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Computer Integrated Surgical Robot System for Spinal Fusion

Sungmin Kim[*1], Goo Bong Chung[*4], Se Min Oh[*4], Byung-Ju Yi[*4], Whee Kuk Kim[*5], Jong Il Park[*4], Young Soo Kim[*2]

[*]Center for Intelligent Surgery Systems, [1]Department of Biomedical Engineering, [2]Department of Neurosurgery, School of Medicine, [3]Division of Electrical and Computer Engineering, Hanyang University, Seoul, Korea
[4]School of Electrical Engineering and Computer Science, Hanyang University, Ansan, Korea
[5]Departmen of Control and Instrumentation Engineering Korea University, Seoul, Korea

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Abstract: A new Computer Integrated Surgical Robot system is composed of a surgical robot, a surgical planning system, and an optical tracking system. The system plays roles of an assisting surgeon and taking the place of surgeons for inserting a pedicle screw in spinal fusion. Compared to pure surgical navigation systems as well as conventional methods for spinal fusion, it is able to achieve better accuracy through compensating for the portending movement of the surgical target area. Furthermore, the robot can position and guide needles, drills, and other surgical instruments or conducts drilling/screwing directly. Preoperatively, the desired entry point, orientation, and depth of surgical tools for pedicle screw insertion are determined by the surgical planning system based on CT/MR images. Intra-operatively, position information on surgical instruments and targeted surgical areas is obtained from the navigation system. Two exemplary experiments employing the developed image-guided surgical robot system are conducted.

Key words: Computer integrated surgery system, Image-guided surgical robot system, Image-guided surgery, Spinal fusion

INTRODUCTION

The operation, in general, requires long experiences and skills of physicians since the surgical environment is uncertain and delicate, and thus a slight mistake might cause catastrophic results to patients. It is a reason why both patients and surgeons are reluctant to be exposed to the robotic system unless they feel that it is very reliable and safe. But it is well known that in open surgery patients need long recovery times and suffer from significant postoperative pain. Thus, it becomes necessary to develop a useful system that is helpful to reduce the operational time and the wound area, and to simplify complicated surgical operations. In these necessity, a computer-integrated surgical robot (CISR) system has been developed, which is very helpful to both patients and surgeons [1-9]. CISR system consists of a surgical robot, a surgical planning system and a surgical navigation system. Thus, close collaboration among diverse technical areas is strongly required and understanding the clinical necessaries and surgical procedures is also very important.

There are some reviews on CISR systems [4-6]. According to these reviews, major fields of applications of medical robot are laparoscopic operations, orthopedic operations, and brain surgery areas. There are few practical case reports on the use of the robot system for spinal surgery in literature up to now even though most of current surgical procedures at hospitals rely on surgeon's experience only with aids of fluoroscopic, computer tomography (CT), or magnetic resonance (MR) images yet in open spinal surgery [7-9].

In this paper, we introduce a new CISR system for the spine surgery. The robotic system called SPINEBOT is reported in our previous study [9]. The major aspect of the CISR system will be discussed through an exemplary spinal fusion. This pilot study would clarify most of current problems that make the spinal fusion difficult. In section 2, architecture of a CISR system and the roles of each parts are described. Two experiments are conducted in section 3. The first one deals with boring a hole on a phantom by a surgeon through the guide hole held by the robot. The other one is the direct boring by a robot. In both cases, the desired position of the robot is determined by the planning system at pre-operative time and instructed by the navigation system at intra-operative time.

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Corresponding Author : Young Soo Kim
Department of Neurosurgery, School of Medicine, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul, 133-791, Korea
Tel. +82-2-2220-1553, Fax. +82-2-2291-8498
E-mail. ksy8498@hanyang.ac.kr

CONCEPT OF THE COMPUTER INTEGRATED SURGICAL ROBOT SYSTEM FOR IMAGE-GUIDED SPINAL FUSION

System Architecture

As shown in Fig. 2, computer integrated surgical robot system, which we called Image-Guided SPINEBOT System, consists of a surgical planning system, a surgical robot, and an optical tracking system. In intra-operative procedure, the optical tracking system and surgical planning system play roles of a navigation system. The registration of coordinates of the robot and the tracking system are performed by using the navigation system. Subsystems are connected to each other through Ethernet. For spinal fusion experiments, we use a phantom that serves as a real surgical area and is on a moving emulating system to mimic a real surgical area motion due to the external force and respiration. Both information of the operational path determined in surgical planning system and the movements of the phantom detected by optical tracking system are transformed to the robot and then the robot conducted the operation while compensating the movement of the phantom.

