A Virtual Interactive Navigation System for Orthopaedic Surgical Interventions

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ABSTRACT

Background and Objective: In the last decade, the field of medicine has ingressed into a new era of technological advancements, driven by an ever increasing demand to reduce patient costs and risks, improve patient safety, efficiency, and surgical outcomes. The need for alternative ways of training and surgery is stronger than ever. Virtual reality based training and surgery systems hold significant promise in this direction. However, development of realistic virtual surgery systems for invasive orthopaedic surgical procedures remains one of the most challenging problems in the field of virtual reality based surgery and training because of the involvement of complex musculoskeletal structures and surgical tools. In recent years, some advances have been made in this area but they have limited practical scope because of their support for small range of procedures and training scenarios. The tools developed so far are either limited in their ability or follow non patient-centric approaches and hence, cannot be considered viable alternatives to the conventional techniques for invasive orthopaedic surgery and training. In this paper, we discuss the challenges and complexities associated with the development of a virtual reality based system for orthopaedic training and surgery, and present our image guidance based navigation system, developed as part of our ongoing research initiative to build a comprehensive tool for realistic virtual orthopedic surgery and training.

Methods: Our image guidance based interactive navigation system provides a common interface for the assembly of different components crucial for a realistic virtual reality based training and surgery application. Presently, the system incorporates various features including rigid body registration, patient-specific three-dimensional model generation, two-dimensional and three-dimensional interactive visualizations, and real time intra-operative surgical guidance. In this paper, we outline the details of our present system along with its key features.

Results: A preliminary version of our proposed virtual reality based orthopaedic training and surgery navigation system is presented. To demonstrate the applicability of our system, a sample application showing the anatomically detailed three -dimensional representations of a patient's knee, derived from the pre-operative image scans, along with the corresponding two-dimensional image details is presented. To the best of our knowledge, this is the first attempt that constructs and integrates patient-specific, anatomically correct, and comprehensive three-dimensional models, with all possible soft tissue details, to provide patient-specific visualization and training capabilities. Preliminary feedback by the orthopaedic surgeons on the prototype of our system is very encouraging and pin points some additional features that can further strengthen the efficacy of our tool and its clinical adoption.

Conclusion: A comprehensive virtual reality based navigation system for orthopaedic training and surgery is presented. The system utilizes patient-specific two-dimensional image modalities and provides corresponding two-dimensional and three-dimensional, interactive visualization capabilities along with real-time tracking of surgical instruments. The present system can be used as an effective tool for anatomy education, surgical planning, diagnosis, and real-time intra-operative surgical navigation. Additional components such as haptics and real-time tissue deformations are currently under development and will soon be integrated with this platform.

Categories and Subject Descriptors

I.3.m [**Computer Graphics**]: Miscellaneous; I.4.m [**Image Processing and Computer Vision**]: Miscellaneous; J.3 [**Computer Applications**]: Life and Medical Sciences.

General Terms

Management, Design, Human Factors, Standardization

Keywords

Three-dimensional, Computer assisted, Orthopaedics, Medical, Visualization, Navigation, Virtual Reality

1. INTRODUCTION

Conventional methods of surgical training are primarily based on animal models, inanimate models, or the Halsted apprenticeship model. In the former two approaches, a trainee surgeon or a medical student acquires surgical skills by practicing on either the inanimate models like cadavers or the animal models. The latter approach is based on the "see one, do one, teach one" paradigm [Halsted 1904]. In this approach, a novice surgeon or trainee acquires different skills under the supervised guidance of mentors or superiors over a period of time. A novice surgeon initially observes the new procedures, then performs these procedures under varied levels of supervision, and finally, upon achieving the required proficiency levels, performs the surgeries autonomously.

These traditional ways, although well adopted, have several limitations. For instance, cadavers cannot yield appropriate physiological response and it is hard to practice real time scenarios on cadavers. Animal models significantly differ in anatomy and are expensive. Their usage may involve ethical issues and complex logistics. Moreover, cadavers and animal models cannot be reused, the availability of pathological scenarios to practice on these is restricted, and only a few trainees can be trained on a cadaver or an animal. Training on real patients is risky and may jeopardize the health of patients and compromise patient safety. These limitations along with other factors like technological advancements, rising patient awareness, increased sub-specialization, and more importantly, patient safety issues, challenge the traditional methods of training [Bridges and Diamond 1999; Gallagher and Traynor 2008; Sachdeva 2002]. There are 44,000 to 98,000 deaths per year due to surgical errors and of these the highest incidence of complications happens in the first case and up to 90% occur in the first 30 cases [Kohn et al. 2000]. Out of these 54% of surgical errors are potentially preventable [Kohn et al. 2000; Gawande et al. 1999]. This clearly indicates that surgeons get better with practice and novel methods of training and surgery can help drop the error rates significantly. All these factors necessitate the need for novel and alternative ways of surgical training and skills enhancement.

