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Real-time advanced spinal surgery via visible patient model and augmented reality system

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ABSTRACT

This paper presents an advanced augmented reality system for spinal surgery assistance, and develops entry-point guidance prior to vertebroplasty spinal surgery. Based on image-based marker detection and tracking, the proposed camera-projector system superimposes pre-operative 3-D images onto patients. The patients' preoperative 3-D image model is registered by projecting it onto the patient such that the synthetic 3-D model merges with the real patient image, enabling the surgeon to see through the patients' anatomy. The proposed method is much simpler than heavy and computationally challenging navigation systems, and also reduces radiation exposure. The system is experimentally tested on a preoperative 3D model, dummy patient model and animal cadaver model. The feasibility and accuracy of the proposed system is verified on three patients undergoing spinal surgery in the operating theater. The results of these clinical trials are extremely promising, with surgeons reporting favorably on the reduced time of finding a suitable entry point and reduced radiation dose to patients.

1. Introduction

Degenerative and osteoporotic spinal diseases have become increasingly prevalent over the past two decades. Compression fracture leading to disability is the most common complication of osteoporosis. The present treatment modality includes percutaneous vertebroplasty, although minimally invasive surgeries (MIS) [39], such as ertibuloplasty or balloon kyphoplasty, are gaining popularity because they can reduce the postoperative recovery time, surgical complications and patient morbidity. The benefits of MIS over open surgery are particularly evident in spinal surgeries. The majority of minimally invasive spinal surgeries, such as vertebroplasty, balloon kyphoplasty and pedicle screw fixation [16], require a series of intraoperative X-ray images using C-Arm, complex navigation systems and robots [1]. Surgeons require extensive, long-term training to master these techniques and implement them with high precision and accuracy, mainly because they must simultaneously view multiple coordinate systems (Fig. 1). Such coordinate systems may include the laparoscope, surgeon's eyes, instrument positions and various display screens from

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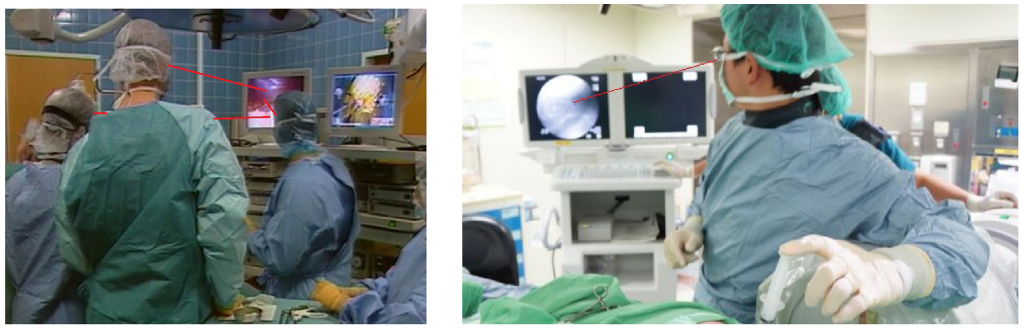

(a) Surgeons viewing monitors during minimally invasive adrenal surgery [25]. The monitors display adrenal tumor and veins.

(b) Surgeon viewing (X-Ray) monitors during traditional open surgery. The surgeon uses the C-Arm camera to seek the target point for spinal surgery.

Fig. 1 – The coordinate transformations during the surgery included open and MIS surgeries. The surgeons calculate and predict positions of instruments, laparoscopes and several display screens.

different cameras. The surgeon must co-ordinate these different views to perform surgery with minimal direct visibility while avoiding damage to neighboring vessels and nerves.

In this paper, we propose an advanced augmented reality-based system for spinal surgery, and apply it to vertebroplasty. Spinal surgeons locate various affected or pathological sites (such as fractured vertebrae) using different technologies. During minimally invasive procedures, they must track needles and other operative instruments. Reliable commercially available technologies for spinal surgeries include fluoroscopy based guidance systems without calibration [9,27], navigation systems [24] and CAMC systems [28] which are available commercially and have proven efficacy. However, these systems are not problem-free. Navigation systems are complicated, expensive and often require extra training. They sometimes need tracking devices, which are themselves invasive since they are fixed to rigid body parts such as bones. In the majority of these guidance systems, surgical instruments and bones [3] are located and tracked using fluoroscopic or C-Arm guides, which provide series of X-ray images. The limitation of these techniques are additional coordinates that must be monitored by the surgeon.

An alternative technique, augmented reality (AR), was introduced to medicine through neurosurgery [22]. AR has been extensively researched for intraoperative visualization throughout the past decade [29,10,8,36,38,31,30,25]. In this technique, real images are merged with computer graphics (virtual view) to enhance the multimedia information surrounding the user. Therefore, we propose that spinal surgeons may be intraoperatively guided by projection-based AR techniques using preoperative CT images of the patient.

The proposed system, called Augmented Reality Computer Assisted Spine Surgery (ARCASS), superimposes the projected image onto the patient's body using an industrial camera and a projector. Camera-projector systems are widely used in the entertainment, industrial inspection, education and training professions. ARCASS system projects a preoperative 3D model of the patient onto the intraoperative scene, namely, the external anatomy (skin) of the patient. The bone image is projected from pre-captured CT images, and a 3D model of the patient undergoing surgery is constructed using the "visible patient" tool [18] developed by the Research Institute against Digestive Cancer (IRCAD) in France and Taiwan. Visible patient is detailed in Section 3.1. The preoperative 3D model is constructed from tomographic images of the patient's torso, referenced by skin markers. In ARCASS system, markers are used to register the 3D model to the intra-operative scene (the posterior aspect of the patient's torso). The markers are posteriorly fixed while tracking is performed in real-time and the 3D model is projected onto the patient.

If successful, the proposed system will provide the following benefits to surgeons:

- First, images extracted from the 3D model can be merged with an external video view of the patient through camera calibration and rigid-transform registration.
- Second, the surgeon can "look into" the patient's body by projection of bony structures onto the body during surgery.
- Third, because the system detects automatic skin markers and tracks postural deformations, it provides an augmented-view, real-time model of a preoperative patient.
- Forth, the ARCASS system providing intuitive and simple access to needle entrance points.
- Finally, the system reduces intraoperative radiation exposure by reducing the number of regular C-Arm checks and X-ray/fluorescence image tracking.

Collectively, these features of the system reduce radiation exposure while minimizing the potential for error during surgery, thereby enhancing the safety of surgical procedures. The benefits come from ARCASS system providing intuitive and simple access to needle entrance points.

2. Related work

AR systems for surgical guidance have independently co-evolved [14], even in otolaryngology [5]. Compared to traditional laparoscopy, AR systems offer extended field of view, multiple viewing directions, flexible positioning of patients and less mismatch between the views of surgeon and instruments. Sauer et al. [37] developed an AR image guidance system in which information derived from medical images