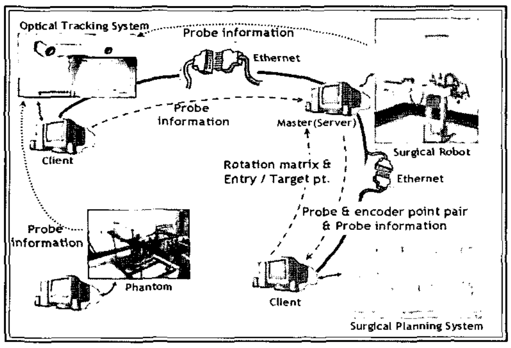


Fig. 1. Setup of image-guided SPINEBOT system

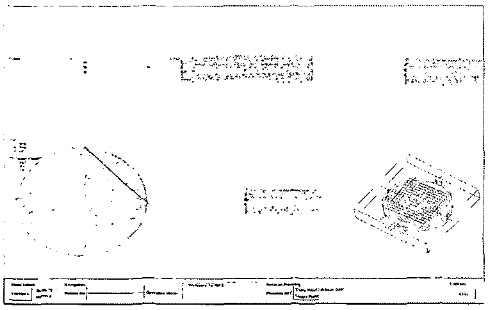


Fig. 2. Surgical Planning System: HexaView Planning System

Roles of Components

Surgical Planning System: HexaView Planning System

In our Image-Guided SPINEBOT System, Surgical Planning System called HexaView Planning System is also integrated to provide surgeons with six different views (three transverse views, two oblique views and 3D view) of surgical area as shown in Fig. 3. Also, the planning system has some functions for surgical planning, monitoring positions of both SPINEBOT and phantom in the intra-operative procedures, and calibration of operation results in postoperative procedure.

After CT images of the phantom structure are loaded in HexaView Planning system, 3D volume is reconstructed from the CT data and used for preoperative surgical planning. Surgeons determine the optimized surgical path viewing these 6 views. After designing surgical path, entry and target points are selected. These position data of two points (entry and target points) are used to measure the direction vector for robot control.

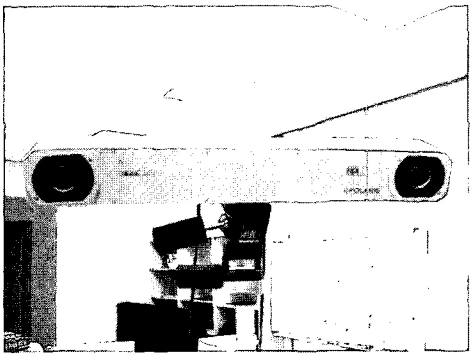


Fig. 3. Optical Tracking System (OTS)

Surgical Navigation System

Surgical Navigation System of The Image-Guided SPINEBOT System consists of a surgical planning system and an optical tracking system. This system plays role of detecting and controlling of motion of SPINEBOT. The Optical 3D digitizer, shown in Fig. 4, developed by NDI Co. Ltd, Canada, could be used as a simple position digitizer, a transformer for registration between two other data sets, or a detector for real-time position of surgical robot for controlling surgical motion. To realize these functions, two systems are linked and performed registrations between HexaView Planning system (image coordinates) and physical space (coordinates of Optical tracking System), and between SPINEBOT (SPINEBOT coordinates) and physical space (coordinates of Optical tracking System).

After all, the other three coordinates are aligned to the coordinates of optical tracking system (physical space). That is, the point set of SPINEBOT and 3D volume data (e.g. surgical planning system) are transformed to the physical coordinate system (e.g. coordinates of Optical Tracking System).

After these procedures, the Image-Guide-SPINEBOT System is commanded to move along the preplanned data. During surgical procedures, optical tracker continuously detects the movement of SPINEBOT and transfers data back to SPINEBOT on line. The implemented system could run at 30Hz which is limited by the maximum measuring rate of the camera of the optical tracking system.

Particularly, in our IGS system, the movement of the robot is measured simultaneously both by optical tracker and by built-in encoders. These redundant measurements of the surgical system are employed in order to further increase safety level.