Virtual Reality (VR) based systems hold significant potential in this domain [McCloy and Stone 2001; John 2002] and are increasingly gaining acceptance in the medical community as they offer safe and viable alternatives to the traditional approaches. These systems can provide the clinicians with interactive, three-dimensional visualizations of the anatomical organs during different stages of treatment and can enable them to practice certain surgical tasks and hone their surgical skills in a virtual world. In contrast to the previously discussed traditional approaches, VR based systems offer several advantages like, cost effectiveness, reusability, improved performance, and better learning efficiency [Wanzel et al. 2002; Wong 2004; Fried et al. 1999; Hammond 2004]. In addition, these systems can help reduce surgery times, intra-operative surgical errors, and risks associated with the acquisition of new skills and can provide a safe learning environment without compromising patient safety [Seymour et al. 2002; Doyle 2002]. The ability of VR tools to model and display medical data can play a significant role in a wide range of areas like anatomy education, surgical training, surgical skills enhancement, diagnosis, planning, and exploration of novel surgical techniques [Ziegler et al. 1995].

Currently available VR tools, based on their applicability, can be classified into two main classes namely, surgical simulation systems and computer-assisted surgery (CAS) systems. Simulation systems are generally used in pre-operative settings and present a predefined, controlled training environment for practitioners to learn and practice some surgical procedures. CAS systems are used in both pre-operative as well as intra-operative settings. In pre-operative settings these systems provide a platform for various tasks like diagnosis, surgical planning, training, and education whereas, in intra-operative settings these systems provide prospects in areas like robotic surgery and surgical navigation. The best simulation systems for training have achieved recognition primarily in the fields of minimally invasive surgery [Basdogan et al. 2004] and endoscopic or endovascular surgeries like endoscopic gastro-intestinal surgery [Neubauer 2005; Simbionix 1997], or arthroscopic knee surgery [Heng et al. 2004; Zhang et al. 2003]. Although popular, these types of procedures represent only a minority of the approaches for surgical interventions. The majority of the surgical procedures are still performed using an open incision [Gallagher and Traynor 2008]. However, similar techniques have so far not evolved for general surgery and especially, invasive orthopaedic surgery. Orthopaedic surgery deals with significantly complex musculoskeletal structures and mechanical instruments. There is a real need for virtual reality based tools to facilitate invasive orthopaedic surgical procedures as these procedures require extensive training and practice.

Our work initiates research in this area. The present system integrates multi-modality, patient-specific data and provides patient-specific interactive two-dimensional (2D) and three-dimensional (3D) visualizations. The system is equipped with navigation tools which can be used to track the position and orientation of surgical tools with respect to the patient's anatomy in real-time. Our framework incorporates different modules such as, multi-modality data integration, intra-operative real-time registration, interactive 2D-3D views, highly detailed patient-specific 3D models, and surgical navigation. To the best of our knowledge, this is the first attempt that constructs and utilizes high level of detail, anatomically accurate, patient-specific 3D models. The main graphical user interface (GUI) of our application provides re-sliced views of computed tomography (CT) and magnetic resonance (MR) image volumes at varied angles along with their corresponding 3D anatomical representation and hence, facilitates easy recognition and visualization of the spatial correspondence of the anatomical features in 2D images in the 3D anatomical space and vice versa.

Orthopaedic surgery requires a good understanding of the intricate and significantly complex musculoskeletal structure geometries and their interactions. Accurate modeling of the involved anatomic details is critical to envisage the restorative functional outcomes of orthopedic interventions. Our system models and integrates all possible soft-tissue information and provides high resolution models in an intuitive 3D format that can benefit trainees, surgeons, and the patients [Angelini et al. 2007]. In addition, six degrees-of-freedom (DOF) tracking data of surgical tools with respect to the patient's anatomy can provide additional information to the surgeons and help facilitate effective decision making. The presently developed system can be used for training, pre-operative visualization, diagnosis, planning, and surgical guidance. Moreover, our patient-specific high level of detail approach can help develop new techniques for various phases of surgical tasks. We plan to enhance the system further and aim to develop a comprehensive surgical training and virtual surgery framework.

