacent (hence ‘thermally connected’), electromagnetically adjacent (not shielded), etc.”

If an organ leaks fluid, we have to consider where that fluid is going and what potential harmful effects it can have on parts it contacts. Smith [50] alludes to inferences such as these. Also, without a sense of the contact among neighbors, there is no way to predict how one part can move when pushed by some force, or how an object can fall or compress as a result of gravity. In designing programs for simulating the body, such as during virtual surgery, we need to provide the total picture. This means considering the spatial aspects of the parts involved, necessitating a representation beyond which parts are physiologically connected.

### 3.3. Anatomical Databases

With the ever-increasing role of computers in medical imaging, efforts are underway to compile image databases, or ‘anatomical databases’, which are essentially indexed, image libraries of both normal and abnormal anatomy and physiology. These databases provide scans obtained from patients through a variety of imaging techniques. While these images are realistic, the extent of the computer’s involvement is typically just in rendering and indexing the images. However, some effort has been suggested for assisting with radiographic diagnosis [6]. Some approaches claim to associate functional knowledge with the parts displayed, but that functional knowledge appears to be somewhat shallow. The
functional knowledge incorporated typically means association of anatomical parts with textual descriptions or labels.

**The Digital Anatomist Program**

The Digital Anatomist Program [8] is an ongoing research effort directed by Cornelius Rosse at the University of Washington. It consists of a number of projects aimed at three-dimensional reconstructions of biological structural knowledge, currently modeling the brain, the knee, the chest cavity, the heart, and the mediastinum.12 Among its goals is to develop a useful representation for anatomical structure to enable the computer’s understanding of anatomy. The program involves both two- and three-dimensional reconstructions using actual radiographic and magnetic resonance images.

One project is used directly to assist health care students by providing a network server database that retrieves and presents requested information. Anatomical information consists of spatial structural knowledge, such as geometric shape and ranges of variations, and symbolic structural data, such as the names of objects, their functions, and their relationships [7]. The knowledge about the function of the objects is currently not in a form usable by a computer for reasoning, being either pure text or concepts arranged in semantic hierarchies.

Since the program thus far deals with actual images, it technically falls into the category of medical imaging, but with the explicit aim that the knowledge will be useful for higher-level reasoning as well. To motivate the interest in capturing structure, Brinkley et al. invoke the hypothesis in biology that structure determines function, so a framework of biological structure is fundamental to any causal biomedical knowledge base [9]: Once structural knowledge at the level of gross anatomy, histology, and molecular biology is adequately represented, it will be easier to add normal and abnormal functional knowledge.

The program is successful in representing a variety of anatomical structures, from the microscopic level (proteins) to macroscopic structures such as the brain. At the center of the representation is their Hierarchical Geometric Constraint Network (HGCN): The basic notion behind the GCN approach is that networks of local geometric constraints between object parts, when interacting together in a constraint propagation process, are able to generate a global description of the shape and range of variation of a particular object class [7].

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12 personal communication
The HGCN is an “abstract object” made up of GCNs or HGCNs, where abstract objects are groups of related sets of objects. Each node is a physical object itself or part of an object, and contains information such as its possible location in space, and its relative orientation. At each level, objects are described by a collection of subparts, and a shape that defines the boundary of the object. Viewed another way, the (constraint) relationships of the subparts give rise to the shape.

To represent two and three dimensional shapes, Brinkley developed the Radial Contour Model (RCM) [6]. This paradigm can model shapes that can be represented as distortions of a circle or sphere. An origin is chosen along the long axis of an organ (such as a two dimensional image of a kidney), and rays extend from the origin at fixed angles. Where each ray intersects the boundary of the object is a landmark on that object. Obviously, all parts are not the same, so the program learns the range of values (distances) for each ray by examining actual data. It refines its model of the object by developing constraints between landmarks. Brinkley uses the RCM to perform automatic image segmentation, where the program starts with models of organs it has learned and applies the knowledge to recognize an organ on a new image it is presented.

VOXEL-MAN

VOXEL-MAN is an ongoing project at the Institute of Mathematics and Computer Science in Medicine, in Hamburg [46]. Its goal is to provide a super-realistic atlas of the human body, enabling exploration and dissection. They argue that graphics applications in medicine leave the image interpretation to the viewer, while Artificial Intelligence techniques in knowledge representation are not concerned about the visualization of knowledge. They propose to link realistic images with symbolic knowledge:

1. Visualization of symbolic knowledge in a realistic visual context (e.g. by creating annotations or textual descriptions related to an actual view).

2. Presentation of visual information based on conditions to symbolic knowledge (e.g. “show all gyri involved in a certain function”).

VOXEL-MAN is a response to earlier work that was limited in the completeness of the model and limited to precomputed views of images. Atlases intended to support automatic interpretation of actual clinical data (noted in [46]) encountered many problems mapping a limited set of anatomical objects with the representation as two-dimensional contours or collections of points. Since the projects analyzed represent the objects as two or three-dimensional contours, essentially as hollow, the Hamburg group thought a more useful
representation for tasks such as dissection would reflect anatomical parts as being “filled”—that is, represent image volume.

Through an interactive process, they segment actual images and define spatial regions and relate them to new or existing objects. Each voxel (the three dimensional equivalent of a pixel) contains information about the object to which it belongs or about that space in particular. Symbolic knowledge, such as attributes and relations, can be added to objects subsequently. With existing objects, voxels inherit properties as a result of being part of an object, e.g., visualization parameters like color. Their “intelligent volume” structure expresses spatial knowledge as one or more “attribute volumes” (presumably the image information) and the symbolic information attached to objects. The advantage they achieve with this representation is they do not have to navigate through a data structure to retrieve information about parts; each voxel contains enough information to supply volume visualization methods.

The database of information organizes objects by their structural relations, functional role, and blood supply. Users can currently navigate the brain and skull models through anatomical connections (physical adjacency), functional pathways, and blood supply. They also have developed less extensive atlases for a human fetus, the upper abdomen, and the heart.

Discussion

These medical imaging projects make use of geometric anatomical representations, with physiology generally limited to indexing images rather than characterizing how objects behave. The approaches focus on the visual impact, and relegate the association of function to some later stages.

The HGCN and RCM are indicative of solid progress toward representing anatomical structure for their purposes. For any approach, the usefulness of representing objects hierarchically is clear, as is the underlying constraint mechanism between object parts. The HGCN is appropriate for representing constraint relationships such as part/subpart, and the nodes could easily contain additional structural information such as material. However, the representation would fall short of representing large structures such as the body, for three reasons. First, it would be awkward to describe the body's shape as a distortion of a circle. The contents of the body, unlike perhaps the kidney, do not obey structural constraints similar to a circle or sphere. More likely, the body's shape would be represented by a collection of pieces, such as horizontal slices. Second, the constraints mentioned, namely distance and position in space, are derived descriptions rather than
constraints that the parts actually obey. Thus, from distance and position constraints alone, the model would not predict the intestines eviscerating in response to a wound in the abdomen. While some structures are harder to move than others, most body parts can be moved, to a degree. These real constraints are dictated more from physical laws of force, space and time, such as the fact that two objects cannot occupy the same space at the same time (at least one must move or be compressed), instead of a derived constraint on distance. Because it is restricted to structure, the representation does not commit how to use knowledge about an object’s material composition. Thirdly, the representation does not lend itself to a particular connection with the function of an object. Rather it focuses exclusively on representing the object’s structure.

Though VOXEL-MAN and the projects of the Digital Anatomist Program label the functional roles of objects they display, only VOXEL-MAN currently uses the functional role as part of the program’s processing. However, while the information is organized by functional categories (i.e. blood supply and other functional pathways), the descriptions serve to label objects for organizational purposes without a methodology for interpreting the labels.

For their purposes, the function of a part is a label and not a behavior. One attribute they mention [46], “blood arrival time” presumably assumes blood is flowing normally. Providing a description of behavior and a simulator to effect that behavior would make an atlas much more realistic. The representation of voxels appears to be a means to store and index data, but not one which other programs could use for understanding the mechanisms of the body.

3.4. Simulation in Medical Education

In medical education, as in science and engineering education, simulation is becoming a powerful tool for enabling students to learn by doing—especially for enabling them to learn complex dependencies that affect, in large part, what consequences actions have on the world.

As we have been recognizing the place our effort fits in relation to other work, we have begun to investigate physiological simulation in bioengineering more deeply since the field is about modeling physiological systems. Computer models in any engineering discipline can be organized by the purpose to which they are applied. In bioengineering, some of the the principal categories are modeling as research vehicles for use in advancing physiological and clinical insight, tools for estimating physiological quantities, models for
control and therapy of on-line systems, and simulation for education and training [37]. We are interested in investigating systems proposed for medical education.

With the high costs associated with surgical training, planning, and execution, one of the enticing applications in this area is virtual surgical simulation. Satava [45] envisions the impact of Virtual Reality on medical education as helping medical students to understand important physiological principles or basic anatomy. In addition to the experience reinforcing information, it may also spark “initiative in learning through the thrill of discovery.” Dickinson points out that it is difficult to capture a student’s interest if he does not feel he is “doing experiments on a simulated human being or animal, but rather simply performing mundane mathematical exercises which have been already designed by his instructors.” [18]

3.4.1. The Road to Virtual Surgical Simulation

Medical professionals will evaluate virtual reality medical applications on their plausibility with actual experience. For surgical simulations, imprecise anatomical representations and implausible behavior will detract from the realism and believability of the virtual experience [44]:

[T]he image must be anatomically precise and the organs must have natural properties such as the ability to change shape with pressure and to behave appropriately in gravity. All the body parts that are represented must be able to be manipulated by grasping, clamping, or cutting, and they must be able to bleed or leak fluids.

Since the visual impact of simulators is critical, much effort has been focused on providing realistic images, through techniques such as interactive laser discs, intense computer graphics simulations, and the integration of actual images with superimposed computer graphics (discussed in [40]). Noar outlines and evaluates considerations for simulating endoscopy, but most of his comments apply to surgical simulators in general, such as the need for both visual accuracy and tactile feedback. Dumay notes that today, the first generation of virtual surgical simulators have been developed with the focus on rendering human anatomy. Physiological and pathophysiological modeling are often neglected in these simulators [19].

Laparoscopic simulations are becoming popular because surgical methods currently involve video screens (as opposed to general, open surgery) so having the computer generate images can be more convincing as alternative video source than open surgery.

