

An Image-Guided Robotic Surgery System for Spinal Fusion

Goo Bong Chung, Sungmin Kim, Soo Gang Lee, Byung-Ju Yi*, Wheekuk Kim, Se Min Oh, Young Soo Kim, Byung Rok So, Jong Il Park, and Seong Hoon Oh

Abstract: The goal of this work is to develop and test a robot-assisted surgery system for spinal fusion. The system is composed of a robot, a surgical planning system, and a navigation system. It plays the role of assisting surgeons for inserting a pedicle screw in the spinal fusion procedure. Compared to conventional methods for spinal fusion, the proposed surgical procedure ensures minimum invasion and better accuracy by using robot and image information. The robot plays the role of positioning and guiding needles, drills, and other surgical instruments or conducts automatic boring and screwing. Pre-operative CT images intra-operative fluoroscopic images are integrated to provide the surgeon with information for surgical planning. Some experiments employing the developed robotic surgery system are conducted. The experimental results confirm that the system is not only able to guide the surgical tools by accurately pointing and orienting the specified location, but also successfully compensate the movement of the patient due to respiration.

Keywords: Image-guided surgery, robot-assisted surgery system, spinal fusion, surgical robot.

1. INTRODUCTION

In most surgery for spinal fusion, the physician directly performs the surgical operation with help of conventional surgical tools along with off-line CT images and possibly with fluoroscopic images that provide the on-line status of current surgical operation for patient. However, the surgical procedure generally

requires accurate operational skills and intuition of the physician. Sometimes, trifling errors or misjudgments during surgical operation could result in unrecoverable damages to patients. Furthermore, in open surgery, the patient needs long recovery time and suffers from significant pain due to the surgical wound. Thus, it becomes necessary to develop a useful system that reduces the operational time and the wound area, simplifies complicated surgical operations, and enhances the positioning accuracy of the surgical tools. To realize these needs, various methods have been proposed for spinal fusion [1-11]. However, there are few practical cases associated with computer-integrated surgery (CIS) systems for spinal fusion [5,6]. CIS systems consist of surgical robots, surgical planning system, navigation system, and so on. Thus, close collaboration among diverse technical areas is strongly required, and understanding the clinical needs and surgical procedures is also important.

In this paper, therefore, we introduce a new CIS system for spinal fusion. This pilot study would clarify most of the current problems that make the spinal fusion difficult. The problems of conventional and image-guided spinal fusion will be discussed in Section 2. In Section 3, architecture and roles of the system components are described. In Section 4, preliminary experiments are conducted to confirm the feasibility of the proposed surgical system. In Section 5, two different experiments are carried out. The first one deals with boring a hole on a phantom by a surgeon through a guide held by a robot. The second one is the direct boring by a robot. In both cases, the

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desired position of a robot is determined by the planning system and instructed by the navigation system. Section 6 draws conclusions.

2. REVIEW OF SPINAL FUSION

2.1. Current procedures for spinal fusion

Fig. 1 shows the conceptual method of spinal fusion surgery. As shown in the figure, fusion is a surgical technique in which one or more of the vertebrae of the spine are fixed by connecting fixtures and rods together to restrict relative motions between them [12,13].

The spinal surgical procedure performed by surgeons without any help of robotic systems can be summarized as follows. In the preoperative stage, CT or MRI images around the surgical area of the patient are scanned and analyzed. Then, a proper surgical plan is established on the images. The area of the surgical operation is sterilized and dissected first in the intra-operative procedure. The surgeon bores guide holes in the vertebrae and inserts screws through them into the vertebrae. In these processes, the surgeon has to monitor fluoroscopic images to make sure that the instruments are on the pre-planned or the desired position. Once all screws required are inserted into the targeted pedicles, those screws are fixed together firmly with a connecting rod as shown in Fig. 1. Lastly, the wound is closed and sutured.

2.2. Problems

Most of the difficult tasks of the spinal fusion are on the process related to inserting screws. Generally, the average diameter of lumbar pedicles is slightly bigger than 6mm and the other pedicles are a little smaller than that [11,14]. Pedicle screws sized to occupy 70% of pedicle diameter are normally used in the spinal fusion. Therefore, the surgeon should carefully insert a screw while paying his maximum attention to the fluoroscopic images available in the surgical operation because there is a small margin of error. Even a slight deviation from the center of the pedicle might cause breakage of a portion of edges of the pedicle into pieces. And the spinal nerve might be damaged, which causes catastrophic results to patient. Also, in the conventional fusion operation, the use of intra-operative fluoroscopy for the placement of pedicle screws has resulted in prolonged fluoro time

and radiation exposure to the surgeon and the patient. The X-ray exposure time to the patient as well as to the surgeon is 0.33 minutes per a screw, which is enormous [15].

The percentage of misplaced pedicle screws that have more than 2mm deviation, is reported 3~55 % in the conventional method [9,10,16-18]. The main reason for incorrect placement of a pedicle screw is probably because of the invisible body of the pedicle being penetrated in the intra-operative operation. On this account, a number of recent papers on image-guided surgery employing navigation systems discussed on the methods to reduce the number of misplaced screws and the exposure to radiation [5,8-10,18]. Actually, accuracy of the operation is improved to some extent by using the image information. However, there still exists high possibility that unintentional deviations due to tremor or slipping may occur during operations since the surgeon must conduct boring and screwing manually. Besides, the surgeon has to monitor the instrument position displayed on the monitor of the navigation systems while she/he conducts the process. This could cause mistakes of the surgeon because she/he cannot fully concentrates on the operating area.

