PART V

Benchmarking Platform for STIFF-FLOP Validation

17

Benchmarking for Surgery Simulators

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Abstract

An increasing number of robotic surgery simulators can be used for validation study of surgical education curricula, their functionality, and testing of their proficiency. These simulators are equipped with a multilevel curriculum, designed with different levels of difficulty for effectively advancing robotic surgery abilities. The most important factor for obtaining an appropriate surgical simulation is creating quasi-natural geometry of surgical scene and physical characteristics of the used materials. In acquisition of classical endoscopic surgery skills, many of the initial challenges are related to a loss of depth perception, the fulcrum effect, and the use of new, different instruments.

Constructing simulators for a completely new type of tool, with variable capacity and controlled geometry, the authors faced a new challenge. The positions created were both research devices of new tools (for engineers) as well as trainers (for surgeons) to discover the optimal use of new functional features of tools for various types of operations.

To support the educational process, the virtual operating room for planning the surgery and training station has been prepared. In this article, the authors show the process of producing the surgical training stations and few examples of the latest realized specialized devices. This platform allows a geometric modeling of the body anatomy, but also the modeling of the physical properties of the living tissues.

Designed and implemented by the Foundation of Cardiac Surgery Development Biocybernetics Laboratory team, special research station modeling selected surgical scenes were used to study all versions of tools and a fully functional robotic Stiff-Flop surgical system.

17.1 Introduction

Minimally invasive surgical procedures are very complex motion sequences that require a high level of preparation and surgical skills training. New tools developed for the use of new medical procedures also require early testing. Benchmarking is an essential part of the design of prototypes. There are many types of simulators that are available for surgical skill training and device testing. Simulators can be broken down into two different groups: high-fidelity and low-fidelity. These models vary widely with respect to their level of fidelity or realism, compared with a living human patient. The fidelity of a simulator is determined by the extent to which it provides realism through characteristics such as visual cues, tactile features, feedback capabilities, and interaction with the trainee. There are a variety of simulators; the following can be a way to categorize them [1, 2]:

- Synthetic models and box trainers;
- Live animal models;
- Cadaveric models;
- *Ex vivo* animal tissue models;
- Virtual reality (computer-based) models;
- Hybrid simulators;
- Procedure-specific trainers;
- Robotic simulators.

Synthetic model trainers using physical objects usually involve models of plastic, rubber, silicone, and latex. These objects are used to render different organs and pathologies and allow a trainee to perform specific tasks and procedures [3]. A box trainer uses the clinically available instruments and optical system to manipulate "synthetic" tissues. Some physical simulators may also reproduce the feedback from the surgical environment. Artificial materials can effectively replace the natural bodies (anatomic sections or tissues) from euthanized animals and may provide approximate haptic feedback.

In general, benchmarking platforms are based on simulators which describe the anatomy, in particular the geometry of the structures involved in a surgical intervention. These platforms allow geometric modeling of the body anatomy, but also the modeling of the physical properties of the living tissues. The implementation of biomechanical properties is necessary to allow realistic interactions between surgical instruments and soft tissues, including deformations and cutting.

Surgery simulators can be classified into three categories, as follows [4]:

- First-generation simulators describe only the anatomy, in particular the geometry of the structures involved in a surgical intervention.
- Second-generation simulators additionally include the geometric modeling of the physical properties of the living tissues to allow realistic interactions between surgical instruments and soft tissues.
- Third-generation simulators combine anatomical, physical, and physiological modeling, for modeling some organic systems' function such as the cardiovascular, respiratory, or digestive systems.

The modeling of biological tissues for second- and third-generation simulators is very difficult. The biological soft tissues have nonlinear force-deformation properties and show viscous behavior. The properties of soft tissues are often anisotropic and heterogeneous and show hysteresis, relaxation, and creep behaviors. Additionally, these properties strongly depend on many factors, including temperature, pressure, and patient health. Dissected tissue often changes its mechanical properties, so literature data may greatly differ among themselves. It should also be noted that the shape and mechanical properties of animal bodies also significantly differ from human organs.