Satava [44] identifies five areas to address for realistic surgical simulation.

1. **Fidelity.** The image should appear real.
2. **Object Properties.** The organs must deform when grasped and must fall with gravity.

3. **Interactivity.** The surgeon's hand and surgical instruments must interact realistically with the organs.

4. **Sensory input.** Force, feedback, tactility and pressure must be felt by the surgeon.

5. **Reactivity.** The organs must have appropriate reactions to manipulation or cutting, such as bleeding or leaking fluid.

Satava also describes the first surgical simulator, the virtual abdomen, which contains the stomach, pancreas, liver, biliary tree, gallbladder, and colon, and a few surgical instruments. The most unnatural aspect of the simulation is that organs do not bend or change shape, and vessels do not bleed when cut. Satava states that object deformation algorithms exist, but have not been used because they are too computationally intensive to be practical. While this may be true for very accurate tissue modeling, certain approximation techniques and faster hardware are enabling some forms of physically-based modeling with today’s technology.

Cover et al [15] review some deformable object modeling methods to contrast with their own physically-based methodology based on energy-minimizing surfaces (they call *active surfaces*) for organ models in laparoscopic surgery. They also stress that existing systems either do not have visually-realistic graphics, the interaction is unrealistic, or the interaction cannot be achieved currently at real-time rates. They observe that most deformable model approaches for soft tissue do not preserve object volume, but then do not indicate how their approach solves it in a natural-looking way. Their implementation consists of deformations to the gallbladder, where they simulate object deformation and the result of collision with surgical instruments. They propose to incorporate interaction among objects and membrane constraints between organs.

**High Techsplanations**

High Techsplanations [35] is one company that produces surgical simulators. From our investigation, they are probably the farthest along with regard to having a finished product. Their focus is on simulators for minimally-invasive procedures such as laparoscopic abdominal surgery, cardiac catheterization, pelvic lymph node dissection, hysterectomies, and hernia repair. As a commercial venture, they are attentive to the clinical requirements for simulators, focusing on issues such as presenting realistic images, interaction, and haptic response.
Their physically-based modeling method, namely spring-mass systems, is the same underlying method we use. However, they use surface models, where we plan to use volumetric models (though the methodology remains the same). Their philosophy is that simulators will be designed for specific procedures where the operator is constrained to relatively small margins of error before the program intervenes [34]. This would be opposed to making an all-encompassing patient in which the operator might wander. One problem of an open system is that it may be too unstructured for most training.

Discussion

Our proposed approach for deformable modeling is most similar to the method that High Techsplanations employs. Spring-mass systems are relatively simple models but can be quite versatile, and with reasonable-looking results should give real-time or close to real-time performance. This approach will also give us a sense for deficiencies that more realistic methods might remedy, such as with the Finite Element Method [55] or hybrid methods (e.g., Metaxas [36]).

In the surgical simulators we have seen, we have noted very little mention of requirements for the underlying physiological modeling. For example, the cardiac catheterization simulation initially gives a patient history, but those values are not used in the simulation. We seek to address this deficiency by developing an approach to physiological modeling that can be integrated with visually-plausible deformable anatomical models.

One question arises naturally when we ask about the underlying physiological and pathophysiological models: how detailed do they have to be?

One obvious but unhelpful answer is “as detailed as they need to be.” While we feel it is important to have a sound foundation for simulating physiological mechanisms, we recognize that in simulations for specific procedures it is reasonable to predetermine the variation the operator can encounter. So long as the actions are fairly well circumscribed, so too can be the reactions. Therefore, less computational effort in general is necessary to maintain the physiological simulation than the anatomical simulation, which is probably more unpredictable as the operator is given fewer movement constraints.

3.4.2. Simulation in Medical Education

We have only started to investigate other programs for assisting in medical education. The biomedical library at the University of Pennsylvania has a number of multimedia medical instruction programs, but the simulation involved is limited to relatively simple calculations about high-level physiological behavior. The anatomical atlases are, in general, limited to one or few viewing perspectives.
To maximize student interest in educational software, programs need to give students the feeling they are participating in real experiments. As Dickinson, creator of MacPuf [18], points out, the value of making comprehensive physiological models for education is in giving the student the feel that he or she is performing real experiments. While we are not seeking to undertake a physiological simulation with the scope of projects like MacPuf [18] or HUMAN [14], we feel we are taking the first few steps for simulating comprehensive physiological models by initiating the link to graphical environments.

**Simulation in Graphical Environments**

The September/October 1993 issue of the educators’ newsletter *Syllabus* is devoted to recent educational technology products that incorporate simulation, highlighting several designed for medical education. What is of interest here are those systems that go beyond an albeit rich multi-media presentation of information, to being true simulations that capture the effect of the student’s actions on the world or object being modeled. We briefly describe three of these systems, and then how our proposed software, in taking the next step in behavioral fidelity of organ models, will enable students to understand better the complex dependencies of structure and function in the human body.

*The Flexing Finger*, developed by a group at St. Louis University led by Dr. Gregary Rinehart, uses animated computer graphics sequences to demonstrate the complex motions of an intact human figure, to clarify the anatomy of the finger, and to depict movement deficits resulting from common hand injuries. This program has won awards from the American Society for Surgery of the Hand and the American Society of Plastic and Reconstructive Surgery.

*The Brachial Plexus Blocks Simulation*, developed by Dr. George Sheplock at the Wilford Hall Medical Center at Lackland AFB, lets students practice doing nerve blocks using actual videos and photos of cadavers. Since the main emphasis of the program is to get students to visualize the anatomy under surface landmarks, the system allows the student to not only view the outside of the patient’s body, but also to uncover the underlying anatomy and view layers of muscle, nerves, and arteries as well.

*The Virtual Clinic*, developed by Ciné-Med (Woodbury, CT), uses both existing images and animation to enable surgeons-in-training to practice doing laparoscopic gall bladder surgery. Instead of going into a real abdomen though, the surgeon’s instruments go into a black box where sensors interpret the movements and display them on a monitor on top of a three dimensional moving image of the organs involved.
Discussion

What all these systems lack though are realistic models of the biomechanical and physiological properties of the tissues and organs they are presenting to the student, so that organs move or deform in response to certain forces and tear or burst in response to other forces. To enable medical education systems to take the next important step ahead, we need to incorporate the interactivity and freedom of surgical simulators, which will involve more detailed anatomical and physiological modeling. This may come as no surprise, seeing that surgical simulation itself can be viewed as a form of medical education.

When we discussed surgical simulators above, however, we were somewhat content with predetermined physiological and pathophysiological behavior. However, when the application proposes to educate the operator in a more free-form simulation, we must insist that our models are more generally applicable. In particular, we need to model the relationships between anatomical and physiological changes in a more automated fashion so as to give the operator the most amount of freedom for experimentation. It is apparent that researchers recognize physiological models as necessary [20, 35]. The details about the physiological models, however, are much less forthcoming. We propose to explore the consequences of anatomical and physiological interaction by developing a serious approach to physiological modeling that can be integrated with visually-plausible deformable anatomical models.

Simulation in Bioengineering

There are many physiological models in the bioengineering literature of varying complexity and physiological detail. While the vast selection is attractive, it is ironically not so simple. One difficulty in building on the work of others is that it either their work is too simple to be useful, or too complex to be understood. Models are designed for specific purposes, so it is not so simple to pick out two or more models and make them work together correctly.

Rideout [42] cites a number of pioneering approaches in his book on computer-based physiological modeling. While we have only begun to investigate approaches in respiratory system modeling through surveys such as [13, 18, 32, 37, 42], all models report their results through graphical plots of system variables. None mention added value in presenting the results in a 3-D environment. Schwid [47] has developed a real-time simulator for training students and residents in anesthesia with a graphical interface—simulations of the equipment one would see in surgery, as well as a very simple patient model that responds to the situation by changing pupil size, skin color, and closing his eyes.

Background
3.5. Summary

This section has discussed approaches from the literature concerning the issues we seek to investigate. Anatomy is clearly a foundational concern for medical modeling, yet researchers have not reached a consensus about what aspects are necessary. This is most likely because different aspects are necessary for different types of reasoning. We have seen programs designed for high-level reasoning lacking a quantitative level for grounding anatomical concepts. Anatomical databases, while providing the raw or segmented images, cannot yet connect with higher-level knowledge because their functional knowledge, expressed in text or rudimentary semantic hierarchies, is still expressed in forms that are meaningful to us only. To the computer, this means that such knowledge remains inaccessible. Surgical simulators, still in their infancy, are more focused on presenting realistic images than physiological fidelity. For surgical simulations, this may be appropriate. For more general medical education, we feel that the integration between anatomical and physiological modeling needs to be more comprehensive because of the greater freedom given to the operator for exploring. Traditional physiological simulation for education, perhaps due to technological limitations in developing a graphical environment, are slowly coming into the age of graphically-based applications.

The concerns we have outlined, of course, point to the purpose of our investigation: to search for a balance between anatomical and physiological modeling. We seek to exploit existing technologies in both arenas to uncover the issues in bringing these obviously dependent activities together. Armed with descriptions of mechanism, we can provide the underpinnings for tools applicable to medical education and clinical use.
4. Design and Method

TRAUMAP's architecture is organized by its three primary functions, outlined in Figure 4.1, the penetration path assessment module, the query interface to TRAUMAP's clinical knowledge, and the dynamic simulator. The Figure shows where the operator can interact with the system and how the modules may communicate their results with one another.

**Figure 4.1. Proposed Interaction Layout**

1. **Penetration Path Assessment.** This component's primary role is for visualizing which organs may have been directly involved in penetrating injuries. The operator enters the location, type (gunshot or stab), and any other information about external wounds (e.g., if it is a known entry or exit wound), and all internal bullet locations. TRAUMAP generates all possible hypotheses for penetration paths (without ricochet effects\(^\text{13}\)). Each hypothesis encodes which spaces have been penetrated as a result of particular hypothesized wound tracts. The operator can choose particular hypotheses to examine visually by navigating cameras about or within a three-dimensional human body.