Some tools and robotic systems have been developed to reduce these unintentional deviations by guiding the instruments and to improve accuracy by targeting the desired position [1,3-7]. In addition, various kinds of experiments such as changing the entry point or the transverse angle of pedicle screws were conducted [10,17,18]. In this paper, we introduce a new surgical system employing the robotic system that assists the surgeon by targeting the desired position to insert screws and that bores holes or screws by itself in the spinal fusion procedure. The system can be instrumental in improving accuracy and reducing the X-ray exposure time and unintentional deviation error.

3. AN IMAGE-GUIDED ROBOTIC SYSTEM FOR SPINAL FUSION

As shown in Fig. 2, the constructed robot-assisted surgery system consists of a surgical planning system, a surgical robot, and an optical tracking system. In the preoperative and intra-operative procedures, the optical tracking system and the surgical planning system play the role of a navigation system. All sub systems share and transfer data through Ethernet.

To align the coordinates of the system components, the optical tracking system is used to obtain the positions of the components in the real world. Using the pre-obtained images of the surgical area, the surgeon determines a desired operational path of the screw on the surgical planning system. The optical tracking system detects the movement of the surgical

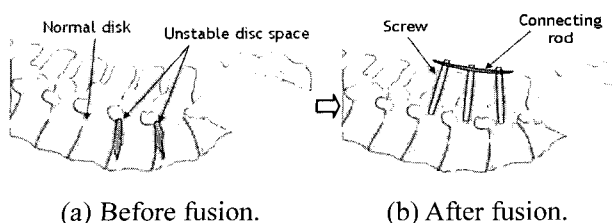


Fig. 1. A method of the spinal fusion surgery.

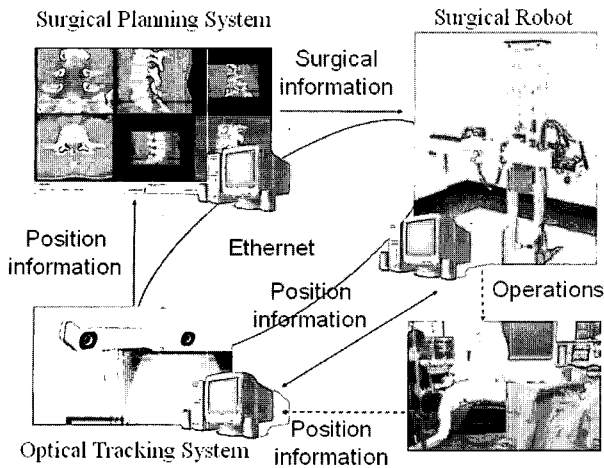


Fig. 2. A Robot-assisted surgery system.

area by tracking the position of a probe attached to the surgical area. Both information of the operational path and the movement of the surgical area are transferred to the robot and then the robot conducts the operation while compensating the movement of the surgical area.

In spinal fusion, the system plays the role of assisting surgeon at several stages. The first and simplest role of the system is to guide surgical tools to perform the screw insertion operation by the surgeon easily. The second role is to perform a task of boring a guide hole in the lumbar. The third role is to conduct a task of inserting screws into the vertebra automatically.

3.1. Surgical planning system: HexaView Planning System

The surgeon can not see the surgical area precisely just by looking at the lateral view by a fluoroscopy and the Anterior-Posterior (AP) view by opening the back of the patient when the pedicle screw is inserted into a lumbar. As mentioned before, the information of the angle to insert screw should be provided. In our robot-assisted surgery system, therefore, surgical

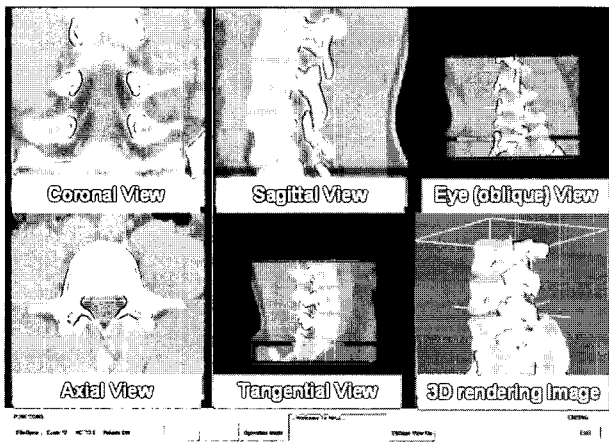


Fig. 3. A surgical planning system: HexaView planning system.

planning system called HexaView Planning System is also integrated to provide surgeons with six different views of surgical area as shown in Fig. 3.

To improve the accuracy of pedicle screw placement, three-dimensional information composed of the coronal view image, the sagittal view image, and the axial view image is very useful. In HexaView Planning system, we can achieve this three-dimensional information from the 3D volume rendering image that is reconstructed by stacking the 2D slices of the surgical area, which is obtained by pre-operative CT scanning. Furthermore, we can get the eye view image and the tangential view image from the 3D volume rendering image, too. The eye view image shows the direction of the operational path of the screw and the tangential view image includes the path. Therefore, these two views help surgeons to make surgical planning more easily since they directly show how the screw is inserted.