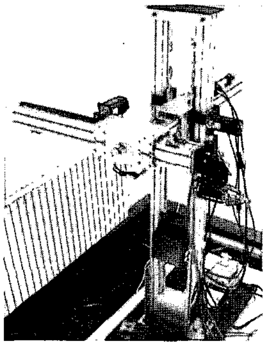


Fig. 4. Surgical Robot System: SPINEBOT

Surgical Robotic System: SPINEBOT

Figure 5 shows the developed surgical robot called SPINEBOT in our previous study [9]. SPINEBOT consists of a Cartesian type 3-DOF system, a 2-DOF gimbals and 2-DOF drilling tool. The SPINEBOT is designed to perform a screwing task into the lumbar of the human spine. The 3-DOF XYZ motions and the 2-DOF motion of gimbals respectively provide the global positional motion of the robot and rotational angles to orient the drill tool. And lastly the 2-DOF drilling tool is designed to be suitable for feeding and drilling a hole to vertebra in percutaneous operation.

At the design stage, it is assumed that the robot is to be used as either a passive arm or an active arm depending on its role in surgical operation. More specifically, it can be used as a guider holding a guide bar pinpointing a surgical location for spinal operation or it can directly drill a hole on a lumbar and insert a screw through the lumbar. Further, it could be used to perform more complicated operation in spinal operation.

At first, SPINEBOT coordinates are aligned to that of the optical tracking system. After the SPINEBOT receives the entry and target points for pedicle screw insertion, it moves along the planned path up to the entry point. And then SPINEBOT holds the guide stick to bore a hole through it, or drilling a hole into the vertebra directly along the preplanned path without any intervention of a surgeon, and simultaneously compensates the movement of the surgical area, which is due to the respiration of the human body. In this procedure, the position of the drill tip is continuously detected through both the navigation system and the encoders of SPINEBOT. Particularly, a significant amount of backlash is observed from the gimbals system developed in previous version of SPINEBOT. Thus, a four-bar linkage based joint using a harmonic driver as shown in Fig. 6 is designed and installed to the SPINEBOT to eliminate such ill effects from backlash.

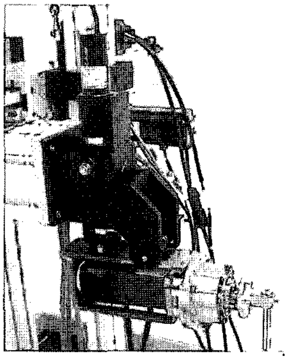


Fig. 5. New design of gimbals of the SPINEBOT

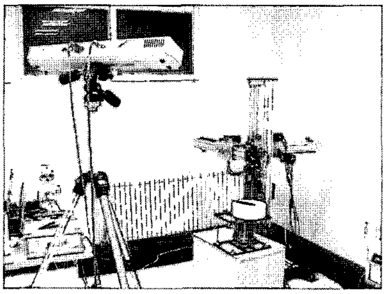


Fig. 6. SPINEBOT with Optical Tracking System

Advantages of Image-Guided SPINEBOT system

The surgeries conducted without the navigation system may be operated by intra-operative image based guiding (e.g. fluoroscopy image and intra-operative CT/MR image). Among these images, fluoroscopy is widely used to provide intra-operative image to surgeons but exposure of surgeons and patients to X-ray causes considerable problems to them. Moreover, due to limited dimension of planar images of the fluoroscopy, it does not provide sufficient information to reconstruct the 3-D volume data of the target object even using bi-planar images. By using Image-Guided SPINEBOT system, the problems of the usage of the fluoroscopy can be removed. Through registration, the preplanned data of the surgical area is aligned to the physical space by the navigation system. Thus, the operating time and the exposure to X-ray are reduced significantly because the surgeon does not need to find the proper surgical path in intraoperative procedure. Furthermore, in comparison to conventional navigation system, while the conventional navigation system is still based on purely manual instrument handling, precise instrument guidance and operating preplanned surgery by navigated surgical robot systems such as our system offer additional significant advantages. High accuracy and safety in the intra-operative task can be achieved, which results from precise guiding by SPINEBOT. The risk of cost intensive postoperative treatment can be minimized. The number of the assistant staff required in the operating room can be also reduced. These will provide patients with many benefits, better support of the surgeon, and yield improved cost/benefit ratios.