\(^{13}\)Currently, we consider penetration paths that go from the entry wound to the exit wound or bullet, without the potential for significant ricochet effect. For our purposes, 'significant' would include consideration of trajectory deflection as a result of contact with bone. Dr. Clarke has suggested extending our method to include known deflection (when, for example, bone chips can be seen on X-ray), but factoring in such deflection probably will not be a part of the currently-proposed system.
trunk (male or female). Also, the operator can choose to have TRAUMAP report information about which organs may have been affected by each hypothesized wound tract.

2. Static, Clinical Knowledge Querying. This component’s primary role is to facilitate access to TRAUMAP’s underlying medical data. The data is primarily about anatomical relationships, but also includes mapping from physical structures to clinical findings (e.g., distended neck veins). We also will annotate our equations that we use in dynamic simulation to enable querying about dynamic, system properties (e.g., forces on structures).

3. Dynamic Simulator. We couple deformable object simulation for organs with physiological variables to imbed in our virtual organs some of the underlying physiological processes. The user will select among different conditions to simulate, in the realm of respiratory and cardiovascular dynamics. Given a particular condition, such as a simple pneumothorax, the simulator will then show how that condition progresses over time both visually (collapsing a lung) and quantitatively (the effects of physiological variables). The user will be able to pause the simulation at any point to ask questions about particular values or relationships. For example, the user could ask about forces on particular regions of objects. However, we have not determined yet to what extent user interaction is appropriate or will be allowed, beyond control of initial settings.

Each module produces results that can be fed into other modules. The penetration path assessment module generates hypotheses that can be used to drive particular simulations or to provide a context for question-asking about an injury hypothesis. During a simulation, the operator will be able to ask questions about particular variables, parameters, and objects.

4.1. Overview

While the three components share underlying data for anatomy, physiology, and pathophysiology, they are distinguished in that they use it differently. In particular, all components use the geometrical anatomical data. The penetration path assessment needs the data for computing candidate affected organs. The visualization (dynamic simulator) module uses this information to illustrate anatomical behavior and infer inter-object effects. For the query interface, the data can be used to determine answers to queries about physical adjacency.
This section describes the three modules and our proposed method for their implementation. Briefly stated, we anticipate implementing these modules as follows:

- **Penetration Path Assessment.** From gunshot wound information that the user provides, we will determine possible pairings of entry and exit wounds and possible pairings of entry wounds with known bullets. The method for determining candidates stems from the approach of Karpf [28]. From each hypothesis, we will report which organs intersect penetration paths. We will assign a probability distribution to the area within a proposed penetration path as well as a probability distribution over the organ location. These will be used to determine an approximate measure for likelihood of injury to an organ based on geometric knowledge alone.

- **Static, Clinical Knowledge Querying.** We will organize our anatomical, physiological, and pathophysiological data in an object-oriented framework. Our main concern will be to encode information about structural relationships, such as physical adjacency, inside/outside relationships, and connectivity. We also will include a mapping from clinical findings to their manifestations.

- **Dynamic Simulator.** There are two main pieces to this work, the anatomical simulation, namely deformable object and environment modeling, and the physiological simulation, namely computation of pressure, volume, and other physiological variable changes. Both consists of lumped-parameter models (anatomical—vector equations, physiological—scalar equations) expressed in ordinary differential equations.

We first present an example scenario using the TRAUMAP system before discussing in more detail the knowledge involved, the implementation, and our preliminary achievements.

### 4.2. Example Session

This section suggests how we envision interacting with the system ultimately. For this example, we are interested in examining the situation where a female has been shot in the right chest. We call up the female torso and place the external wounds on the body in the appropriate locations. Figure 4.2 shows three views of the patient: the left view is the main window in which the user navigates in the 3-D environment; the panels on the right give an anterior and posterior view of the torso. From these views, we can see that this injury most likely penetrated the right lung, as well as some skeletal structures such as the attachment of the fourth and fifth rib to the sternum. Posteriorly (bottom right), we can see that there may also be skeletal involvement. To examine the wound more closely or to get a
Figure 4.2. Perforating gunshot wound to right chest. The black cones in the chest represent the space of possible trajectories, given the external wound pairings. Left scene shows user-defined perspective. On the right, from top to bottom, the windows show the anterior view (front) and posterior view (back).

better perspective on the penetration path, we can rotate and re-position the cameras arbitrarily.

In Figure 4.2, the black conical regions represent the space of possible trajectories (a penetration path hypothesis), given that the wound followed a fairly straight path from entry to exit wound. We can have the program determine which anatomical parts are affected by this proposed hypothesis. Since there is a single entry and exit wound with no bullets, the system generates only the single hypothesis. If there were more external wounds or bullets, TRAUMAP would generate all possible pairings for consideration.
For our example, TRAUMAP would report the following:

External Wounds:
(1) Right Anterior Chest Above Nipple Level
(2) Right Posterior Chest Below Scapula

Hypothesis 1 (of 1):
(1) <-> (2) suggests possible damage to:
    rib 4, 5 anterior
    rib 7, 8 posterior
    right lung
Physical effects:
    torso is penetrated
    right chest cavity is penetrated
    right lung is penetrated

While it describes the 3-D location of external wounds in symbolic terms (namely the region in which the wound is located), TRAUMAP uses the 3-D location in all geometric calculations. From its (simple) mapping of anatomical parts and physical effects to their physiological involvement, TRAUMAP could add

The lung is part of the respiratory system, which may mean respirations are now impaired. The penetrated chest cavity may mean air can enter or blood can escape. The penetrated lung may mean fluid can enter or air can escape.

In considering the current hypothesis, TRAUMAP could continue

If this (Hypothesis 1) is correct and yet there is bleeding, it probably is from the lung vasculature or an intercostal artery because the injury has not affected a major artery or vein.

and relate them to conditions:

The penetrated chest cavity could result in a pneumothorax, a hemothorax, or a hemopneumothorax. The penetrated lung could result in a pneumothorax, a hemothorax, or a hemopneumothorax.

The boldface text means the program has made a hypothesis that can be inspected by the operator. If there was bleeding from a major vessel, we could probe our static knowledge to describe features of that vessel, such as in which cavity it is located and to what other vessels it connects. The reader will note a duplication in proposing a hemothorax, pneumothorax, or hemopneumothorax. This is because these injuries can occur as a result of the penetrated chest cavity, which would mean the passage is between the outside and the intrapleural space, or as a result of the penetrated lung (or more appropriately a penetrated bronchus or bronchiole), which would mean the passage is between the respiratory tree and the intrapleural space. Though TRAUMAP will not consider these situations differently, one might imagine extending the models to capture any differences.
Giving the program the clinical finding that there is a sucking sound from one of the chest wounds, the program would respond

The sucking sound reflects air entering a clear passageway into the intrapleural space. This is consistent with the hypothesized penetrations. The sound indicates an open sucking chest wound.

The operator may select any hypothesis, such as open sucking chest wound to pass to the simulator (however, open sucking chest wounds are more common with stab wounds than with gunshot wounds). In preparing the simulation, TRAUMAP may require more information (with suitable defaults provided), such as

Please estimate the diameter (in cm) of the sucking wound:
Please set or approve airway and compliance values:

The simulator may also need to know whether this injury is isolated or with other physiological involvement:

Do you want to consider this injury with a hemothorax?
Please estimate the rate of bleeding:

If the operator had selected pneumothorax from the entry for chest cavity penetration, the simulator would have then requested

Of the conditions I know how to model, the pneumothorax could be a simple pneumothorax, an open sucking chest wound, or a tension pneumothorax. Please be more specific.

Once the simulation parameters have been established, the system will display a panel of graphs alongside the three-dimensional torso. On the graphs, the system plots physiological variables (of which the user may choose) such as intrapleural pressure, lung volume, and blood pressure. The simulation always begins from normal, quiet breathing. As air enters the intrapleural space, the user will see the lung collapse as the diaphragm continues to contract and relax. If the condition is severe enough, the model will show some mediastinal shifting to the side opposite the collapsed lung (during inhalation). This may have some effect on the cardiovascular model in terms of disturbing venous return.

At any time during the simulation, the operator can re-position views, freeze the action, or discontinue the demonstration. Because we will model inter-object forces, the operator could reposition the body to see some effects on respiration, for example, of a lower-extremities-raised position (Trendelenberg position). Perhaps ultimately the operator could also cover the wound and see that the lung collapse halted, or insert a chest tube that drains the air.
4.3. Component Information

Each component defines methods that use anatomical and physiological information. This section describes the expected information requirements for each component and a sketch of the proposed representations. Table 4.1 summarizes the overall information requirements by module and type.

Our three main divisions for type of information are (1) Anatomical Object, or physical characteristics of objects, how they are constrained, and the space in which they reside; (2) Physiological Process, or characteristics related to process descriptions and how processes effect change; and (3) Integration, or information relating physiological mechanisms with involved anatomical structures, as well as the anatomical and physiological implications of some pertinent clinical findings, such as distended neck veins.

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Table 4.1 Summary of information by module and type

To enable more efficient organization of the information, we may not instantiate all relations of all parts at the time of system initialization. Rather, we see value in accessing information as Davis [17] advocates, using a ‘lazy instantiation’ approach. This approach means that we only provide what is necessary to support the current level of detail. As the operator requests more detail, we retrieve the more detailed levels. This may have application to (a) information querying, in exploring part/subpart or inside/outside relationships; (b) geometric reasoning, such as by instantiating major organs, regions, and vessels initially to perform computations, then using more detailed anatomical knowledge if
the operator so requests; and, (c) physiological model organization, where a phenomena could be viewed from varying levels of detail.

4.3.1. Anatomical Object

Anatomical information describes the physical structures in our environment and their spatial relationship to each other. Since we require enough detail for visualizing the anatomy, most of this information is quantitative. However, we envision creating functions that would abstract to symbolic information from the numerical data, such as determining higher-level descriptions of adjacency and connectivity. The features of anatomical objects, listed below, will be collected in an object-oriented data structure. The object data structures will be organized in graphs by physiological system involvement and topology.

- Geometry. This is the numerical description of our objects. The basic representation for objects is an object surface approximation by a mesh of planar polygons. In its simplest form, the state of each object is characterized by a set of node positions, node interconnections (edges), and faces. For our deformable objects, we also approximate internal structures (volume) for solid organs and include in their description parameters for their dynamics.

- Environmental Factors. This has to do with values for factors that affect structures in our virtual environment, such as gravity. We do not anticipate making an explicit declaration about concepts like gravity, except in noting that it is a component of the total forces applied to an object.