The coordinates of these six images are matched with those of the real patient's anatomy by using the optical tracking system. Then, a surgeon determines the correct positions of the pedicle screws in the preoperative surgical planning. After designing the surgical path, an entry point and a target point are selected. These position data of points are transferred to the robot.

Also, the planning system could have some functions to monitor the positions of surgical instruments in the intra-operative procedures as a part of a navigation system and to calibrate the operation results in postoperative procedure.

3.2. Optical tracking system

The robot-assisted surgery system consists of an optical tracking system (OTS) for detecting the positions and movements of the robot's end-effector and the surgical area. The optical tracking system, 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 control of the surgical robot. To realize these functions, the HexaView system and a robot system are linked to the optical tracking system via Ethernet.

In our robot-assisted surgery system, the first role of the optical tracking system is to align various

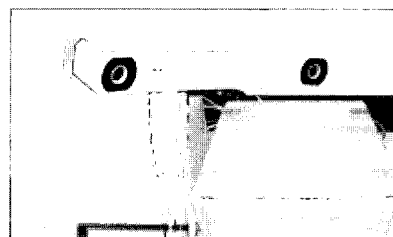


Fig. 4. The optical tracking system.

coordinates of systems. The coordinates of the optical tracking system is used as the base coordinates in the real world. We obtain the position of the selected fiducial marker on the image displayed in the surgical planning system with respect to the image coordinates, and measure the position of the corresponding point of it in the real world by using the OTS. Repeating selection and measure, we get nine point pairs and, using this point sets, the transformation between the coordinates of the image and those of the real patient's body, i.e. the OTS coordinates, is obtained by applying a least-square method to 3D point sets [21-22]. Similar to this process, we transform the robot coordinate into the coordinate of the OTS. We attach a probe of the OTS at the end of 3-DOF xyz positioning system of SPINEBOT. Thus, we can obtain the end position of SPINEBOT from the forward kinematic information of the robot and the detected position of the probe with respect to the coordinates of the robot and the OTS, respectively. Accordingly, the robot knows where a point indicated on the surgical planning system is in the real world, and vice versa.

During surgical procedures, the optical tracking system continuously detects the movement of the patient's body and transfers the data back to the robot 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 surgery system, the movement of the robot could be measured simultaneously both by the optical tracking system and by the built-in encoders. These redundant measurements of the surgical tool could be employed in order to increase safety level of the robot.

3.3. SPINEBOT

We developed a surgical robot, called SPINEBOT, which is designed to perform a drilling task into the lumbar of the human body, consists of a Cartesian type 3-DOF XYZ positioner, a 2-DOF gimbals and a 2-DOF drilling tool shown in Fig. 5, 6, and 7, respectively. The 3-DOF positioner and the gimbals provide the global translational motion and the 2-DOF

rotational motion to orient the drill tool, respectively. The gimbal is designed to exert the large force. As shown in Fig. 6, the first axis of the gimbal is designed with a 4-bar linkage having a linear ball-screw joint for a pitch motion and a harmonic drive is employed at the second joint for a roll motion. The 2-DOF drilling tool is designed suitable for feeding and

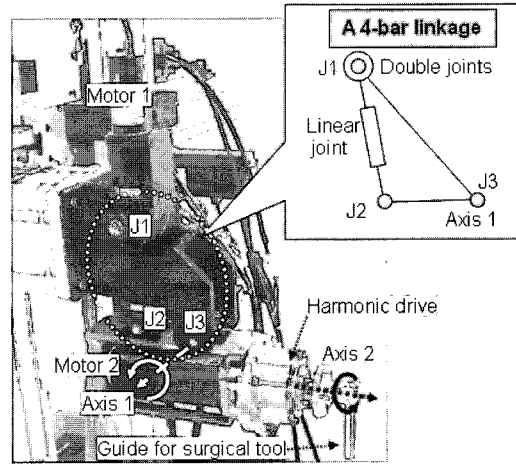


Fig. 6. The 2-DOF gimbal.

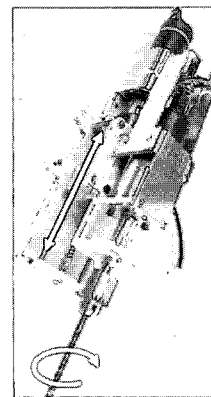


Fig. 7. The 2-DOF drill tool.

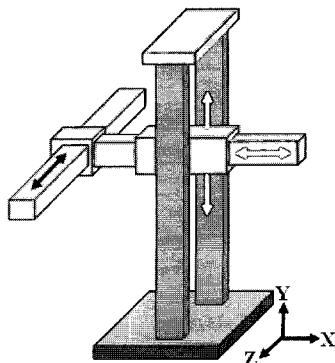


Fig. 5. The structure of the 3-DOF positioner.