The Foundation of Cardiac Surgery Development is a well-known research center for surgical robotics. The development Robin Heart robot and mechatronic tools are underway for clinical application. The STIFF-FLOP project focused on a new kind of robot, design bioinspired by octopus anatomy. The benchmarking system equipped with a sensorized phantom of chosen surgical scene allowed to assess the progress at each stage of the design of these innovative surgeon's tools under the STIFF_FLOP project.

17.2 Testing and Training Station Description

17.2.1 The New Scaled Surgery Benchmarking Platforms

The Foundation of Cardiac Surgery Development (FCSD) prepared a surgery benchmarking platform for the STIFF-FLOP robotics tools' test and modeling of chosen surgical procedure. Based on some minimally invasive procedures, essential benchmarking scenarios have been defined and designed, and fabrication of special test rigs and objects (such as phantoms representing organs with variable stiffness) has been carried out.

Figure 17.1 presents the different modules being connected with a central computer control and a monitoring system. This system is also developed for

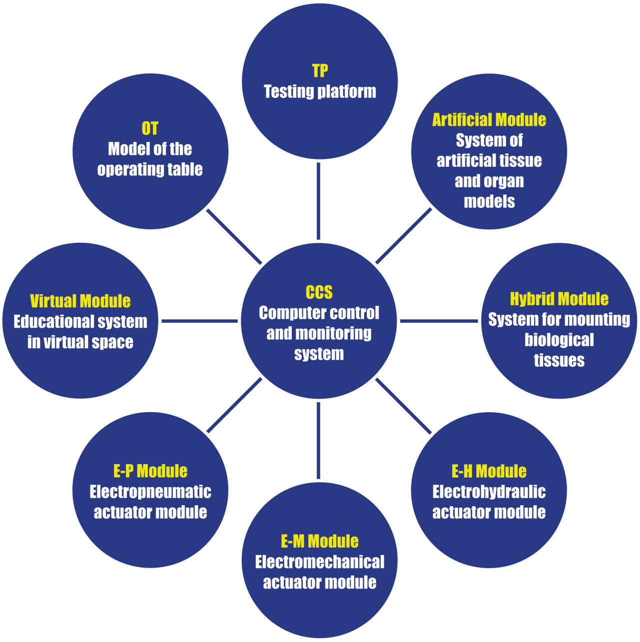

Figure 17.1 STIFF-FLOP robot testing system diagram.

supporting educational activities, and provides, therefore, several components enabling the control of various elements (such as the electromechanical, electro-pneumatic, or electro-hydraulic modules). In addition, the virtual module is envisioned to provide to the students a virtualized version of the whole system (even though no interaction mean with the operation site is currently implemented).

To model the functions of some organic systems such as the cardiovascular or digestive systems, it is necessary to take into account anatomical, physical, and physiological properties. There is an additional degree of complexity due to the coupled nature of physiological and physical properties. Two types of test stands are designed and manufactured:

- Benchmarking platform – mainly reflecting functional characteristics for medical procedures including the obstacle track for training and evaluation of surgical skills;
- Anatomical – mainly based on the anatomical model which reflects the real geometry of the bodies.

Due to the heterogeneity of the biological material, the modeling of mechanical properties of human organs by artificial organs' material is very difficult. The selected artificial materials cover the basic range of variability of the mechanical properties of the bodies used to simulate the surgical procedures. Our platform fulfills the conditions of second-generation simulators as it describes the anatomy, in particular the geometry of the structures involved in a surgical intervention, and it includes the modeling of the physical properties of the living tissues. The introduction of biomechanical properties to our platforms is essential to allow realistic interactions between surgical instruments and soft tissues, including deformations during basic manual operations like cutting or sewing. Due to the large size of the STIFF-FLOP arm prototype at the time, it was necessary to make the platforms in 2:1 scale.