- Material Properties. We will investigate studies on biomechanical properties of tissue, but most likely our encoding for material properties will be customized for our deformable-object modeling method based on a subjective estimate of dynamic appearance and correspondence with our physiological predictions (pressure-volume relationships). In other words, we will adjust material properties for deformable objects so they behave in a visually-plausible manner as opposed to striving for tissue segment fidelity.

- Connectivity. The form of this information depends on the application. For the dynamic simulation, we encode which surfaces are physically attached, such as the attachment of muscles to bones (e.g., the diaphragm), or vessels to one another.

While we encode which objects are physically connected, we also must address the issue of connections between spaces, since it is the presence of a passageway between compartments that can enable processes such as fluid flow. The reasoning we do about
this type of connectivity will most likely be explicit in simple rules for suggesting the potential for interaction among the contents of the newly-connected compartments.

Our original intention was to construct equations dynamically from such descriptions, in the manner of Qualitative Process Theory (Forbus [24]) and the Qualitative Process Compiler (Farquhar [22]). However, we have subsequently focused our attention on addressing more basic issues in a quantitative framework.

- Adjacency. We feel that other approaches have neglected the explicit encoding of adjacency relationships in their anatomical descriptions. Because we have geometric object descriptions and methods in our virtual environment for determining contact, we can immediately determine if two objects are in contact.

- Inside/Outside. This relation is important for identifying simple spatial inferences such as if a vessel is injured, into which cavity it is most likely to bleed.

- Part/Subpart. We will use this information mostly for descriptive and organizational purposes. An example would be that the inferior vena cava is part of the systemic venous system, which is part of the cardiovascular system. It is an important factor for data organization in providing hierarchies to arrange our data.

Some of these relations, such as inside/outside and adjacency, could quite reasonably be abstracted from our geometric organ descriptions. In spatial reasoning, Magee et al [33] discuss their approach for capturing salient object features in symbolic form (such as surface depressions or protrusions) from raw geometric data. They are careful to note that the idea of ‘salient’ feature is dependent on how one views the object, therefore they conjecture that the set of ‘salient’ features is not a closed set. Cui et al [16] use the convex hull of an object in their logical formalism for predicting spatial changes. Forbus et al [25], by their Metric Diagram/Place Vocabulary hypothesis (MD/PV), claim that quantitative, geometric detail is necessary for spatial reasoning to clarify assumptions of the symbolic interpretations. The metric diagram is a combination of symbolic and quantitative information used as an oracle for simple spatial questions. The place vocabulary is a purely symbolic description of shape and space, grounded in the metric diagram [25].

For the static knowledge querying, we hope to derive symbolic relationships among parts directly from the low-level geometric knowledge automatically. Until we resolve the

---

14This is true only if we define precisely what are relations mean. For example, we use ‘inside’ to mean an object completely enclosed within the convex hull of another object.
feasibility and value of that, we will imbed the symbolic information explicitly in the part description.

### 4.3.2. Physiological Process

Our interest in physiological processes is to describe their dependencies and influences on environmental and structural parameters. Our models used in dynamic simulation will be a set of pre-determined equations, but we also want to describe pieces of the equations for inspection and modification during operation. In our parameter and variable descriptions, we will include links to relevant processes (equations), namely those in which the parameter or variable participates. Similarly, our process descriptions need to include links to parameters, variables, anatomical structures, and types of connections involved. Our equations take two forms: (1) the representation passed to the numerical integrator for solving the equations; and (2) textual descriptions of the relationships, forces, and which processes are involved. We intend to describe the relationship among variables and parameters in equations based on the model abstraction work of Iwasaki and Simon [26]. In this work, Iwasaki and Simon describe an algorithm for computing dependency relationships among parameters and variables in systems of differential equations. This type of information could be useful for operators to investigate the underlying relationships involved in the physiological processes.

### 4.3.3. Integration

This last category is for information relating physiological and anatomical information, though the process descriptions mentioned above will encode some correspondences. We specifically have identified two types of information related to the linking of anatomical objects with physiological mechanisms:

1. **Parameter-to-Object Map.** We need to associate which parameters and variables in the physiological simulation relate to which anatomical features. For example, the physiological concept of resistance to flow is dependent on the radius of the conduit’s cross-section.

2. **Clinical Findings Mapping and Relation of Anatomical and Physiological Manifestations.** If we want to relate the results of the simulation to clinical findings, we need to know which names have been given to which conditions. For example, we need to know that jugular vein distention means that a certain section of the cardiovascular system (namely the exterior jugular veins) has more volume than normal. Another example is shock. Shock is typically defined for the normal adult as a systolic blood pressure of less than 90 mmHg. We can envision attributing decreased
breath sounds or muffled heart sounds as typical findings resulting from certain injuries. This type of reasoning will most likely take the form of simple associations or rules.

4.4. Theory and Implementation

The TRAUMAP system will consist of a command module, implemented in Common Lisp, coupled with the visualization interface, code, geometric knowledge, and low-level geometric reasoning encoded in C. While we could argue that having the higher-level knowledge accessible in Lisp facilitates the interaction with other Lisp-based applications (such as TRAUMAID [53]), the truth is that this separation reflects limitations of our working environment rather than a philosophical distinction among modules. The Jack environment (Badler, et al [4]—our environment for Virtual Reality) currently runs only on Silicon Graphics machines, whereas our most accessible, full-fledged implementation of Common Lisp (Lucid Common Lisp 4.1) is only licensed for our Sparcstation servers. Figure 4.3 summarizes the routines and information on each platform. The components will communicate in a text protocol via Unix sockets.

![Diagram of TRAUMAP system components]

4.4.1. Penetration Path Computations and Assessment

We limit our coverage of injuries to penetrating trauma, specifically those injuries resulting from gunshot or stab wounds. With these types of wounds, we need to determine the extent of direct damage and anatomical (structural) alteration, to present to our simulator potential effects on physiological systems.
We exploit this module to identify which structures are likely to have been injured as a result of a gunshot or stab wound. From information about external wounds and known bullet locations within the body, the geometric reasoner generates different possible penetration paths and computes which anatomical structures lie in those paths. To determine potential injury to an organ, we use standard methods of three-dimensional polyhedral intersection. From simple rules about which organs and spaces could have been penetrated, TRAUMAP compiles a list of possible injuries related to the topological changes.

As Figure 4.3 indicates, part of the work in this module is done with low-level geometric reasoning (the penetration path computations), while the higher-level aspects (computing different hypotheses, evaluating the hypotheses, etc.) are done in the reasoner module.

One important aspect of this module is that it can be improved incrementally without affecting other parts of the system. While the initial version of TRAUMAP will only consider situations where the number of bullets is known, one could develop the geometric reasoning in this module to estimate likely trajectories in the absence of knowledge of bullet count, possibly incorporating factors such as weapon type, shooting distance, projectile velocity, and human body dynamics (predicting how a person might contort [e.g., twist or bend] due to the force of a projectile, and how that might affect the trajectories of subsequent bullets).

Direct Injury Assessment

Once we have computed the set of possible penetration path hypotheses, we assess the impact of the different hypotheses for the model selection phase. For each hypothesis, we use our static, geometric, anatomical model to determine which anatomical parts may have been affected. After computing these, we can calculate useful information such as which part has been hit in any hypothesis (the union of all possible penetration paths) and which parts would have been hit regardless of the configuration (the intersection). Using the 3-D torso, we allow the user to inspect penetration path hypotheses visually.

We see our penetration path reasoning as one part of the wound assessment in the pursuit of determining organ involvement.\textsuperscript{15} The idea is that this type of reasoning will complement another component that considers other clinical findings. These two components will have a certain power to support or contraindicate particular diagnoses. For example, the reasoner may indicate that there is a ninety-five percent chance the injury

\textsuperscript{15}This idea is from Dr. Clarke.
penetrated the left lung given the locations of external wounds and likely trajectories. Even if there are normal breath sounds on that side, the high likelihood of penetrating the lung from the geometric evaluation alone might suggest that the breath sounds should be re-examined or perhaps considered less significant.

4.4.2. Static Anatomical and Physiological Knowledge

The intent of this module is to organize and view our knowledge about anatomical structures and physiological mechanisms. It is implemented as a collection of structures in Common Lisp, where each structure consists of slots appropriate for that type of information. Types are organized in a directed graph (in the object-oriented framework CLOS\textsuperscript{16}) that relates types to supertypes and subtypes.

Since we will include geometric information as both quantitative detail and symbolic abstractions, such as part/subpart, inside/outside, etc., other applications may exploit this module for their purposes—applications designed for assisting in medical reasoning could use our geometric data (either quantitative or symbolic). This would provide two levels of granularity for describing anatomical knowledge. In his circuit-fault diagnostic system, Davis [17] discusses the importance of different perspectives on adjacency, and how each layer of his multi-layered model encodes explicit assumptions that can be probed if higher-level analysis fails to yield adequate results.

4.4.3. Dynamic Simulation

The dynamic simulation module is the central feature of TRAUMAP. It combines deformable object modeling, using lumped-parameter, 3-D organ models, whose behavior is described in (vector) ordinary differential equations, with lumped-parameter physiological descriptions expressed in (scalar) ordinary differential equations. We interface these components at the level of mechanical description. Anatomical objects respond to forces that affect their shape, volume, and motion, and physiological processes compute pressures and volumes that are translated as vector forces and 3-D displacements on those objects.

The integration between the anatomical and physiological modeling centers on the role of pressure and volume variables as the principal links. For anatomical modeling, pressure gradients across object surfaces result in forces that influence shape and motion. For physiological modeling, our equations relate pressures and volumes, which in turn may influence other physiological behavior. Figure 4.4. illustrates this concept graphically. As

\textsuperscript{16}Common Lisp Object System, the object-oriented part of Common Lisp.
shown, we could use the pressure and volume variables as input signals to models of other physiological behavior, such as biochemical processes (e.g., oxygen uptake) and system control (e.g., affecting respiratory rate and muscle effort).

For ‘hollow’ organs, such as the lung, we use the pressure gradient between the inside and outside pressure. For solid tissue that divides anatomical regions (such as the diaphragm or mediastinum), we use the pressure gradient across the structure to determine forces. If the boundary between two anatomical regions in which different pressures exist becomes breached, we identify the breachpoint and apply a force that acts on objects within the regions. In this way, we intend to simulate hernias. These ideas are obvious simplifications of physical phenomena, and we may need to seek a more sophisticated solution. We shall discuss subsequently the three categories for forces (internal, contact, and body) listed.

