The Next Challenge in Healthcare and Medical Robotics:
Real-time Physically-Based Computational Physiology

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The next-generation surgical systems will increasingly use minimally invasive techniques that operate inside the body through a narrow opening with robotic devices, thereby reducing disturbance to healthy tissue, minimizing risk of infection, and accelerating recovery. These techniques, including laparoscopy, brachytherapy, and catheterization, are already transforming the way how surgeries are performed today. Due to constraints on visibility and the complex nature of human physiology, radical advances in "physics-based computational physiology" to support training, planning, and guiding the next generation of surgical systems are needed.

Human organs are notoriously difficult to model. Their structure is highly non-uniform, deformable, and time-dependent, they are constrained by ligaments, bone, and other organs, and they are subject to dramatic structural changes due to absorption or loss of blood, bodily fluids, gases and radiation. Materials are viscoelastic or plastic, and are subject to tearing and puncture. Any computational techniques and representations must accurately reproduce non-linear behavior in near real-time. Although techniques for modeling human organs have been extensively studied, dramatic improvements are needed to facilitate the extremely rapid handling of nonlinear deformations and structural changes for real-time robot assisted procedures and medical simulation. Insights from robotics can be used to develop new approaches to modeling, simulation, planning, guidance, validation, and interface design. Among many open research challenges that fall under the general umbrella of "physically-based computational physiology", we highlight several key unsolved problems below:

Motion Planning of Deformable Robot in Complex Environments

Endoscopic manipulators for minimally invasive surgery, power assist suits for human-movement support, and flexible agents for entertainment are some examples of a growing number of "deformable robots" populating through many different applications. One of the major challenges in this area is controlling and planning the motion and behavior of these robots in complex environments. The problem of computing a collision free path for a robot through an environment has been extensively studied for decades. Practical path planning algorithms are known for rigid or articulated robots. In contrast, current planners for deformable robots are only capable of handling simple robots in relatively simple environments. These planners can take minutes to compute a collision-free path. Motion planning for deformable robots introduces two major challenges. First, simulating physically verifiable deformation for a robot interacting with complex deformable environments is still considered a difficult problem in practice. In order to create any planning algorithm for flexible robots in a real-time application, we need to model the physical properties and mechanical constraints of the robots. The computational requirements of generating an accurate deformation using a continuum model can be rather high. The second challenge is fast and accurate collision detection between a deformable robot and surrounding obstacles.

Physics-based Modeling for Deformable Image Registration

Deformable image registration has become a critical area of research in radiation therapy for cancer, as clinicians seek to correct for organ motion and achieve the tightest possible dose distribution about the treatment target. Modern techniques of adaptive and image-guided radiation therapy (ART and IGRT) involve the collection of multiple images over the course of treatment to guide patient setup and enable adjustment of the treatment to cope with organ motion (see Fig. 1). Deformable registration produces a transformation indicating how the tissue has moved between the planning image and the treatment image. This transformation can be used directly in patient setup, and also as a way to answer the key question of what dose has actually been delivered to the target, in the presence of organ motion. Knowing the dose delivered over a portion of the treatment course, a clinician can adjust the treatment plan to correct for deviation from the desired dose. With more assurance that the dose delivered will correspond to the dose planned, it becomes possible to consider tighter margins and higher doses to the tumor, potentially improving outcomes.

Dose accumulation requires reliably accurate deformable image registration algorithms. But under some circumstances, the results of current deformation algorithms can be substantially in error. Quantitative measures of error are usually in terms of distance of visible features from their true locations, as seen by inspection. But from a clinical perspective the main concern is how the error effects the calculation of dose to the target and critical organs in the patient. It is important to develop novel physics-based deformation modeling algorithms and simulation techniques to investigate applications to deformable registration. In addition, fluid phenomena, either in liquid or gaseous form, play an important role in modeling of biological systems, such as bodily fluid, bowel gas, etc. The computational complexity of fluid behavior comes mainly from the complex interplay of various factors such as convection, diffusion, turbulence, and surface tension. It is important to consider design of numerical methods and simulation techniques that can be mapped well to *many-core architectures*. In addition, we need to integrate the ability to simulate mechanics of multiple phenomena (e.g. soft bodies and fluids) and their interaction with micro- or nano-robots on the same computational domain as well.

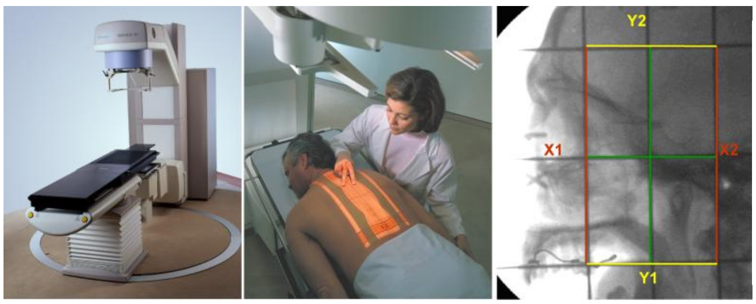

Fig. 2 LEFT: Physical device with imaging components; CENTER: Aiming, shaping a radiation beam by projecting a light field onto the patient's skin. RIGHT: Simulation image of a lateral head field with beam info superimposed.

Real-Time Robot-Human Interaction

Exploration of new robot-human interfaces, such as touch-enabled haptic interaction is especially important for medical procedures that rely heavily on hand-interaction with the patients, such as palpation, cutting, etc. However, haptic rendering requires KHz update rates, thus leading to many computational challenges that need to be addressed, in order to introduce haptic interaction into future robot assisted surgical and training systems.

With the rapid changes in information technology -- bigger bandwidth, faster processors, and "computers" everywhere -- we expect robotics to become ubiquitous in all walks of our life, especially in healthcare and medicine. We will be able to "preview" how various biological structures (e.g. tissues, bones, and organs) interact and react to external stresses, examine and even "virtually try out" new medical devices, analyze data by simulating varying hypothetical conditions, and to be able to share these experiences with someone at remote locations. However, to achieve such capabilities, not only do we need technological advances in communication and networking, computer architecture, hardware technology and software infrastructures, but also fundamentally new robot algorithms and simulation techniques in the areas of *physics-based computational physiology* mentioned above.

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