The benchmarking platform (Figure17.2), like the anatomical model, includes a flexible abdominal wall made from silicone. It is fixed by special

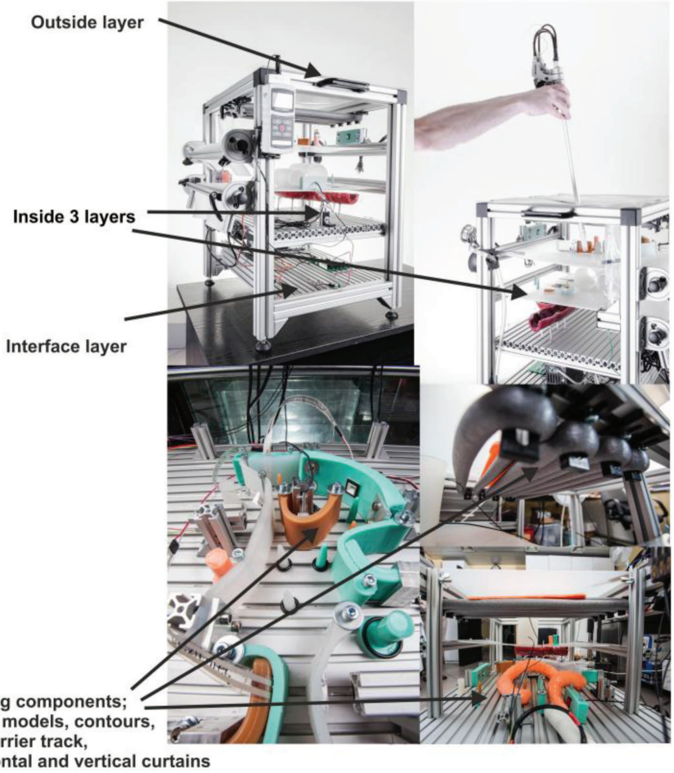

Figure 17.2 The multilayer benchmarking platform [5].

couplings to the chassis so that it can be freely configured (move and change the number of layers). However, in contrast to the anatomical model, the test platform enables research in 3D space, and is freely scalable (maximum scale 4:1). The frame of the platform and basis allows attachment of any organ model and sensors for testing. In addition, we can change the workspace by the movement of profiles in X, Y, and Z directions.

The operational area allows installation of flexible elements to simulate abdominal organs, and can contain measuring sensors. Each element can be easily adapted to the needs of the benchmark. The original solution to our benchmarking platform is the usage of the so-called multi-story system allowing the free distribution of platform elements in 3D space. This system consists of a number (one to three) of additional flexible planes, stretched at different heights and different widths. These planes can play functionality features of a variety of abdominal organs by attaching the various testing components and also properly formed organs of different shapes by cutting (incision) of different shapes. Sensors may serve as additional test elements on their own. In this way, an additional 3D plane (contours, the barrier track, and horizontal and vertical curtains) makes easy modeling of any surgical procedures.

17.2.2 Sensorized Operation Site

Technical benchmarking of the robotic arm performance will be realized by measurements of the position of the end tools and the force acting on the soft tissues. This apparatus is presented in Figures 17.3 and 17.4. The design of this system is modular to enable an easy reconfiguration of the setup on demand. Flexible elements installed on the apparatus permit emulating the human cavity.

As illustrated in Figure 17.3, the sensors that were envisioned and embedded were as follows:

- Flexi Force Sensor PHI-3100_0 with FlexiForce Adapter–1120
- Foil electrical resistance sensor Tz Fs-10/350 (Tenmex, Poland)
- Force Sensors Mark-10 (Mark-10 Corporation, United States)
- Plastic Fiber Optic Sensor– D10 Expert Sensor (Banner, United States)
- Simple displacement sensors (resistor) and push-buttons.

During the Surgical STIFF-FLOP Workshop in Zabrze (Figure 17.5), the current advancement of these systems has been presented, and discussed with the partners, surgeons, and medical students.