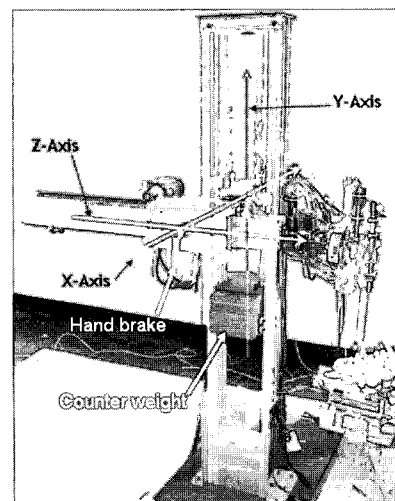


Fig. 8. Surgical robot system: SPINEBOT.

drilling into lumbar.

Fig. 8 shows the prototype of the implemented SPINEBOT. As can be seen in the figure, the gravity load along the vertical direction is compensated by connecting a counter weight to the sliding device through wires. And a hand brake is installed to the SPINEBOT. It can be used either to stop the motion of SPINEBOT manually in case of emergency or to lock the robot at a suitable position for operation by the surgeon. SPINEBOT is able to operate either in passive mode or in active mode, depending on its roles in surgical operation as mentioned above. More specifically, in a passive mode it firmly holds a guide pinpointing a surgical location for spinal operation so that the surgeon could perform surgical operation much comfortably. In an active mode, it can directly bore a hole on a lumbar and insert a screw through the lumbar automatically. Further, it could be used to perform much more complicate operation in spinal surgery as well as compensating the movement of a patient.

At first, to perform the surgical intervention, the coordinate of SPINEBOT is aligned to that of the navigation system. After the SPINEBOT receives the entry and target points for the pedicle screw insertion task from the planning system, it moves along the planned path up to the entry point. And then SPINEBOT holds the guide to bore a hole through it, or drills a hole into the vertebra directly along the determined path without any intervention of a surgeon, and simultaneously compensates the movement of the surgical area, which is detected and transferred by optical tracking system to the robot.

4. PRELIMINARY EXPERIMENTS

In this Section, two experiments are conducted. One is to test that the SPINEBOT is able to position and orient a guide holder sufficiently close to the targeted position and the orientation when the targeted surgical area is in motion. This experiment is to confirm whether the SPINEBOT can successfully play the first role discussed in Section 3. The other is to measure interaction forces and torques felt at end-effector of the SPINEBOT when it performs either boring task or screwing task while tracking the motion of the surgical area. Through the data analysis collected from this second experiment, the applicability of the SPINEBOT can be examined.

4.1. Compensation of the target movements

During actual spinal operation, the surgical area is continuously moving due to both the patient's respiration and external screwing forces by the surgeon. Fig. 9 shows a probe attached to the spinal process of the patient. The OTS detects the movement of the spinal process by tracking the probe. Fig. 10

shows the actual respiratory movement of the patient measured by the OTS. It is shown that the maximum amplitude of the periodical respiratory movement along the Y-axis is around 3 mm. In Fig. 10, the X, Y, and Z-axis is the lateral, AP, and axial direction of the patient lying in a bed, respectively. This movement of the patient's lumbar due to his/her respiration is not negligible and needs to be compensated by some means, in order to perform more accurate spine surgical operation successfully. Three different approaches could possibly be considered as compensation methods for the patient's movements in surgical operation and the movements may not be necessarily due to the respiration of the patient. The

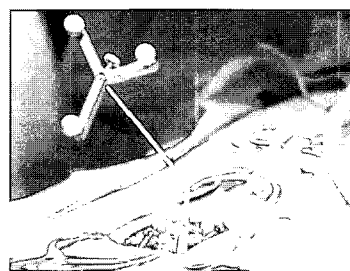


Fig. 9. A probe attached to the spinal process of the patient.

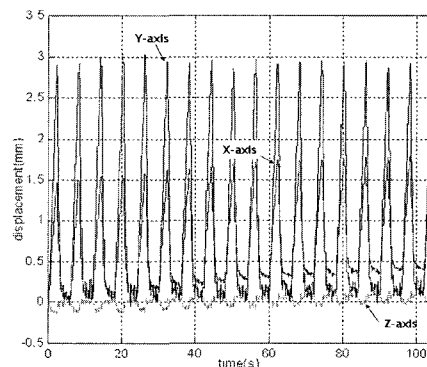


Fig. 10. Actual respiratory movement of the patient measured by OTS.

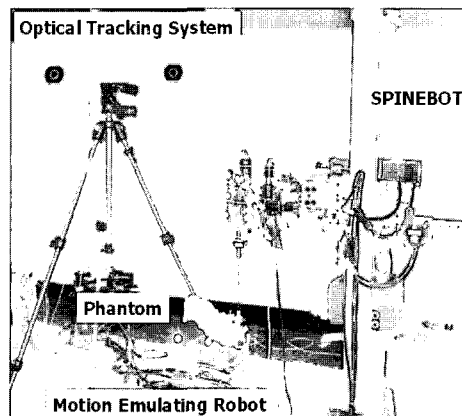


Fig. 11. Experimental setup for respiratory movement compensation.

first method is that the robot compensates the movement by directly following the respiratory movement of the human body, the second one is that

the surgical bone is fixed firmly to some type of fixtures, and the third one is that the surgical robot is attached to the surgical bones [1]. As the third approach, Shoham et al. [1] suggested a bone mounted spine surgical robot. However, it is only effective for strong lumbar. In this work, the first approach will be taken into account.