EXPERIMENIS

The role of surgical robotic systems has been argued whether it is adequate for assisting surgeon or replacing surgeon. A clear answer cannot be given easily, but rather it seems to depend on circumstances of surgical operations. In this work, we try to investigate this question by performing two different experiments for inserting pedicle screws in spinal fusion. In the first experiment, the surgeon performs a drilling operation manually but with the limited help by the robot that guides the drilling tool along the preplanned path by the surgical planning system. In the second experiment, the surgical robot directly conducts boring a hole with a drill, without being interrupted by the surgeon. The purpose of the second experiment is to test the capabilities (e.g. observing environment, operating by preplanned data, tracking the sensed signal, and reliability) of autonomous surgical robot system. Figure 7 shows the experimental setup for these experiments.

The two experiments will be conducted with a phantom. This phantom is laid on a three degree-of-freedom robot as shown in Fig. 8, which is designed for emulating the movement of the real surgical area due to the human respiration and an applied external force. The phantom is scanned by a CT imaging device, and the obtained data is used for preoperative surgical planning and intraoperative registration procedure to align the preplanned data to physical space (i.e., coordinates of optical tracking system) as shown in Fig. 9.

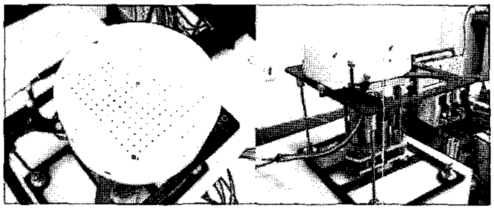
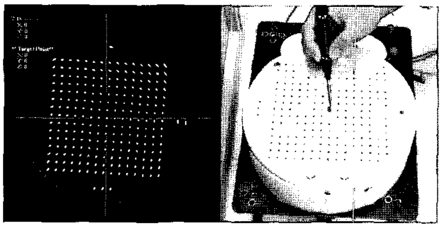


Fig. 7. phantom on the moving emulating system



(a) Points in 3D Image (b) Points in physical space

Fig. 8. Getting corresponding points for registration

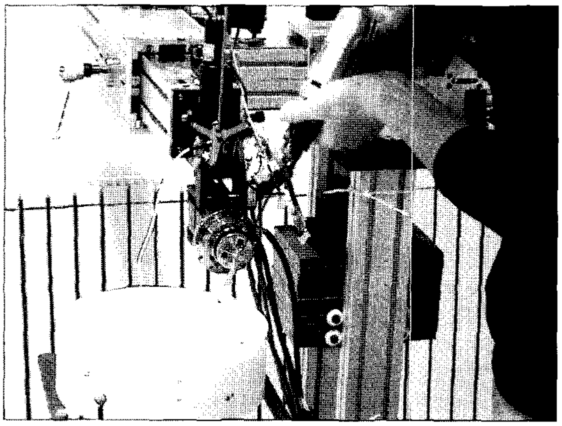


Fig. 9. A feature of manual drilling by human

After then, the robot automatically moves to the entry point and precisely is positioned along the preplanned surgical path determined by surgical planning system in preoperative operation. Up to this stage, two experiments take the same procedure. In the following steps, while the drilling operation is conducted manually by the surgeon in the first experiment, the same surgical intervention is done by the robot itself according to the preplanned data in the second experiment. Figure 9 and 10 describe a feature of the human drilling in the first experiment and drilling by SPINEBOT in the second one, respectively.

The experimental results can be summarized as follows. After the operation, we scanned the phantom again to validate the results. Then, the CT data are reconstructed as a 3D volume data and using this data, the path of the drilling tool are obtained as Figure 11 and 12. It is observed from these figures that the directions of the actual path are almost the same as the desired paths in all cases.

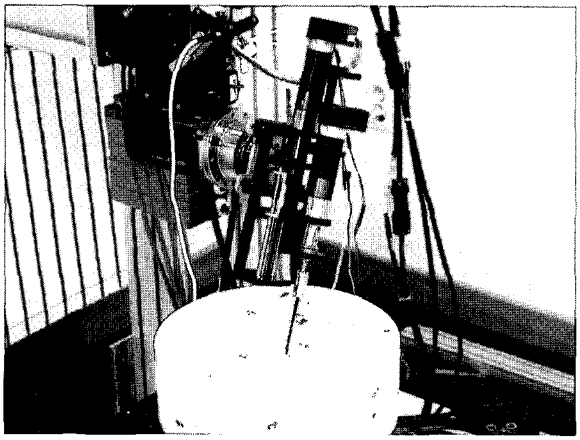
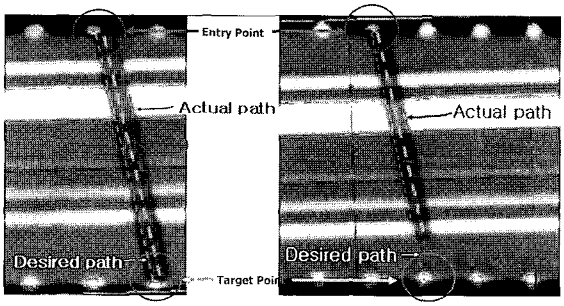
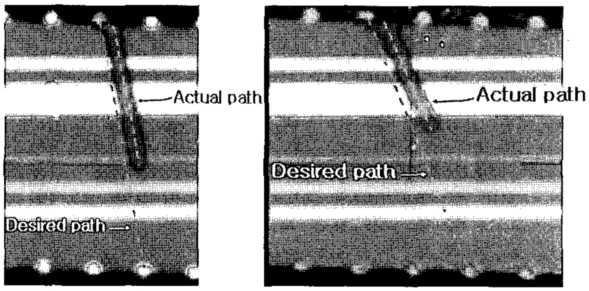