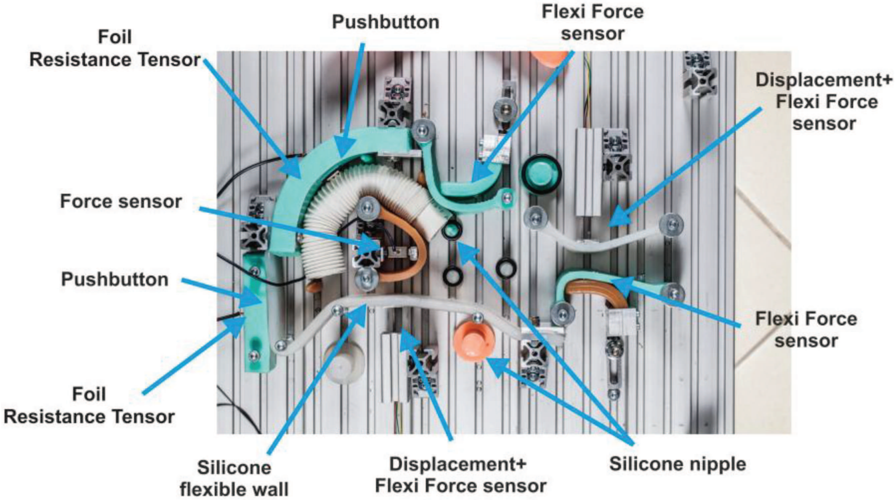

Figure 17.3 Illustration of the instrumentation of the operational site. The figure illustrates the current system that can be extended with some of the systems proposed within this section.

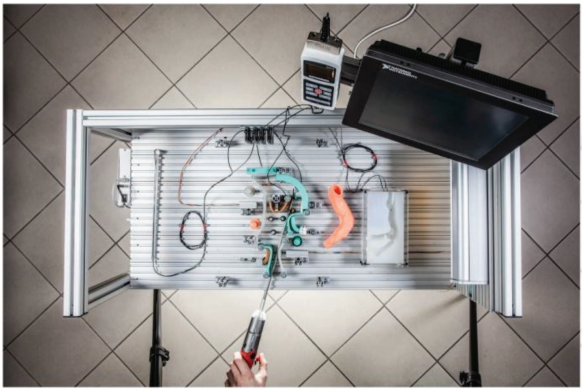

Figure 17.4 Illustration of the potential use of the phantom environment for capturing and analyzing the action of the robotic arm. Experiments can use the STIFF-FLOP arm directly inside such a system.

The results obtained during the workshop have been used to improve the next version of this prototype (Figure 17.6).

Through a workshop with surgeon partners, the following decisions were made to improve the system (Figure 17.6):

Figure 17.5 Illustration of some evaluation platforms that could be extended to perform some training of the STIFF-FLOP arm with surgeons and/or students: (a) presentation of the platforms during the Zabrze workshop, (b) Robin Heart control system using vision, (c) laparoscopy training stations requesting to perform some specific tasks, and (d) virtual laparoscopy training session [6].

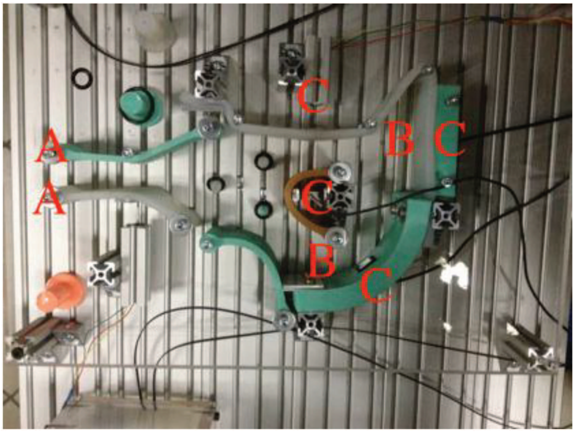

Figure 17.6 First analysis of the phantom hybrid system: suggestions provided by the surgeons to improve the current setup during the Zabrze workshop.

- The fixed points at the entry of the phantom (A) should be replaced with non-rigid structures with embedded sensors in order to understand the lateral pressures realized as well as the traction forces.
- More vertical nipples should be placed (B) in order to make specific exercises of moving rubber circles from one pin to the other.
- These new pins should be placed close to the walls annotated (C). In each of these walls, a pressure sensor should be placed to verify eventual wrong movement.

It was concluded that due to the current module prototype module size, such platform should be realized at a scale of two or three times the current size. In addition, the esophageal model illustrated in Figure 17.7 was prepared.