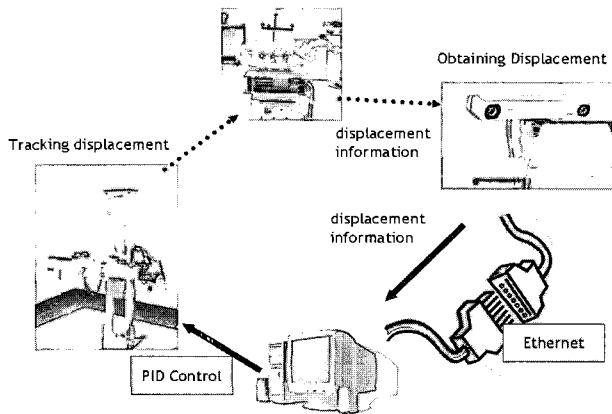


Fig. 12. Signal flow diagram of the whole system.

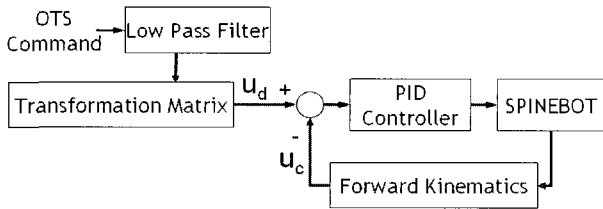


Fig. 13. Control block diagram for the mockup experiment.

Fig. 11 shows the mockup setup for respiratory movement compensation experiment. In the mockup experiment, the respiratory motion emulating a human respiratory movement is generated by using a robot named, Motion Emulating Robot (MER). To locate the exact surgical position, the OTS measures the movement of MER continuously by tracking a probe attached on MER. The measured data is feedback to SPINEBOT and SPINEBOT is commanded to track the target position on MER. Another probe is attached to SPINEBOT to obtain the transformation between the OTS coordinates and the robot coordinates as mentioned in Subsection 3.2. Fig. 12 shows the signal flow diagram of the whole system employed in mockup experiment and the control block diagram is described in Fig. 13. The signal output from the OTS is directly sent to the SPINEBOT controller via Ethernet and low-pass filtered as shown in Fig. 13.

Fig. 14 shows the tracking errors of SPINEBOT that tracks the motion of MER, which is given a sinusoidal function with the amplitude of 2 mm and the period of 5 seconds. Fig. 15 shows the errors

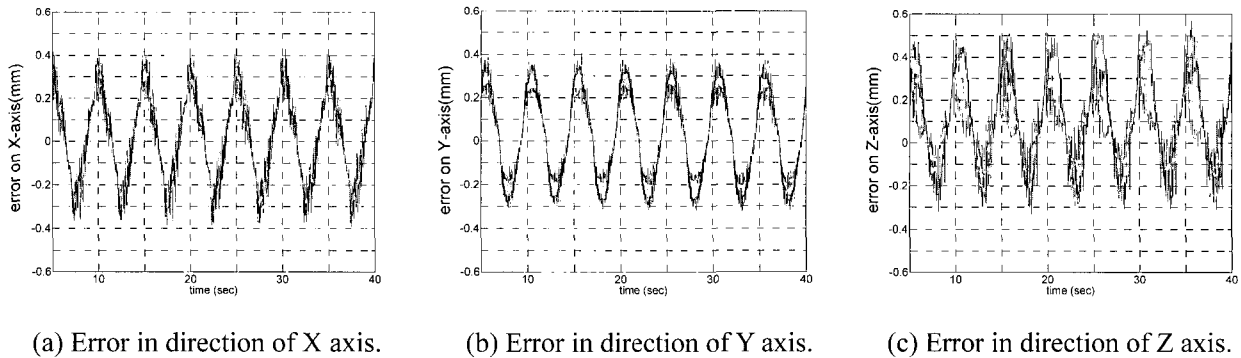


Fig. 14. Errors between the motion of MER and tracking motion of SPINEBOT.

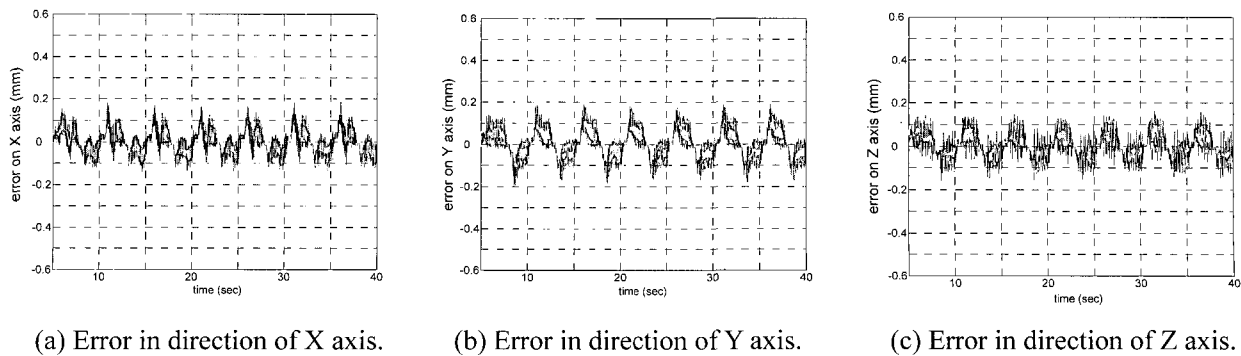


Fig. 15. Errors between the movements measured by OTS and tracking results of SPINEBOT.