In this formulation, we have two descriptions for mechanical behavior—one in terms of scalar quantities (generalized forces and displacements) for presenting behavior in an abstracted form, and the other in terms of 3-D objects (forces and displacements) for presenting behavior visually. In our physiological description of objects, there is a single value (compliance) that dictates the pressure-volume relationship for the material. In contrast, elasticity in our 3-D organ models is distributed.

Figure 4.4. Interaction of anatomical and physiological models.
To maintain physiological fidelity, it is imperative that these descriptions remain consistent with each other during simulation. In other words, the pressure-volume relationships for organs predicted in the physiological models must agree with the force-displacement results in the anatomical models, otherwise our integration will not be accurate and the behaviors will be incorrect. In practical terms, this means that we must assign appropriate material properties to our 3-D objects such that if a certain pressure gradient (force) is applied, the object will reach the predicted volume (displacement).

While the pressure and volume simulation in the center feeds modules both upwards and downwards in Figure 4.4, we also need to determine how and when simulation parameters can be affected. This should capture the dependence of physiological processes on physical features (e.g., resistance and compliance). When an organ is exposed to external forces, we use these physical dependencies to determine the impact on the physiological process.

The interactions described should demonstrate that we see these components (anatomical and physiological modeling) as complementary. In other words, we are developing two components that each are influenced in some way by the other. In the bioengineering literature, Rideout defines a concept called multiple modeling [42]. A multiple model is one that combines two or more models that deal with different phenomena but interact in some way. For example, a blood flow model might describe pressures and volumes in compartments of the cardiovascular system. A diffusion model might describe chemically how certain substances carried in the bloodstream (such as anesthetics) permeate tissue and affect physiological behavior. Putting the model together, one would have a multiple model in which diffusion factors are linked to flow variables and diffusion effects may impact processes that adjust blood flow quantities (e.g., heart rate, venous resistance, etc.). In a subsequent section, we shall discuss how we view our work relating to multiple models. First we address the particular methods we employ for anatomical and physiological modeling.

**Anatomical Modeling**

Since our principal aim is to couple deformable object modeling with underlying physiological process simulation at interactive rates, we are looking to adapt existing deformable object methods which encode force-sensitive objects and capture gross deformation behavior. To meet these requirements, we have chosen viscoelastic, lumped-

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17Diffusion is the chief process by which cells obtain necessary ingredients to support life processes and remove waste products.
parameter models, a straightforward and versatile technique from the physically-based modeling literature [54]. In this approach, one models surfaces or volumes as a collection of nodes and edges between nodes. Mass is concentrated (lumped) at the nodes with dampened springs along the edges. In spite of their relative simplicity in the physically-based modeling spectrum, lumped-parameter models can exhibit a wide range of interesting behaviors [54]. The term ‘lumped-parameter’ is used because we model all the mass for each element\(^{18}\) concentrated at nodes, as opposed to the Finite Element Method which distributes mass continuously over each element.

The system state is described by the position and velocity of the node collection. For every two nodes that are connected by an edge in our object, we model the edge as a dampened spring and compute forces on those nodes as follows. Given position vectors for nodes \(\mathbf{a}\) and \(\mathbf{b}\), the edge between them is the vector \(\mathbf{l}\) such that \(\mathbf{l} = \mathbf{a} - \mathbf{b}\). We record the resting length of each edge, storing it in \(r\). We compute the force \(f_{ab}\) on node \(\mathbf{a}\) from interaction with node \(\mathbf{b}\) through a viscoelastic element (edge) as

\[
f_{ab} = -\left( k_s \left( ||\mathbf{l}|| - r \right) + k_d \frac{\mathbf{1} \cdot \mathbf{l}}{||\mathbf{l}||} \right) \mathbf{l}
\]

(4.1)

For node \(\mathbf{b}\), the force \(f_{ba}\) is \(f_{ba} = -f_{ab}\). The constants \(k_s\) and \(k_d\) are elastic and damping coefficients, respectively. Nodes have a mass \((m)\), position \((\mathbf{p})\), and velocity \((\mathbf{v})\). Applying Newton’s Second Law, \(m\mathbf{a} = \sum f_{ij}\) for node \(i\) and its connections to each node \(j\) \((i \neq j)\) we compute each node’s acceleration and integrate to yield velocity and position.

Given this formulation, we still need to assign appropriate elastic coefficients so as to keep an object consistent with pressure-volume predictions of our physiological model. Determining realistic elastic properties will involve much more work. As a first approximation, we can assign a constant elastic coefficient \(k_s\) throughout the lung. The damping coefficient \(k_d\) can be computed from \(k_s\) assuming that the lung parenchyma is roughly critically damped. Since the volume changes proportional to \(k_s\), we can use an iterative method to find a value of \(k_s\) that makes the lung consistent with a predicted volume.

It is worth noting that we will not model all structures in our environment as deformable objects. We feel that there is not much value for our purposes in modeling parts such as

\(^{18}\)An element is a geometric structure representing the space on the object. For a surface model, elements are polygons. For volumetric models, elements are polyhedra.
bones in terms of the deformable objects, since we are not considering forces great enough to break bones nor the manner in which bones break.

Forces

In our virtual environment, objects deform and move in response to forces. We organize these forces into three categories: internal, contact, and body forces.

- *Internal forces* are those produced from deformation through the dampened springs as the object tries to return to its resting shape.

- *Contact forces* are those that apply to surfaces as a result of pressure gradients across a surface or contact among bodies. We need to assign a 3-D interpretation for force given scalar pressure differences. Currently, we apply pressure gradients along predefined vectors that approximate the expanding and contracting shape of the material.

- *Body forces* are those acting on all bodies in a space, such as gravity. Incorporating these types of forces is easy for force-based modeling approaches because they can be added directly to the sum of current forces on each node.

Body parts are usually always in contact with their anatomical neighbors. Many are physically attached, such as muscles and bone, but some achieve a resting state as a result of force balances. We specifically mention points of attachment to distinguish our encoding from those which assume parts exist in predefined relations to other parts [7]. It is understandable to make such an assumption to avoid the continual assessment cost for checking object repositioning or deformation. However, we want to emphasize that parts stay in a particular place because of contact with other parts, so if one part moves then other dependent parts may move or deform. We need to model the propagation of forces to effect those changes.

Collision Detection and Resolution

Determining collisions and resolving them in a general way is a very hard problem. We need to look at the specific types of collisions we expect to encounter to design a method that handles them adequately for our simulation.

For example, our lung model currently involves the simulation of intrapleural fluid. The intrapleural fluid in the intact lung allows the lung to slide along the chest wall.\(^\text{19}^\) As a first

\(^{19}\)We refer to the unit representing the ribcage, the diaphragm-abdominal combination, and the muscles involved in respiration as the 'chest wall.'
approximation, we simulate the intrapleural fluid by enforcing a minimum distance\textsuperscript{20} between the lung and the chest wall. When a node on the lung reaches this distance from the inner surface of the chest wall, we remove the velocity in the direction of the surface normal. In this way, the node can slide along the surface but not penetrate it. We do not model viscous shear forces, but they could be added for additional realism.

By encoding collision detection and resolution in the fashion we intend, our system should naturally respond to situations where objects deform or move in response to the physical situation and body forces, such as abdominal evisceration into the chest (herniated through a lacerated diaphragm).

**Organ Models**

The organ models we use currently have been provided courtesy of Viewpoint DataLabs. From these surface descriptions, we create deformable organ models which then are responsive to forces. We can also specify that any surface is attached to another, though the constraints we currently use are fairly simplistic.

For some organs, such as the lungs, we need to modify the original geometric models to suit our purposes. For example, the original models give us the shape of an intact lung. By ‘intact’ lung we mean the lung as it would appear in a normal individual at rest. However, the normal (inflated) lung is under tension because of the pressure gradient across its surface. We need to create a collapsed lung model and enlarge it by applying appropriate forces. The intact lung, on the other hand, can represent the starting shape for the parietal pleura (the chest wall), though we also need shapes for the expanded chest wall.

An exciting prospect for visual presentation in surgical simulation and education involves potential uses for the data collected in the Visible Human Project \textsuperscript{1}. The Visible Human Project is an endeavor to create a complete, anatomically detailed, three-dimensional representation of the male and female body, from CT, MR, and cryosection images. Part of the long-term goals for the Project is to develop basic research into representation of structures, particularly encoding the connection between structural-anatomical to functional-physiological knowledge.\textsuperscript{21} For our purposes, such data could provide static organ models and realistic-looking images to map onto them, using the real-time texture-mapping

\textsuperscript{20}The minimum distance should be inversely proportional to the surface area of the lung because the fluid is incompressible.

\textsuperscript{21}Excerpt from the long-term goals. Current information on this project is available through the World-Wide Web at http://www.nlm.nih.gov/extramural_research/visible_human.html.
hardware. We still would need a method for approximating how the shape of an organ changes as a means for designing and validating the biomechanical properties we assign.

**Physiological Modeling**

The lumped-parameter models we build for physiological mechanisms reflect traditional bioengineering approaches for simulation. We express our models in ordinary differential equations (ODEs), currently limiting ourselves to first-order approximations of real-world phenomena.

Since we are interested in simulating mechanical interactions among body systems, we are first building mechanical descriptions of our virtual physiological systems. By focusing on modeling the mechanics, we expect to provide the support for higher-level physiology such as biochemical and electrical activity. This higher-level physiology may in turn influence the mechanical processes by, for example, increasing respiration rate or airway dimensions such as resistance in response to hypoxia or hypercapnia.

One major issue we have not resolved yet is how precisely to organize our physiological models. We know that certain models are applicable in certain situations, but we need to develop a principled organizational framework for activating or disabling models (sets of equations) based on features of the current context. Since the simulations reflect the choice that the operator has made about the types of injuries to consider (i.e., which hypothesis is currently being considered), we might use information from that hypothesis (such as a penetrated chest wall) to select an appropriate set of equations. Our current approach is to build general models that include the influences in which we may be interested. The general models express the influences in such a way that they can be ‘turned off’ by setting them to zero or some other constant value.