17.2.3 The Scaled Surgery Benchmarking Platforms

Based on selected minimally invasive procedures (as proposed by STIFF-FLOP medical partners), FCSD defined and built essential benchmarking scenarios and designed and fabricated special test rigs and phantoms representing organs with variable stiffness.

The phantoms combine anatomical, physical, and physiological modeling of the functions of natural organs systems.

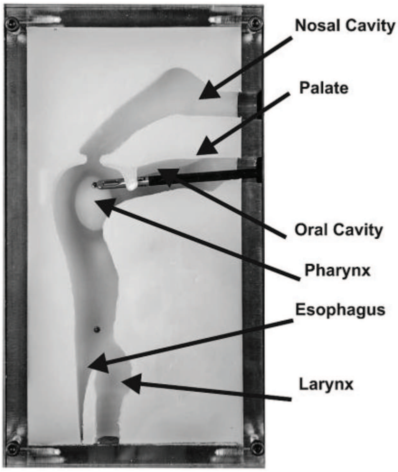

Figure 17.7 Anatomical phantom for otolaryngology. One objective is to study the integration of all the sensing elements within some elastic elements made of silicone and urethane rubber that would enable the provision of a realistic emulation of human cavities.

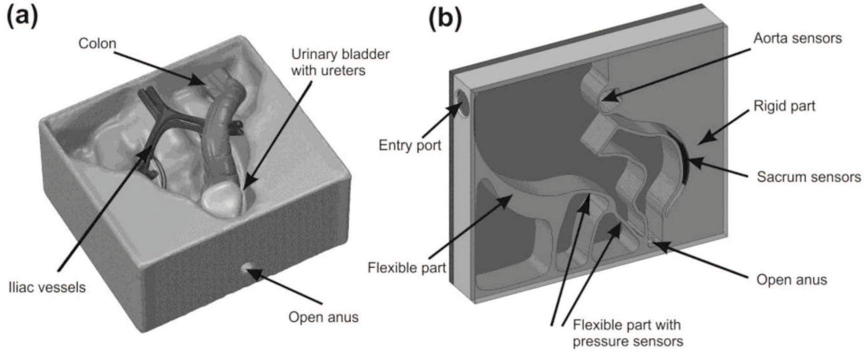

Figure 17.8 The design of a new anatomical phantom model of the lower gastrointestinal tract (scale 2:1) in the frontal (a) and sagittal (b) plane.

To simulate surgical procedures in the quasi-3D platforms (in scale 2:1) of the lower gastrointestinal tract (Figure17.8), a model based on the anatomical shape of the gastrointestinal tract in the sagittal and frontal plane was created.

While building platforms, the authors paid special attention to the internal geometry of the operating field and functionality of minimally invasive procedures. The generally available materials like silicone and urethane rubber (Smooth-On, Inc., United States) with different mechanical properties have been used.

Due to the heterogeneity of the biological material, the modeling of mechanical properties of human organs using artificial organ material is very difficult. Selected artificial materials that cover the basic range of variability of the mechanical properties of the human organs tissue to simulate the selected surgical procedures have been used. The platform satisfies the requirements which were proposed for this second-generation simulator because it describes the anatomy, in particular the geometry, of the structures involved in a surgical intervention, and includes the modeling of the physical properties of the living tissue. The introduction of biomechanical properties to our platforms is essential to allow realistic interactions between surgical instruments and soft tissue organs, including deformations during basic manual operations like grasping, retraction, cutting, or suturing.

Due to the large size of the STIFF-FLOP robot arm prototype at the time, it was necessary to realize the test platforms at a scale of 2:1. It is noted that the quasi-2D phantom models of the lower gastrointestinal tract were made only in two planes: sagittal and frontal.

The anatomical areas of this model allow studying and benchmarking surgical robot systems, as follows:

- Colonoscopy or sigmoidoscopy – for the endoscopic examination of the large bowel and the distal part of the small bowel with a camera passed through the anus for visual diagnosis and for biopsy or removal of suspected colorectal cancer lesions;
- Proctocolectomy – for the surgical removal of the rectum and all or part of the colon;
- Colectomy – for the surgical resection of any extent of the large intestine (colon resection).

