Physicians are increasingly performing surgical procedures using minimally invasive instruments that operate inside the body through narrow openings. This reduces disturbance to healthy tissue, minimizes risk of infection, and speeds recovery. However, these procedures are often challenging for physicians to visualize and perform due to reduced visual and tactile feedback compared with traditional open surgical procedures. Fast and accurate computer simulations of these procedures can facilitate physician training and assist in pre-operative planning and optimization.

Surgery simulation creates a virtual environment in which a physician can interact with organs and tissues that are simulated on a computer. Simulations are being developed for a wide array of medical procedures, including laparoscopic surgery [189], bronchoscopy [42], and endoscopic surgery [24]. Surgery simulation aims to complement the traditional apprenticeship model of physician training; physicians can train in a controlled environment that exposes them to both common and rare cases and can practice new techniques without risks to patient safety. Studies indicate that surgical skills learned using computational simulators directly improve operating room performance by significantly decreasing procedure time and reducing the number of medical errors [88, 184, 189]. In one videotaped study on gallbladder dissection, physicians trained using surgery simulation performed the task 29% faster and with six times fewer errors than traditional training [189].

In addition to training, surgery simulation can also be applied to medical procedure planning. With patient-specific imaging data and a sufficiently realistic simulation of a procedure, a planner can search the space of possible tissue/tool interaction sequences to identify a plan that is best suited to accomplish the clinical objectives. The ultimate goal is to provide a pre-operative plan, integrated with medical imaging, to the physician or robotic hardware that will perform that procedure [182, 183, 199].

Just as flight simulators give pilots an opportunity to learn and practice flying in a variety of visibility and weather conditions, surgery simulators aim to allow physicians to perform a procedure “virtually” on a computer to practice on difficult patient cases without risking patient safety. But whereas flight simulation
requires models of airflow and rigid objects such as the plane, landforms, and buildings, the key challenge in surgery simulation is simulating deformable tissue interactively. Accurately simulating and displaying tissue deformations and tool-tissue interactions in real-time poses a computationally challenging problem and is the topic of much current research.

In this chapter, we combine methods from classical finite element methods with recent approaches from computer graphics to create a real-time interactive simulation of soft tissues. The simulation achieves sufficient accuracy to warrant further investigation for clinical applications. We use the simulation of deformable soft tissues as a building block in chapter 3 to simulate and plan needle insertion procedures and in chapter 4 to simulate and plan needle steering. In both of these cases, accurately guiding a needle to a specific target inside the human body is crucial for the success of the procedure. However, significant errors are common in current practice due to soft tissue deformations.

In this chapter, we first provide background on simulation of deformable objects before presenting our simulation of soft tissues. In section 2.1, we provide an introduction to continuum mechanics, a mathematical framework that has successfully been used to characterize living tissues and their deformations under applied forces. We then discuss research on soft tissue simulation in section 2.2. Next, we present a finite element method for interactively simulating 2-D tissue deformations, including real-time visualization using texture-mapping. This simulation will serve as a building block for the simulators, planners, and registration tools in chapters 3 and 4 and appendix A.

2.1 Fundamentals of Continuum Mechanics

Continuum mechanics aims to describe the effect of external forces or disturbances on the global behavior of solids, liquids, and gases. The theory behind continuum mechanics was originally developed in the early nineteenth century by Claude-Louis Navier, Siméon Denis Poisson, and George Green [213]. It has since been successfully applied in a broad variety of domains, from airplane and bridge design to animating feature films. Since living tissue is composed of discrete cells, which in turn are composed of molecules and atoms, living tissue, like other materials, is not purely continuous. However, a large class of living tissues has been successfully characterized using the methods of continuum mechanics [44, 46, 86, 126].

In continuum mechanics, we assume that field quantities such as the densities of mass, velocity, and energy are continuous over time and space inside the material [87]. We will consider a deformable body, a continuous material within a closed surface. We can use continuum mechanics to study how such a deformable body behaves when it is subjected to external influences such as forces or temperature changes.

In this section, we will describe the fundamentals of continuum mechanics. We start by formally defining a deformable body. We then introduce the basic concepts of continuum mechanics using a simple 1-D example, and then generalize