between the commanded input (measured data of the MER motion by the OTS) sent to SPINEBOT and the tracking output by the SPINEBOT, which is measured by encoders of SPINEBOT. The maximum deviation error in the experiment is about 0.45 mm as shown in Fig. 14. It can be seen from Fig. 15 that SPINEBOT follows the command input from OTS very closely with the error bound of about 0.15mm. Thus, it can be easily seen that a relatively large portion of these deviation errors comes from the OTS. In fact, the OTS employed in the experiment provides the measured data output only at maximum 30 Hz and its accuracy is around 0.35mm 3D RMS [19]. With these experimental observations, it can be contended that SPINEBOT is sufficient to conduct respiratory compensation for the patient in spinal surgical operation. To enhance tracking accuracy further, we plan to replace the current OTS by a more advanced OTS in near future.

4.2. Measurement of the interaction forces

Additionally, while tracking the target position, SPINEBOT is commanded to insert a K-wire into a hole on MER using a drill tool attached to the end of SPINEBOT. Particularly, during insertion, the interaction force between the K-wire and the hole of MER is being measured to examine some undesirable effects caused by position error between SPINEBOT and MER. The interaction force represents a similar

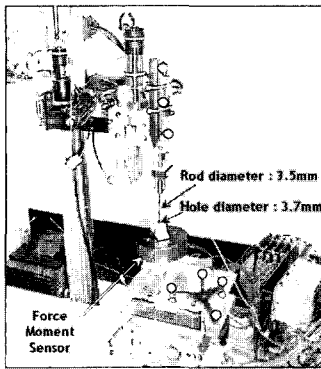


Fig. 16. Force measurement in the feeding.

reaction force when the surgeon would experience during actual operations. Fig. 16 shows an experimental setup to mimic the intervention of SPINEBOT in actual surgical operations such as boring a hole or inserting a screw into the lumbar. SPINEBOT is commanded to insert a rod of 3.5 mm in diameter into a 3.7 mm hole in diameter on the surface of the MER while following the movement of MER that is commanded to move along a sinusoidal trajectory with the amplitude of 1.5 mm and the period of about 6.5 seconds.

Fig. 17 shows the measured interaction forces. Intervals A and E represent the states that the rod and the hole are separated. Interval B and D represents insertion state of the rod into the hole and extraction state of the rod from the hole, respectively. Interval C represents the state that the rod is inside the hole. In interval C, MER moves back and forth two and half times. As shown in Fig. 17, the magnitude of the measured interaction forces turns out to be relatively small. Particularly, noting that the allowable range of motion accuracy required in spinal operation is about 1~2mm in most cases, it can be assured that the developed SPINEBOT system in the current mockup experiment would be able to successfully perform the designated roles in spinal operation, without seriously degrading the performance of most spinal procedures. However, in some higher levels of interventions of the SPINEBOT, which may require a very precise positional accuracy, these force feedback data can be used effectively to compensate for the position error or unwanted interaction force by employing a certain type of admittance control law.

5. EXPERIMENTS

The role of surgical robotic systems has been argued whether it is adequate for assisting surgeons or replacing surgeons. 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 in the spinal fusion procedure.

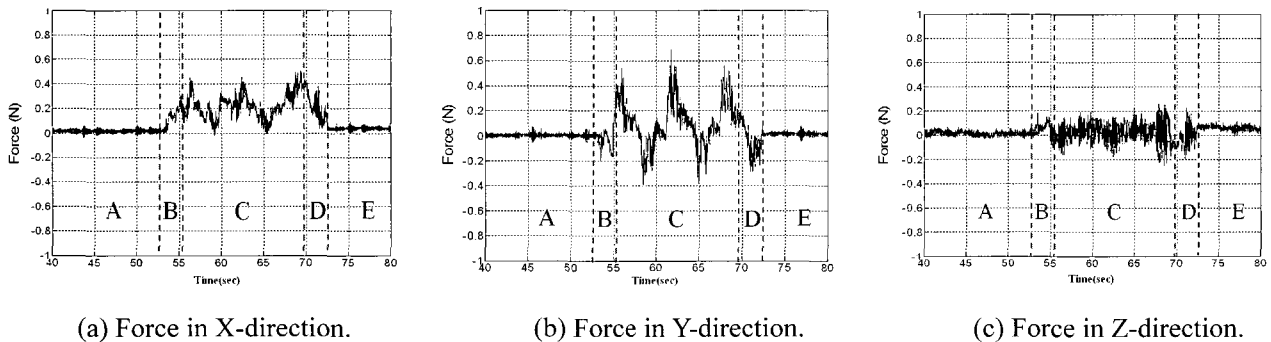


Fig. 17. The measured interaction forces.