The phantom model includes a flexible abdominal wall made from silicone (Figure 17.9). The operational area allows the installation of flexible elements to simulate abdominal soft-tissue organs, and has been equipped with a suite of sensors, including force and tactile sensors to reach the functionality needed for minimally invasive test procedures.

The new (modernized) phantom model in the sagittal plane included (Figure 17.10) the following:

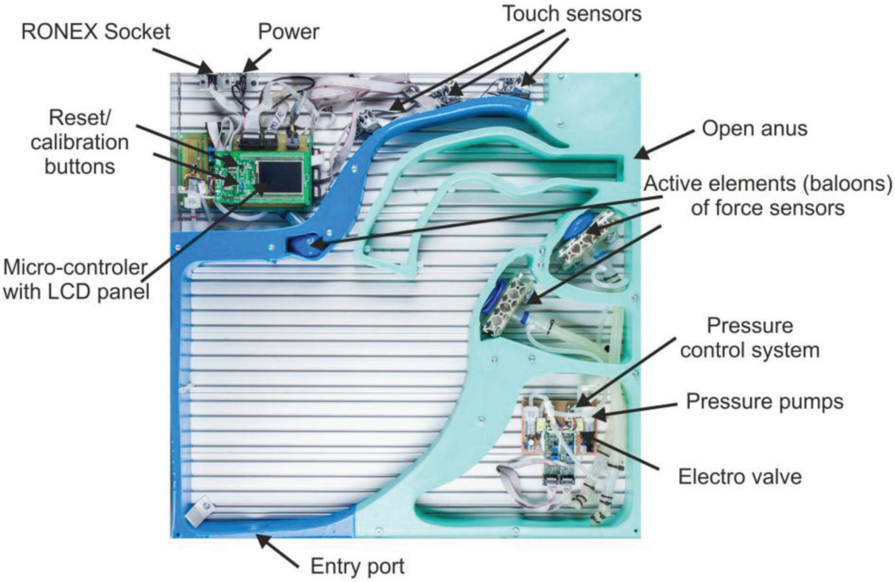

Figure 17.9 The scaled phantom models in the sagittal plane.

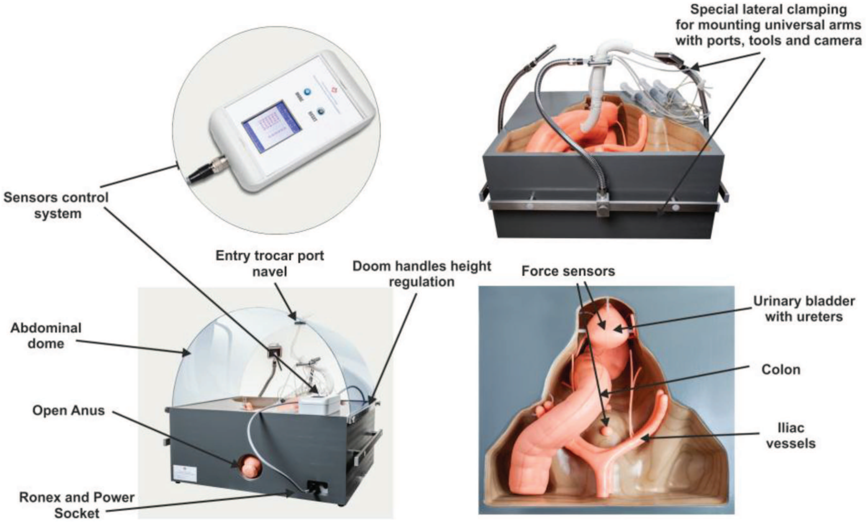

Figure 17.10 The scaled phantom models in the frontal plane.