**Respiratory Mechanics**

Mechanics describes the relation among forces, displacements, and their derivatives. Respiratory mechanics is the study of mechanics applied to the respiratory system. In reviewing respiratory mechanics modeling, Ligas and Primiano [32] distinguish two model paradigms: classical and formal mechanical modeling. The distinction refers to the form of the model and variables. Classical mechanical models represent forces and displacements as scalar values, such as volume to represent generalized displacement and pressure differences to represent generalized forces. Formal mechanical models express forces and displacements as vectors, applying principles of continuum mechanics.

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22In fact for this thesis we are only concerned with building mechanical models.
One important distinction between these approaches is that classical models are based on *observable* variables such as pleural pressure change, lung volume change, airway pressure, etc. Formal mechanical models, on the other hand, are based on more detailed measurements that may not be readily accessible (e.g., specific tissue segment displacements).

The basic equation for classical models relates a sum of pressure differences to a function of volume, its derivatives, and derivatives of pressure differences [32]:

\[
\sum \Delta P = f(V, \dot{V}, \ddot{V}, ..., \Delta \dot{P}).
\]  

(4.2)

In the classical model formulation, the respiratory system is considered a series of deformable or rigid compartments through and into which gas flows. The variable \( \Delta P \) represents a pressure difference, typically between the ends of a compartment or across a surface.

For our initial effort, we consider the lung as a single-compartment, viscoelastic structure. Its \( \Delta P \) to \( V \) relationship will therefore include volume and only its first derivative. We approximate equation (4.2) by truncating the Taylor series expansion about an operating point \((P_0, V_0)\):

\[
\sum (\Delta P - \Delta P_0) = (\partial f / \partial V)(V - V_0) + (\partial f / \partial \dot{V})(\dot{V} - \dot{V}_0).
\]  

(4.3)

Following the convention of [32], we represent the change about an operating point in lowercase letters. This reduces equation (4.3) to the general form for our models:

\[
\sum \Delta p = (\partial f / \partial V)v + (\partial f / \partial \dot{V})\dot{v}.
\]  

(4.4)

In equation (4.4), the coefficient of volume is *compliance* and the coefficient of the volume's first derivative is *resistance*.

It is important to recognize that this approach dictates that the change in a particular physiological variable is the same regardless of its physical position in the system. It does not mean, however, that the absolute value is the necessarily the same. For example, in an upright torso, the pleural pressure at the lung apex is less than the pressure at the base of the lung. Our approach merely assumes that for small maneuvers, the change in pleural pressure is approximately the same.

**Anatomy, Physiology, and Pathophysiology**

The lung and chest wall (a unit comprised of the ribcage, diaphragm-abdominal combination, and the muscles involved in respiration) are elastic structures. In normal physiology, the lung and chest wall are separated by a thin layer of fluid called the
intrapleural fluid that transmits forces between the two. The fluid acts to resist their separation in a similar way that two moist pieces of glass resist separation. Also, the fluid allows the lung to slide along the chest wall. The pressure in this space (the intrapleural or pleural pressure) is subatmospheric. The slightly negative pressure keeps the lung inflated and in contact with the chest wall. At the end of quiet exhalation (functional residual capacity), the elastic tendency for the lung to recoil from the chest wall is exactly balanced by the chest wall’s elastic tendency to recoil from the lung [26].

Inhalation is an active process, whereas quiet exhalation is passive. During inhalation, the muscles of respiration (the diaphragm principally in quiet breathing, assisted by intercostal muscles for deeper respiratory maneuvers) contract. This increases the volume of the thoracic cavity and decreases the pleural pressure. That decrease causes the lung to expand further. As the lung expands, the airway pressure decreases slightly which triggers air flow into the lungs. At the end of inhalation, the muscles relax and the recoil of the lung (through the intrapleural fluid) pulls the chest wall back to its resting balance.

Figure 4.5 shows some of the physiological parameters and variables involved in respiratory mechanics. Volume variables are denoted as $V$, pressures as $P$, flows as $Q$, and resistances as $R$. Subscripts indicate to which entity the variable pertains, where $l$ is for the lung, $cw$ is for the chest wall, $pl$ is for the intrapleural space, $bs$ is the body surface, $ao$ is the airway opening, and $aw$ is the airway. The symbol $\Delta P_m$ denotes the muscle effort cast as an effective pressure difference.

If we assume that air is incompressible, $Q_l$ equals the change in the volume of the lung, $\dot{V}_l$. We can write equations for normal, quiet breathing as

$$v_{cw} = v_l \quad (4.5)$$

$$p_{bs} - p_{pl} = \Delta P_m - v_{cw} / C_{cw} - R_{cw}v_{cw} \quad (4.6)$$

$$p_{ao} - p_{pl} = v_l / C_l + R_{aw}\dot{v}_l. \quad (4.7)$$

Equation (4.5) is a volume constraint, (4.6) is a generalized force balance on the chest wall, and (4.7) is a generalized force balance on the lung. Note that the variables represent changes about an operating point (lowercase letters), and not the absolute values (uppercase

Figure 4.5. Some physiological parameters and variables in respiratory mechanics.

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letters) for pressures and volumes. This means that equation (4.5) is read “the change in the chest wall volume is equal to the change in the lung volume.” Note that we need to add a resistance term to the chest wall \( R_{cw} \) since we are modeling it as a viscoelastic structure. Also, we are technically incorrect in referring to the coefficient \( R_{aw} \) of the rate of change of the lung volume \( (\dot{v}_l) \) as the airway resistance only—this coefficient should also include the mechanical resistance of the lung tissue.

In addition to the pressure variables included in the equations above, we may be interested in seeing the alveolar pressure. It has been ‘canceled out’ in deriving Equation (4.7). We know that the air flow into the lung is proportional to the difference between the change in the airway opening pressure\(^{23} \) \( (p_{ao}) \) and the change in the alveolar pressure \( (p_l) \). Therefore we can compute the change in the alveolar pressure as \( p_l = p_{ao} - R_{aw}Q_{pl} \).

**Pneumothoraces**

Pneumothoraces, or the pathological presence of air within the intrapleural space, can result from penetrating trauma to the chest. Any more than a small amount of air in the intrapleural space will impede normal lung function. This can be life-threatening. Air enters the intrapleural space either from the outside through a breach in the chest wall (Figure 4.6), or from the bronchial tree through a hole.

In a *simple pneumothorax*, air gets trapped within the intrapleural space but the source does not continue to leak. In an *open sucking chest wound*, illustrated in Figure 4.6, gas (air) may enter and leave the intrapleural space through a hole either in the chest wall or bronchial tree. As the amount of gas in the intrapleural space increases, the lung collapses and impedes respiration.

The simple pneumothorax is not particularly interesting to model because we assume air is incompressible and our equations remain the same (any difference would be in our compliance and resistance values). The open sucking chest wound, on the other hand, requires us to model the change in volume of the intrapleural space. We also add Equation (4.8) that relates gas flow into the intrapleural space, \( P_{pl} - P_{bs} = -R_{pl}Q_{pl} \), or

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\(^{23}\)The change in the airway opening pressure and body surface pressure is typically zero.
\[ P_{pl} - P_{bs} = -R_{pl} \dot{V}_{pl} \]  \hspace{1cm} (4.8)

(as we assume the gas is incompressible, \( Q_{pl} = \dot{V}_{pl} \)). Together with the generalized force balance and volume constraint equations, our model becomes:

\[ v_{cw} = v_{t} + v_{pl} \]  \hspace{1cm} (4.9)

\[ p_{bs} - p_{pl} = \Delta P_{m} - v_{cw} / C_{cw} - R_{cw} \dot{v}_{cw} \]  \hspace{1cm} (4.10)

\[ p_{ao} - p_{pl} = v_{t} / C_{l} + R_{aw} \dot{v}_{t} \]  \hspace{1cm} (4.11)

\[ p_{pl} - p_{bs} = -R_{pl} \dot{v}_{pl}. \]  \hspace{1cm} (4.12)

**Lung Parameters and Operating Points**

To use the models presented thus far, we need to estimate lung parameters such as resistances and compliances. Our current estimates are

\[ R_{aw} = 1.7 \frac{\text{cmH}_2\text{O}}{\text{liters / sec}} \]

\[ R_{cw} = 0.3 \frac{\text{cmH}_2\text{O}}{\text{liters / sec}} \]  \hspace{1cm} (4.13)

\[ C_{l} = 0.2 \frac{\text{liters}}{\text{cmH}_2\text{O}} \]

\[ C_{cw} = 0.15 \frac{\text{liters}}{\text{cmH}_2\text{O}}. \]

We have been able to verify airway resistance \( R_{aw} \) and lung compliance \( C_{l} \) measurements in the physiological literature [2], but have not yet verified such for the chest wall structure.

For operating points, we use the following (estimated from [2]):

\[ P_{atm} = 1029.81 \text{ cmH}_2\text{O} \]

\[ P_{bs_{o}} = P_{atm} \]

\[ P_{ao_{o}} = P_{atm} \]

\[ P_{pl_{o}} = 1022.31 \text{ cmH}_2\text{O} \]

\[ \Delta P_{m_{o}} = 0 \text{ cmH}_2\text{O} \]

\[ V_{cw_{o}} = 2.4 \text{ liters} \]

\[ V_{t_{o}} = 2.2 \text{ liters} \]

\[ V_{pl_{o}} = 0 \]

\[ \dot{V}_{cw_{o}} = 0 \]  \hspace{1cm} (4.14)

\[ \dot{V}_{t_{o}} = 0 \]

\[ \dot{V}_{pl_{o}} = -\frac{P_{pl_{o}} - P_{bs_{o}}}{R_{pl}}. \]

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**Multi-Compartment Systems**

The models considered thusfar are for a single compartment lung. It is straightforward to make two compartments, one for each lung, by duplicating the equations and adjusting resistance and compliance values. By themselves, two lung models are no more interesting than one. What will make them more interesting is a model for the mediastinum and effects that pneumothoraces have on displacing the mediastinum. A displaced mediastinum is interesting not only for its impact on the other lung, but also for the effect on structures within the mediastinum. We shall discuss this type of effect shortly when we examine the tension pneumothorax.

As we become more interested in modeling the relationship between lung volume and gas exchange, for example as input signals to a model for controlling ventilation, we will need to add more realistic models of clinically-significant volumes such as ‘dead space’ compartments. Since gas exchange occurs at the terminal portions of the airways, the gas the occupies the rest of the respiratory system is not available for gas exchange with pulmonary capillary blood [27]. This type of detail, though, is beyond the scope of the proposed work.