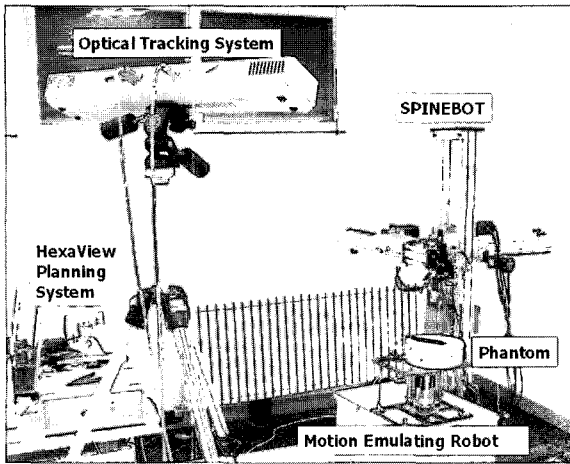
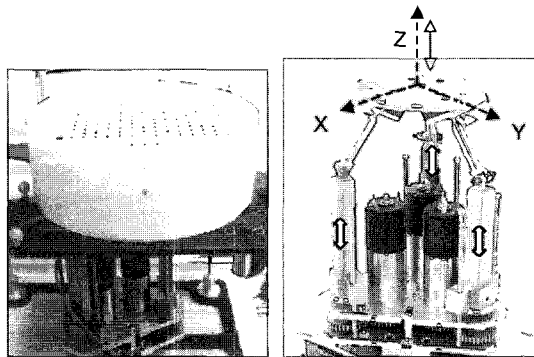


Fig. 18. Experimental setup of the robot-assisted surgical system.



(a) Phantom. (b) The 3-DOF MER.

Fig. 19. The phantom and the 3-DOF motion emulating robot.

Our task is boring a hole to insert a screw in both automatic and manual ways. In the first experiment, the surgeon performs a drilling operation manually, but the robot plays the role that guides the drill at the desired point while compensating the movement of the surgical area. 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 capability of the autonomous surgical robot system.

Fig. 18 shows the experimental setup for these experiments. For the two experiments, we use a phantom that serves as a real surgical area. This phantom is laid on a 3-DOF parallel robot as shown in Fig. 19(a), which is designed to emulate the movement of the real surgical area due to the human respiration and an applied external force. The motion emulating robot can generate the translational motion in the z direction, roll, and pitch as shown in the Fig. 19(b). The structure of the robot is proposed in our previous work [20].

The experiment is conducted as shown in Fig. 20. First of all, the phantom is Scanned by a CT imaging

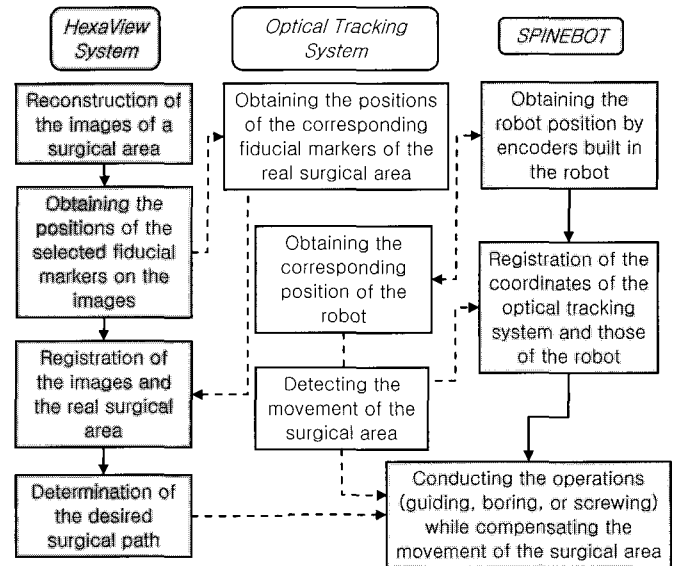
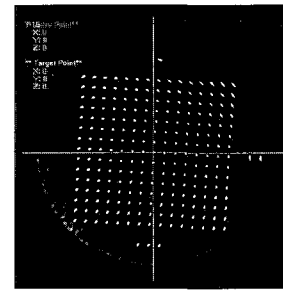
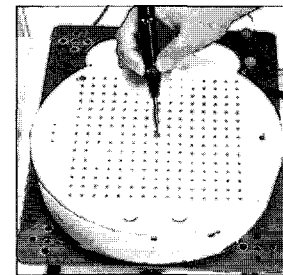


Fig. 20. Sequence for experimental procedures.



(a) Getting the position of the selected fiducial marker on the reconstructed image.



(b) Getting the position of the corresponding fiducial marker on the real phantom.

Fig. 21. Registration of the real phantom and the reconstructed image.

device, and the obtained image data are reconstructed in the surgical planning system. Then a registration procedure to match the image data to the physical phantom is processed as mentioned in Subsection 3.2. Fig. 21(a) shows getting the position of the selected fiducial marker in the reconstructed image and Fig. 21(b) describes that the position of the corresponding fiducial marker in the real world is measured by using a pointing device of the optical tracking system.

Repeating these processes and applying the least-square method [21,22], we get the transformation between the coordinates of the real phantom and those of the image. We attach a probe of the optical tracking system at the end of 3-DOF xyz positioning system of SPINEBOT. Thus, similar to the process mentioned above, we can calculate the transformation between the optical tracking system and SPINEBOT from the forward kinematic information of the robot and the detected position of the probe. Then, SPINEBOT receives the entry point and a surgical path from the surgical planning system.