- Reduced-width silicone walls;
- Replacement of pressure sensor and force sensors (originally potentiometer-based sensors) with new highly sensitive force sensors;
- New electronics;
- New calibrated sensors;
- The possibility to change the mechanical properties of the wall;

The new force sensor was based on the Honeywell pressure sensor and pneumatic system with a balloon as the active element. The anatomical shape with the abdominal surface was made from PET (polyethylene terephthalate, P.W. Masterchem S.J., Poland) with different thicknesses and different numbers of layers (transparent or opaque).

This phantom model can be used in two versions, the first with dome containing one Trocar port and the second without a dome but with special lateral clamping for mounting universal arms with ports, tools, and cameras. The flexible artificial organs like colon, urinary bladder with ureters, iliac vessels, and anus were made from silicone and urethane rubber (Smooth-On, Inc.) through molding.

This phantom model was equipped with pressure sensors based on the Honeywell 1PSI AXIAL sensors, similar to the sensors used in the phantom model of the sagittal plane. However, instead of adjustable balloons as the active elements, the sensor elements that are inflated to a fixed level are used. The sensors (for the measurement of the strength of up to 4 N with an accuracy of 0.1 N) were placed below the bladder, on the sacrum, iliac vessels, aorta, and the colon near the anus.

17.2.4 The Virtual Reality Model

Designing physical models of test devices should be preceded by projects in the virtual space.

The 3D virtual-reality technology can verify the basic functional assumptions at the design stage of simulators, as well as possibly enhance surgeons' learning experiences by providing them with a heuristic and highly interactive simulated virtual environment. The created virtual models are independent test objects that can be used to plan surgical operations or training strategies (Figure 17.11).

In the design process, virtual phantom models were used to verify and check the functionality of both the flexible STIFF-FLOP arm and the haptic control system with haptic feedback.

Virtual reality technology is an interdisciplinary technology, integrating CAD/CAM technology, artificial intelligence, computer networks, and sensor technology. It is widely used in the design and testing of mechanical models. EON Studio is the software tool using graphical interfaces and used for research and development of real-time 3D-modeling applications. This method has been used by FCSD for interactive virtual modeling of the flexible STIFF-FLOP robot arm and motion simulation with interaction between the model of the STIFF-FLOP arm and the surgical environment. The virtual scene reflects the real phantom model of the abdomen in the frontal plane with elements of flexible organs like colon, urinary bladder with ureters, and iliac vessels. Using virtual reality technology to plan surgery procedures

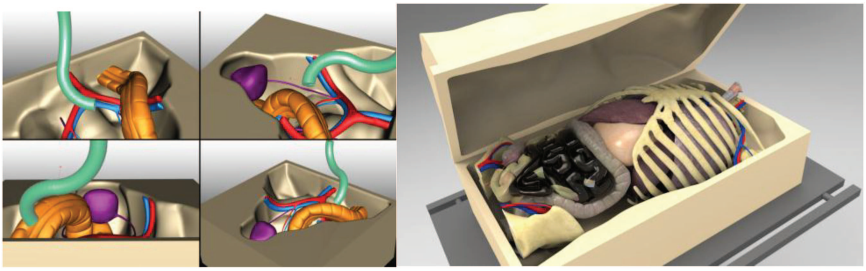

Figure 17.11 The virtual reality phantom models.

increases the efficacy of methods and helps to verify the design and concept of STIFF-FLOP arm.

17.3 Conclusion

An increasing number of robotic surgery simulators can be used for the validation study of surgical education curricula, their functionality, and testing medical procedures.

The surgical simulator must not only accurately maps the anatomical details and deformation of the organ, but also feed-back realistic tool-tissue interaction forces. Therefore, development of realistic surgical simulation systems requires accurate modeling of organs/tissues and their interactions with the surgical tools.

However, to the heterogeneity of the biological material, the modeling of mechanical properties of human organs by artificial organs material is very difficult. Artificial materials selected by us cover the basic range of variability of the mechanical properties of the bodies used to simulate the surgical procedures.

The artificial surgical scene and described devices for testing tools and surgeons create possibility of standardization for the educational and research process. Thanks to various artificial surgical scenes, we can better and more effectively assess the usefulness of new surgical instruments (mechanical, mechatronic, and robotic) for use in various medical procedures.

Acknowledgments

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