The models we have described treat the chest wall as a unit. This is obviously unrealistic because chest wall mechanics results from several coordinated components: the diaphragm, the ribcage, the abdominal muscles, and the intercostal muscles. Based on the work by Primiano [41], we intend to incorporate component models for those parts. These types of additions will make our simulations more accurate and enhance their potential for educational and clinical investigations.

**Cardiovascular Modeling**

Our cardiovascular model will be derived from the cardiovascular (CV) approach of Neumann [39]. She is developing her model for use in predicting blood loss over a period of minutes to hours, due to acute hemorrhaging.
Her approach considers the cardiovascular system as eight compartments in Figure 4.7. Her model is based on time-varying, ventricular compliances which yield the pulsatile behavior. Using an electrical analog of resistors, capacitors, and diodes, the model represents blood flow through the closed CV system by means of the pressure-flow equation \( Q = \frac{(P_b - P_a)}{R} \), and by adherence to Kirchhoff’s Law (all currents at any node in a system sum to zero). A set of eight equations, solved simultaneously, yields pressure changes for each of the eight compartments over time.

We propose to modify her model by identifying different parts of the circulatory system with different major vessels. In particular, we will add segments for those sections that are visible (such as the exterior jugular veins) or potentially exposed to anatomical object influences (such as the inferior vena cava). More importantly, because we are modeling intrapleural pressure, we may be able to approximate the effect of ‘negative pressure’ in the chest cavity that assists (or impedes, if an injury produces positive pressure) venous return.

**Multiple Modeling**

We suggested earlier that our combination of anatomical and physiological modeling might be considered as a form of *multiple modeling* [42]. Again, a multiple model is one that combines two or more models that deal with different phenomena but interact in some way. The value of multiple modeling is to produce a more complete model that benefits from interaction among the models. In the literature, multiple models are typically composed from models of the same dimensionality (usually scalar). We believe our approach is novel in at least one respect, that we are integrating scalar and vector models.

One may question our motives in combining scalar and vector models. Certainly it would be easier to combine models of the same dimensionality. However, because we want to
visualize 3-D deformable objects (organs) accurately, we must use an underlying vector-based method. We use scalar equations for describing physiological changes because we believe it is more clinically relevant, available, and useful. Not only is it more difficult to grasp for educational purposes, but model validation is more difficult when the number of variables is much larger than those directly measurable in the system.

In our situation, the pressure gradient values from our physiological modeling influence our 3-D organ models via applied forces. The resulting anatomical deformations may then affect physiological parameters or variables. The interesting examples of interaction occur when the anatomical deformations caused by one physiological system affect physiological parameters of other systems because of physical space constraints.

So far, we see inter-object forces potentially affecting simulation parameters in at least two ways, impacting pressures or resistance:

**Pressures.** The descent of the diaphragm is influenced by the muscle forces, expressed as an effective pressure difference across it. If an abdominal organ is pressing against the diaphragm, it will increase the pressure on the diaphragm’s abdominal face, which should act to reduce the effective pressure gradient. By reducing the gradient, the diaphragm will not descend to the same depth as before.

**Resistance.** For flow equations, we encode the dependence of vessels on cross-sectional area, in terms of resistance. If, as a result of simulation, the cross-sectional area is affected, we update the resistance values accordingly.

To demonstrate the value in considering such an integration, we consider the tension pneumothorax.

**One Thesis Challenge: the Tension Pneumothorax**

A medical condition known as a tension pneumothorax typifies the interaction that our approach seeks to address. A tension pneumothorax is a condition where a flap of tissue either in the lung parenchyma or the chest wall allows air to enter the intrapleural space but not to leave, effectively creating a one-way valve. As the intrapleural pressure increases, the mediastinum is pushed to the side of the normally-functioning lung. The mediastinal displacement has the ultimate effect of interfering with venous return to the heart. Figure 4.8 illustrates this phenomenon.
normal tension pneumothorax

Figure 4.8. Mediastinal shift affecting inferior vena cava.

The venous blood return impedance is a result of kinking the great vessels and causing the collapse of the inferior vena cava from intrathoracic pressure. The vena cava is attached to the diaphragm where the vessel enters the chest cavity. The displacement of the mediastinum, which also can happen with severe open sucking chest wounds, results in a life-threatening emergency.

We propose that our anatomical and physiological modeling approach is well-suited to address this condition in a natural way. Physiologically-speaking, we model the mediastinum as a membrane and apply forces to our 3-D mediastinum based on any pressure gradient across the ‘membrane.’ All structures within the mediastinum are affected by any force applied to it. In particular, the pressure on the exterior of the vena cava will increase causing the vessel to collapse. If we define our blood vessel segments in our cardiovascular model to be sensitive to their cross-sectional area, the collapsing of the (inferior) vena cava will cause an increase in venous resistance and impact the blood flow simulation.

Therefore, this enables us to predict physiological interactions between body systems that occur as a result of applied forces. We need to encode anatomical-to-physiological relationships within a physiological system such as cross-sectional area with resistance, but we do not need to encode explicitly knowledge such as the dependence of the vena cava’s structure on mediastinal displacement.

Returning to the theme of multiple modeling, we see our anatomical and physiological mechanical modeling acting in complementary (but sometimes redundant) roles. The physiological modeling affects anatomical structures through pressure gradients applied as forces. The anatomical modeling transmits the impact of a system’s mechanical behavior to physically adjacent physiological system models.
4.5. Preliminary Results

Having outlined the particular methods we will employ to achieve our objectives, we now summarize the work done to date on the different components of the system. Most of the work completed and directions pursued have served to define the path we will take in achieving the thesis objectives.

4.5.1. Penetration Path Assessment

Most of the penetration path computation, that is the work involved with computing candidate organs based on a hypothesized wound path space, has been completed.\textsuperscript{24} An operator may place external wounds on the body and generate possible hypotheses about wound-to-wound or wound-to-bullet pairings. We also have completed the component that generates the alternative hypotheses. We now need to connect these components across the network, as indicated in Figure 4.3. Work in progress involves two areas:

1. developing the probabilistic model that computes the likelihood of direct damage as a result of the injuries; and

2. building a simple rule system to map from penetration hypotheses to the anatomical spaces they compromise (i.e., determining new topological connections).

4.5.2. Static Anatomical and Physiological Knowledge

This module is an attempt to organize the data that TRAUMAP uses in such a way that can assist an operator in navigating body system knowledge. We have defined a preliminary class hierarchy, part of which is shown in Figure 4.9, to categorize the types of concepts that our anatomical and physiological parts embody. We created this hierarchy from our own sense of medical concept organization, so inevitably it will change as we start to organize our data by it and review the class distinctions with medical professionals.

\\textsuperscript{24}This work has been completed by the author and Omolola Ogunyemi.
Each class may have specific properties that initially will get encoded in text fields. For example, we define the `ORGAN` class as objects which have specific functions occurring within them, such as the liver or stomach. Any structure categorized as an `ORGAN` will inherit properties that result from it being an `ANATOMICAL-SPACE` (implying that can occupy a volume) and it being a `TISSUE` (implying that it has tissue properties).

It is also worth noting that our intent is merely to provide some structure for our existing information and not to develop a general-purpose knowledge representation language for medical concepts. This latter objective is a thesis topic on its own. Some discussions towards representing medical knowledge can be found in [11, 27, 38].

4.5.3. Dynamic Simulation

We initially believed that qualitative physiological models, based on qualitative differential equations (cf. Kuipers [30]), would provide a sufficient basis for driving our visualization (our initial results were presented in [29]). Qualitative differential equations are mathematical abstractions of ordinary differential equations where variables range over discrete sets of values. Qualitative models are good for systems that may be too difficult to model quantitatively, or in situations where qualitative descriptions are sufficient. We realized that our modeling approach can be described adequately in quantitative terms, and we need quantitative detail (as far as the shapes of pressure-volume curves are concerned) to drive our anatomical models.

We have developed physiological models using ordinary differential equations to couple with our deformable object modeler that we also created. Current work includes defining environmental conditions (interaction among objects) and ensuring consistency between pressure and volume calculations from our physiological models with appropriate interpretations in our 3-D deformable objects.
We now turn to examining current results for our single-compartment models. While this work is still preliminary, the results are consistent with qualitative expectations and are sufficiently precise for clinical confirmation.

In Figure 4.10, we show the lung and chest wall system during inhalation. The black mesh is the chest wall structure, while the lung is shaded within. Figure 4.10(a) is a snapshot at the beginning of quiet inhalation. Figure 4.10(b) shows the system at the end of inhalation. The pressure gradient across the lung is computed from the physiological model and applied to our deformable lung model. The chest wall shape is computed via linear interpolation between a resting and expanded shape, and controlled during the simulation by the change in the chest wall volume variable ($v_{cw}$).

![Figure 4.10. Inhalation for quiet, normal breathing. The black mesh represents the chest wall, with the lung shaded inside. Pane (a) shows the system at the end of quiet exhalation, where (b) shows the system at the end of quiet inhalation.](image)

The organ models illustrated in Figure 4.10 are being driven by some of the physiological variables plotted in Figure 4.12.
Figure 4.11. Quiet, normal breathing for single lung compartment: (a) is $\Delta P_m$, the muscle effort (quarter-sine wave); (b) is change in lung and chest wall volume ($v_l = v_{cw}$); and, (c) is change in alveolar pressure (top—$p_l$) and pleural pressure (bottom—$p_{pl}$).

The variables in Figure 4.11 are from the dynamic simulation of Equations (4.5)-(4.7). The dominating force in the model is a modified, quarter-sine wave that we estimated to simulate the muscle force $\Delta P_m$ (Figure 4.11(a)). Figure 4.11(b) shows the change in chest wall volume over time. Since the change of the chest wall volume equals the change in lung volume (Equation (4.5)), this function is the change in lung volume as well. Figure 4.11(c) plots the values for change in pressure variables. The function closer to the top is the change in alveolar pressure, while the other function is the change in pleural pressure. It is important to remember that the equations represent and resulting graphs show the change about an operating point and not an absolute value for volume or pressure.

Figure 4.12 shows the physiological variable results (Equations (4.9)-(4.12)) of simulating a hole in the chest wall without muscle activity (i.e., $\Delta P_m = 0$). The pneumothorax starts at 10 seconds after the beginning of simulation.

