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Interaction model between elastic objects for haptic feedback considering collisions of soft tissue

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Summary The simulation of organ—organ interaction is indispensable for practical and advanced medical VR simulator such as open surgery and indirect palpation. This paper describes a method to represent real-time interaction between elastic objects for accurate force feedback in medical VR simulation. The proposed model defines boundary deformation of colliding elements based on temporary surface forces calculated by temporary deformation. The model produces accurate deformation and force feedback considering collisions of objects as well as prevents unrealistic overlap of objects. A prototype simulator of rectal palpation is constructed on general desktop PC with a haptic device, PHANToM. The system allows users to feel different stiffness of a rear elastic object located behind another elastic object. The results of experiments confirmed the method expresses organ—organ interaction in real-time and produces realistic and perceivable force feedback.

1. Introduction

Virtual reality (VR) technologies enable physicians to interact with flexibly customized simulated environments based on visual, auditory and haptic feedback without potentially harmful contact with real patients. For this reason, VR-based simulation has

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attracted considerable attention as a key technology for the advancement of medical treatments and improvement of quality of human life. In the field of medicine, VR simulators are applied for uses such as education, therapy and rehabilitation, procedural training, surgical planning, rehearsal, and interoperative support [1,2]. Though many simulators have been developed, and a few even commercialized [3—6], most have dealt with single organ objects without handling collisions between multiple organ objects [4—9]. This makes them unsuitable for VR simulation of the human body, a system with many organs which often collide. Haptic feedback is especially important in delicate surgical pressures requiring fine sensations, especially when slightly excessive pressure can injure a patient. Haptic sensation is also significant in palpation: as the physician examines the characteristics of an organ beneath the body surface with the tips of his or her fingers, collisions of the soft tissues are inevitable. This paper proposes a model of interaction between soft tissues, in order to provide a virtual environment simulating haptic feedback from the collisions of soft tissues.

Palpation and surgery simulations require the use of physics-based deformable models to accurately calculate the deformation and force caused by physical action on soft tissue. This adds considerably to the challenge of simulation, however, as physics-based deformation models generally require more computations than the geometry-based deformation models used in computer graphics. A comprehensive simulation of multiple characteristics of soft tissue all at once is tremendously difficult. Elasticity, a property related to force and displacement, is one of the most important characteristics of soft tissue. Accordingly, this paper treats soft tissues as elastic objects and seeks to model the interactions between them. The interaction model presented here must perform three important functions.

1. To allow interactive manipulation in real-time.
2. To take into account the physical properties of colliding objects.
3. To produce an adequate visual reality.

Interactive manipulation, an operation performed in both palpation and surgery, requires real-time computation of soft tissue deformation and reaction forces. When a soft elastic object and a hard object collide, the former deforms more, as shown in Fig. 1. In addition, the reaction forces during the collision depend on the extent of the deformations in the collision area. Thus, the interaction model must represent the deformation on the basis of the physical properties of both elastic objects. Visual reality is one of the most important functions for effective simulation. Excessive invasion of colliding objects must be avoided.

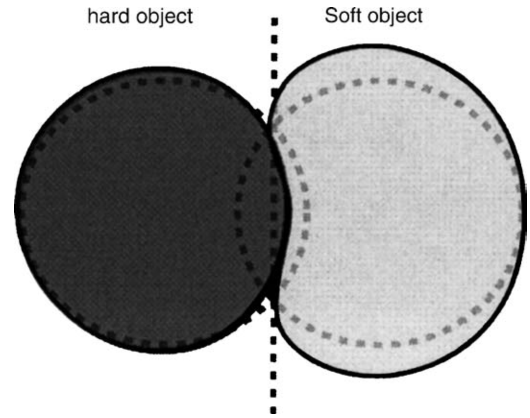

Fig. 1 Deformation caused by collision of elastic objects with different stiffnesses. The soft object deforms more than the hard object.

In this paper, we propose an interaction model between elastic objects that performs the above functions. After describing the proposed model, we evaluate its performance and validity by applying it to the development of a rectal palpation simulator.

2. Background

The simulation of physical phenomena has been a key technology to enhance visual and haptic reality in medical simulations. Studies in biomechanics and computer graphics in the field have devoted particularly close attention to soft tissue modelling [10—13]. Many kinds of physics-based deformable models have been proposed for deformation and force feedback [13—19]. One such model, the mass-spring model, represents an object as points of mass joined by springs [15,16]. Though effectively applied for a variety of uses, the model does not perform adequately when simulations require accurate calculation of deformation and reaction force [7]. The mass-spring model also requires fine-tuning of physical parameters to represent certain physical characteristic, and improper parameter values lead to system instability. The boundary element model (BEM) and long element model (LEM) have also been proposed for deformation and force feedback. Though both are capable of fast computation [12,17,18], they have limitations in surgical and palpation simulations. An organ with internal lesions possesses several distinct physical properties, yet BEM assumes that an organ is homoge-