The rest of the paper is organized as follows: The Methods section delineates the key functional components along with their operational details. The Results section demonstrates the applicability of our system and presents the results. The Conclusions section summarizes the main conclusions and discusses possible future improvements.

2. METHODS

We followed a tiered-modular approach for the application development. The application framework consists of several tiers where each tier incorporates a unique functional aspect of the system as described below. Each tier comprises of a combination

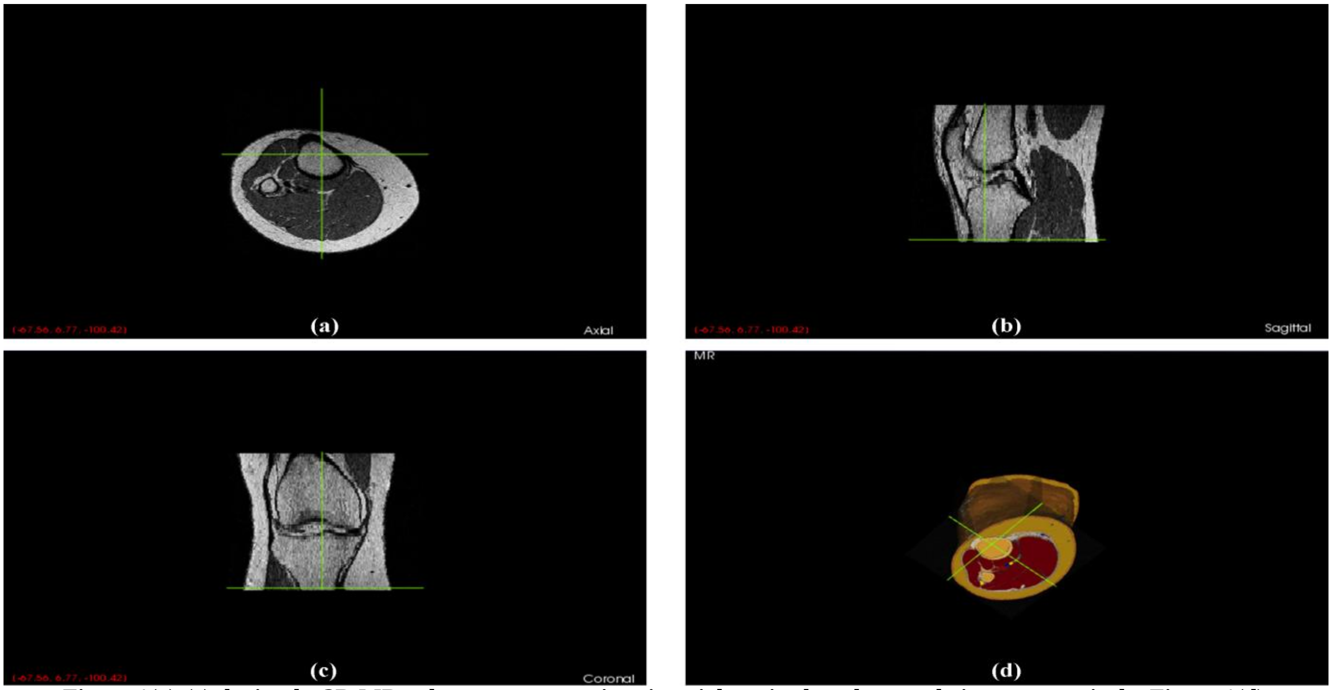

Figure 1(a)-(c) depict the 2D MR volume representations in axial, sagittal, and coronal views, respectively. Figure 1(d) illustrates the detailed 3D knee model along with the corresponding MR re-sliced planes. Distinct color maps characterize different tissue classes in the 3D knee model representation.

of independent and dependent modules. Independent modules provide tier-specific functionality and are decoupled with the rest of the tiers whereas dependent modules provide common functional features and can be referred to from other tiers in an object oriented manner. The developed application is platform-independent. It can be extended, with minimal effort, to incorporate additional features like haptics and can easily be customized for other surgical specialties.

2.1 Data Acquisition and Pre-processing

For the initial phase, pre-operative images were obtained from MR and CT scans of volunteer subjects. The slices were acquired with a slice thickness of 1.7mm and 2.0mm for MR and CT modalities respectively. The main application GUI provides options to select and load patient-specific images corresponding to these modalities. Validation checks are performed to ensure the compatibility of loaded data with the patient specific information, like patient’s name and age, entered as part of the patient registration process which precedes the current phase. Additional options are provided to adjust image contrast and brightness of the loaded grey-scale images.