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Figure 4.12. Pneumothorax without muscle effort, $R_{pl}=70.0$: (a) is change in intrapleural volume (top $v_{pl}$), change in chest wall volume (middle $v_{cw}$) and change in lung volume (bottom $v_l$); (b) is change in pleural pressure (top $p_{pl}$) and alveolar pressure (bottom $p_l$).

The hole has the resistance value $R_{pl} = 70.0$ cmH$_2$O/liters/sec, while the airway resistance is $R_{aw} = 1.7$. Since resistance is inversely proportional to radius to the fourth power, this means that the hole is between one-half and one-third the size of the airway. In Figure 4.12(a), we show the change in volumes. Once the chest wall is breached, air begins to enter the intrapleural space, increasing the intrapleural volume (the topmost function). At the same time, the lung deflates (bottommost), and the chest wall (middle) expands. Looking at the pressure values in Figure 4.12(b), we see the pleural pressure (which starts at a subatmospheric value, approximately -7.5 cm H$_2$O) increase. We also see the alveolar pressure (bottom) that causes air to flow out and the lung to deflate. Figure 4.13 shows successive views of the lung and chest wall as the lung deflates. Note how the chest wall expands passively once the fluid coupling is broken.
The final demonstration of the physiological simulation is the open sucking chest wound in Figure 4.14. The graphs show the mechanical behavior as the lung deflates, and the chest wall expands. The chest wall expands due to both the muscle effort (which artificially remains constant) and the natural tendency of the chest wall to recoil from the lung. The parameters for this are the same as for the previous example.

We start the pneumothorax after 10 seconds of simulation. One sees from the “Volumes” plot in Figure 4.14(a) how after the mark, the lung and chest wall decouple and the intrapleural volume increases. The function that reaches the topmost portion of Figure 4.14(a) is the change in the intrapleural volume ($v_{pI}$). The middle function is the change in the chest wall volume, and the bottom-most function is the change in the lung volume. In Figure 4.14(b), the “Pressures” plot, one can observe the intrapleural pressure steadily increasing (approaching body surface pressure, which is usually standard atmospheric pressure) as the intrapleural volume increases.

One of the consequences of our using constant compliances and resistances is that the chest wall and lung excursions (amplitude) remain the same regardless of volume. Also to blame is that our muscle effort $\Delta P_m$ remains the same (see Figure 4.11(a)). In real life, the chest wall and lung become stiffer as they move away from functional residual capacity (the resting point after quiet exhalation). Also, the ventilation control system in the brain would most likely deepen the inspiratory effort (increasing the amplitude of $\Delta P_m$) once it sensed the diminished lung function.

To improve the realism of our models, we need to consider non-linear compliances. Also, we need to distinguish more degrees-of-freedom and effects to the system, such as...
including the mediastinum and separating the chest wall into diaphragm, abdominal muscle and accessory muscle components (following the approach of Primiano [41]). These additions will then have more direct correspondences to our anatomical models.

![Figure 4.14](image)

Figure 4.14. Pneumothorax with regular muscle effort, $R_{pl}=70.0$: (a) is change in intrapleural volume (top—$v_{pl}$), change in chest wall volume (middle—$v_{cw}$) and change in lung volume (bottom—$v_l$); (b) is change in pleural pressure (rising—$p_{pl}$) and alveolar pressure (steady—$p_l$).

### 4.6. Summary

We have reviewed a hypothetical session with the TrauMAP system, followed by detail about the proposed implementation approach and preliminary findings. We have discussed the platforms on which we will build the final system in addition to the modeling methods we will employ to achieve that final result. TrauMAP is distributed between work done in C within the Jack environment, namely the components involved with the geometric computations and visualization functions, and a Lisp-based interface to components involved in higher-level reasoning and interface tasks.

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In discussing how we expect to implement the system, we have also described the specific methods and issues we feel will enable us to accomplish the thesis objectives. The central feature of TrauMAP is dynamic simulation that integrates mechanical models for 3-D, deformable objects with physiological models that describe pressure-volume relationships. We argue how that integration is similar to the “multiple modeling” concept proposed in the bioengineering literature [42]. Our preliminary results are encouraging, but there are a number of issues such as applying inter-object forces and encoding the relationship between anatomical features (e.g., radius) and physiological concepts (e.g., resistance) that we need to address in order to demonstrate the value of our integrated approach.
5. Conclusion

Most approaches in medical modeling, either for instructive purposes or research endeavors, typically involve a level of structural (anatomical) and behavior (physiological) detail. This is because medical phenomena, like events or activities occurring in other domains, involve dependencies between structural characteristics of the environment and processes that can or cannot occur within those structures.

The TRAUMAP system described here is an effort to elucidate this interaction, to ‘bridge the gap’ between modeling the interaction between physical structures and the physiological processes occurring within them. In particular, we want to demonstrate how the interaction between structures can result in the impairment of underlying processes, for conditions such as the tension pneumothorax and the pericardial tamponade.

The main components of TRAUMAP are designed to support and describe dynamic simulation for aspects of the respiratory and cardiovascular systems. Our approach integrates a flexible, physically-based modeling paradigm, the lumped-parameter models, with traditional engineering tools for simulating physiological and pathophysiological mechanisms, namely ordinary differential equations. While our preliminary results indicate this will be a promising approach, there remain issues as to whether this integration will yield a flexible enough structure to support more detailed anatomical and physiological modeling.

We have also described accompanying modules for the generation and inspection of wound hypotheses and TRAUMAP’S medical information. These modules add functionality to our virtual environment in support of the dynamic simulation in addition to having potential as stand-alone applications. The resulting form and use for these modules depends on the course of development for our dynamic simulation.

We see one impact of an integrated approach as a critical step towards the ambitious goal of surgical simulation. We have described some existing approaches and indicated how we feel they can be enhanced by a sound methodology for physiological modeling. We have also described approaches that focus on anatomical exploration, such as anatomical databases, and those that pre-determine physical structures to focus on physiological effects. We look to these approaches to identify the types of reasoning potentially enabled by a lower-level treatment of anatomical detail or dynamic physiological modeling. In the bioengineering arena, we see many different types of physiological models that we expect
to draw on in developing our physiological models, but we have not seen one that couples 3-D deformable models with underlying physiological behavior in a virtual environment.

We feel approaches such as the TRAUMP system will have their greatest impact in enabling students to explore the static and dynamic aspects of body systems, particularly in situations that involve multiple systems with both structural and physiological change. We believe our three-dimensional, interactive environment will contribute principally in two ways. First, the environment reflects basic spatial relationships that exist in our world, encoding them for the computer on which future applications can build. We expect that the physiological mechanisms we describe in this environment and the way they interact can provide the basic understanding for models applicable to medical education. Second, from the educational perspective, the environment can serve to enrich the educational experience through Virtual Reality. Satava [44] addresses critics who might view the navigation around and through the body as trivial play: “these extraordinary perspectives impart a deeper understanding and appreciation of the interrelationship of anatomical structure which cannot be achieved by any other means, including cadaveric dissection.” As more detailed anatomical data becomes available, as with the Visible Human project [1], and more emphasis is placed on developing and integrating realistic physiological simulation, it is thrilling to think about the potential impact on medical education and clinical applications.

Conclusion
Appendix. Medical Terminology

Some of the definitions for these terms have come from the New American Pocket Medical Dictionary [43].

**compliance**
Measure of object stiffness, equal to the change in volume divided by the change in pressure. Small values imply stiff objects, while larger values imply more pliable objects.

**CPR**
Cardiopulmonary Resuscitation, a method of compressing the chest cavity directly over the heart and supplying ventilations manually to provide circulating blood and oxygen to a patient whose heart has stopped beating.

**flail chest**
The condition where three or more ribs are broken in two or more places. The broken ribs are separated from the skeleton and thereafter move in response to changing pressures, rather than in response to the muscles that move the other ribs. Because of the negative pressure in the intrapleural space, this results in "paradoxical breathing," where the fractured ribs move in the opposite direction of the rest of the ribcage.

**functional residual capacity (FRC)**
The resting lung volume after quiet exhalation and before inhalation.

**hemothorax**
The accumulation of blood in the intrapleural space, which impedes normal lung functioning.

**hernia**
The abnormal protrusion of an organ, or part of an organ, through an aperture in the surrounding structures. A *diaphragmatic hernia* is a protrusion through the diaphragm.

**intrapleural space**
The space between the visceral and parietal pleura, usually occupied by a small amount of fluid (liquid).

**mediastinum**
The region in the center of the chest between the two cavities that enclose the left and right lung. The mediastinum contains important structures such as the heart, the great vessels (vena cava, aorta, pulmonary vessels, etc.), the trachea, and esophagus.

**paradoxical motion**
Conventionally associated in trauma with *flail chest*, paradoxical motion (or breathing) also describes a condition seen with infants and children where the chest wall moves paradoxically during breathing with respect to the abdomen—instead of expanding during inhalation and contracting during exhalation, the motion is reversed.

**parietal pleura**
The lining of the chest wall surrounding the lung, separated from the visceral pleural by a thin film of liquid.

**pericardial sac**
The rigid sac containing the heart.
**pericardial tamponade** The pathological condition where the injury punctures the heart, which bleeds into the pericardial sac. The accumulation of blood then impedes the flow into the heart by exerting pressure on the vena cava.

**pleural space** Same as **intrapleural space**.

**pneumothorax** Air in the intrapleural space, which interferes with normal lung function.

**resistance** Resistance to flow. Also used as the coefficient of damping in modeling viscoelastic objects.

**supine** Lying on one’s back.

**tension pneumothorax** Pathological condition associated with a pneumothorax. If the lung or chest wall has been penetrated, it is possible for the tissue at the site of the injury to act as a one-way valve. During inhalation, the flap of tissue permits air to enter the intrapleural space, but during exhalation it closes over the hole and does not let air escape. This situation leads to an accumulation in the intrapleural space of air whose pressure can exceed atmospheric, which can ultimately push the mediastinum toward the other lung and kink the inferior vena cava, thereby impeding blood return to the heart.

**visceral pleura** Casing of the lung tissue (parenchyma).
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References


[54] Witkin, A., “Particle System Dynamics,” in *Introduction to Physically-Based Modeling*, SIGGRAPH 94 Course Notes. 1994,