Fig. 10. feature of direct drilling by SPINEBOT



(a) Result #1 (b) Result #2

Fig. 11. Experimental result : the path of drilling by human

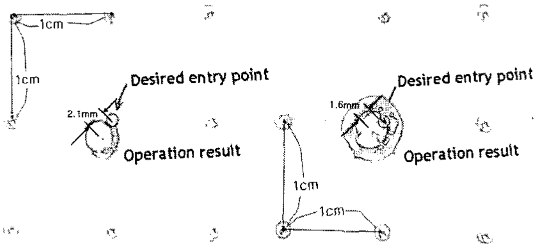


(a)Result#1 (b) Result #2

Fig. 12. Experimental result : the path of drilling by SPINEBOT

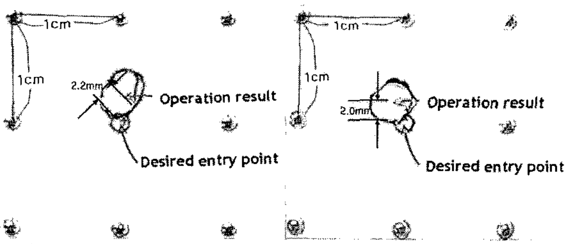
Figure 13 and 14 show the deviation of the entry point by the human drilling and the SPINEBOT drilling, respectively. There are about 1~2mm difference between the desired entry point and the bored holes. This deviation may come from the registration error, the tracking system error, and the robotic manufacturing error, etc. However, in our experiment, it is believed the significant amount of the deviation errors comes from the optical tracking system (OTS). Actually, by separate experiments of the performance of the OTS, the accuracy of the OTS to the moving objects was measured about 1mm. Thus, we believe that if the OTS is replaced with the high-quality system, the deviation error could be reduced. Also, most of other problems related to deviations could be resolved by employing more accurate system components and better calibration methods along with repeated work flows of previous experiments.

Note, particularly, that as shown in the experimental results in Fig. 13 and Fig. 14, the deviation in drilling by human is smaller than that by the robot. Actually, in drilling, some slips and bending of the drill tool could occur at the initial contact point of the drill on the object. If it happens, the human is able to sense such circumstances and immediately provide a remedy action for such deviations by his own decision. However, our robot is not yet equipped with such advanced high-tech sensory systems and intelligence to provide such actions equivalent to the human. This explains why the operation by the robot has more deviation than the one by the human.



(a) Result #1 (b) Result #2

Fig. 13. Entry point deviation in drilling by human



(a) Result #1 (b) Result #2

Fig. 14. Entry point deviation in drilling by SPINEBOT

CONCLUSIONS

In this paper, an Image-Guided SPINEBOT system for spinal fusion is integrated and tested. Two different experiments for the system are conducted: a task by only guiding and the other task by automatic drilling. In the first experiment, the Image-guide SPINBOT system successively provided the surgeon with useful information by guiding him to the target position and orientation for drilling. Also, in the second experiment, the system accomplished a successful drilling task in an automatic mode. But, a significant deviation error was observed in the experiments. The deviation error comes mostly from one specific inaccurate sensory system component, optical tracking system. Replacement by a more accurate OTS along with employment of better calibration methods for the system components would reduce the deviation error and lead to successful implementation of the computer integrated surgical robot system for spinal fusion. If then, it could successively assist the surgeon by providing a guide and perform drilling and screwing sub-tasks in the real spinal surgery.

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