2.2 3D Model Generation

The first step to create a patient-specific, anatomically detailed, and accurate 3D model begins with the process of Segmentation. This process involves classification of pixels in an image volume followed by the delineation and labeling of each of the individual tissue classes. These labeled classes are then extracted for further processing. To capture different soft tissue details we utilize MR image volume for this step. Soft tissues are layered and exhibit nonlinearities. To derive an anatomically detailed and correct model it is important to accurately model the intricate and complex structures of the various soft tissues involved. The presence of strong tissue inhomogeneities, caused by factors like partial volume effects and inherent statistical noise [Megibow 2002], in MRI volumes add to the difficulty of the segmentation process.

We have adopted a hybrid segmentation scheme consisting of both automatic and manual modules for tissue segmentation. Our automatic module implementation is primarily based on seeded region growing, morphology, and thresholding algorithms [Ibanez et al. 2005] and is used in conjunction with the manual segmentation. Unlike with MR, the automated segmentation modules work very well with CT images. Therefore, their usage is weighted depending upon the type of the input image modality used. In the next step, a surface model is constructed from the segmented volume using the Marching Cubes algorithm [Lorensen and Cline 1987]. The model is then optimized and a closed, water-tight, and computationally efficient model is generated for each of the tissue classes using our novel surface reconstruction scheme that will be discussed in a future publication.

2.3 Registration

Registration is the process of establishing spatial correspondence between the coordinates of two or more image spaces. In our system, the physical patient space coordinate system is registered with the virtual space, image data, to establish a one to one correspondence between the two. We used a rigid body registration technique based on anatomical image landmark points and patient fiducial markers to accomplish this task. In the rigid body registration approach, the mapping transformation between the two image spaces is generally characterized by translation and rotation. It is based on the assumption that the mutual distances of points remain preserved during transformation.

In the current implementation, a four paired-point rigid body

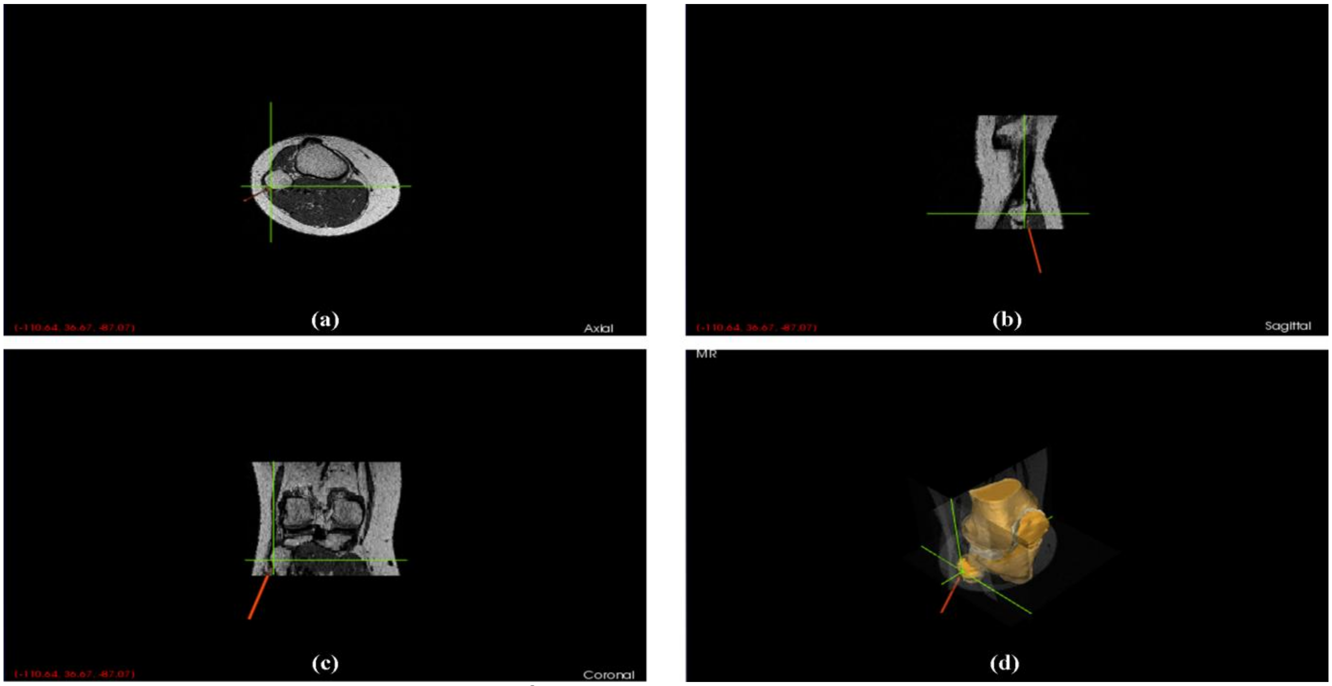

Figure 2(a)-(d) show the tool (orange) position information in the axial, sagittal, coronal, and 3D views, respectively. A subset of the knee 3D model comprising of mainly the Femur, Tibia, Fibula, and Patella bones is shown along with the corresponding MR re-sliced planes.

registration is performed to compute the transformations between the physical patient space and the virtual space coordinate systems using a landmark registration based algorithm [Ibanez et al. 2005]. The application GUI provides options to select and change reference points in real-time for the image and patient spaces. Image landmarks are selected using a mouse pointer whereas patient landmarks are selected using a tracking tool.

2.4 Navigation

Tracking is an essential component of an image-guided navigation system and is used to track the position and orientation of the surgical instruments with respect to the patient's anatomy. The proposed application provides virtual representations of the tracked tools or surgical probes and displays their real-time position and orientation information in the virtual scene with respect to the anatomical model. The image volume is re-sliced based on the position of the tracked instruments. We use an optical tracking device to obtain the position and orientation data of the tracked instruments. The tracking tools are calibrated following a pivoting procedure. It is important to establish spatial correspondence between the patient physical space and the virtual space prior to navigation. Therefore, the registration step is carried out before this step.

Orthopaedic surgery and training deal with significantly complex anatomical structures. Different surgical approaches, planning rationales, and instruments are selected and deployed based on the specific region of interest and procedure involved. In the next section, we present the results of our prototype application customized for Knee as the region of interest. The application can easily be used for other anatomical regions.

3. RESULTS

We developed an image guidance based navigation system for Knee following our patient-centric approach. It can be used as an effective tool for knee anatomy education, training, surgical planning, diagnosis, and real-time intra-operative surgical navigation. The following subsections present the details of our prototype application.

3.1 System Details

The application has been developed and deployed on a Microsoft Windows based personal computer using C++, OpenGL, and Qt.

3.2 Visualization

PD FSE MR Images with 1.7mm slice thickness and spacing were acquired at a hospital. Only axial image slices were used for the volume generation and segmentation purposes. The application interface presents interactive multi-planar 2D (axial, sagittal, coronal) and 3D views that allow easy navigation through different slices and visualization of the re-sliced representations at any selected point within the volume. The GUI also provides options for patient registration, multi-modality image loading, image-patient registration, planning, and display enhancements like zooming and rotation. Figure 1 illustrates the 2D and 3D representations of a patient's knee derived from the patient's pre-operative scans.

3.3 Navigation

We used NDI Polaris Optical Tracker [NDI 1981] to obtain 6DOF tool tracking information. The application GUI provides options to select and track different surgical tools. Registration must be performed successfully prior to this step. Currently, Fiducial Registration Error (FRE) based on the Root Mean Square (RMS) error value is used to determine the registration accuracy and acceptability. Transformations computed during the registration step are used to establish appropriate mappings between the elements of patient space and those of virtual space. Our application provides virtual tracking tool representations and displays real-time tool position and orientation information, with respect to the patient anatomical model, in the virtual scene using the obtained tracking data. Figure 2 depicts the mapped surgical tool position in the virtual patient space comprising of the Femur, Tibia, Fibula, and Patella bones corresponding to their phantom based physical patient space. The image volume is re-sliced based on the position of the tracked instruments. The graphics update rate of 30 Hz is used in the current implementation.

4. CONCLUDING REMARKS

In this paper we presented our patient-centric, virtual navigation system. It utilizes pre-operative 2D image modalities and provides corresponding 2D and 3D visualization capabilities along with real-time tracking of surgical instruments. To our knowledge, this is the first attempt that constructs and integrates patient-specific, anatomically correct, and comprehensive 3D models with soft tissue details. The present system can be used as an effective tool for anatomy education, training, surgical planning, diagnosis, and real-time intra-operative surgical navigation.

The system has been implemented in a highly modular manner to allow easy integration of additional suggested features, such as haptics, deformation modeling, and robotics, currently under development. We plan to explore and deploy more accurate registration mechanisms in the future. We will also investigate the in-vivo tissue characteristics to incorporate appropriate biomechanical behavior in our models for realistic haptics interactions and deformation computations.

5. ACKNOWLEDGMENTS

The authors would like to thank Dr. John M. Marzo, Dr. Michael A. Rauh, and Dr. Geoffrey A. Bernas for their valuable feedback and comments.

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