After then, the robot automatically moves to the entry point of the drill and is positioned precisely along the preplanned surgical path determined by the surgical planning system. Up to this stage, two experiments take the same procedures. In the following steps, the surgeon manually bores a hole through the guide tool held by the robot in the first experiment and SPINEBOT guides the drill to the desired position and path at the same time. In the second experiment, the same surgical intervention is done by SPINEBOT itself according to the desired path. In both experiments, SPINEBOT compensates the movement of the phantom while the boring operation is conducted.

In intra-operative stage, the control block diagram of the system is described in Fig. 22. Fig. 23 shows the first experiment; the human drilling through the guide tool. Fig. 24 shows the high-speed drill tool used for the second experiment; the robot directly

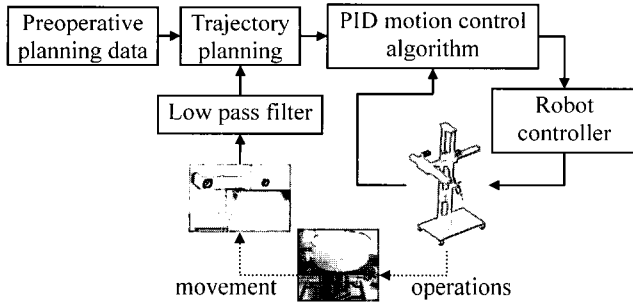


Fig. 22. The control block diagram.

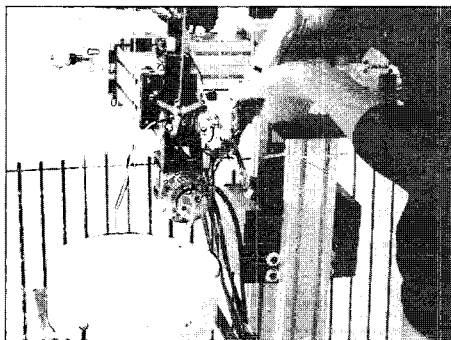


Fig. 23. The manual drilling by human.

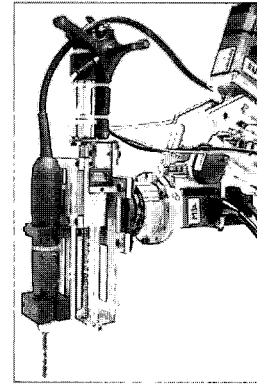
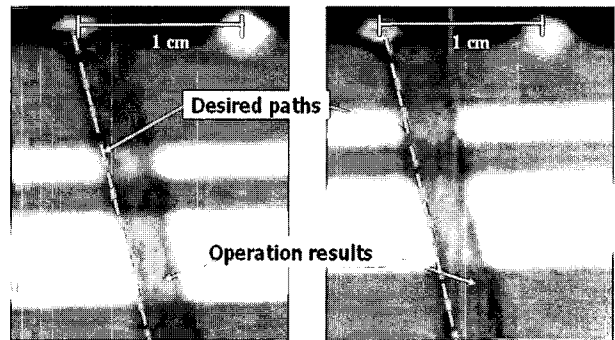


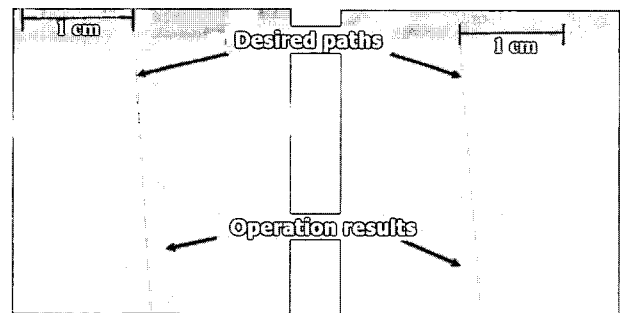
Fig. 24. The high-speed drill tool.



(a) Result #1.

(b) Result #2.

Fig. 25. Experimental results of drilling by human.



(a) Result #1.

(b) Result #2.

Fig. 26. Experimental results of drilling by the robot with high-speed drill.

bores a hole into the phantom. Actually, in drilling, some slips and bending of the drill tool could occur at the initial contact stage of the drill on the object. If it happens, the human is able to sense such behavior immediately and provides a remedy action for such deviations by his own decision. To overcome such slip and bending problem, we can consider the high-speed drill tool, a short and thick drill bit, and additional sensors such as a force/torque (F/T) sensor or vision sensor. Therefore, we employed a high-speed drill for the robotic drilling operation.

After the operation, we scanned the phantom again to validate the results. Then, the CT data are

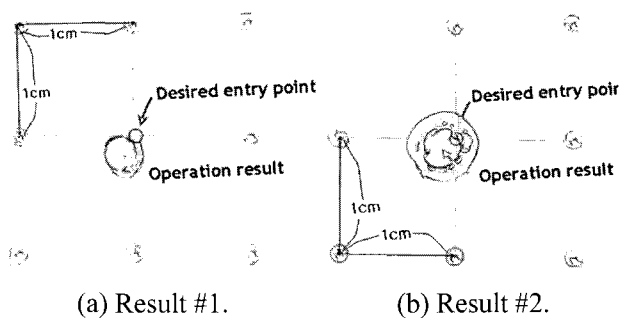


Fig. 27. Entry point deviation in drilling by human.

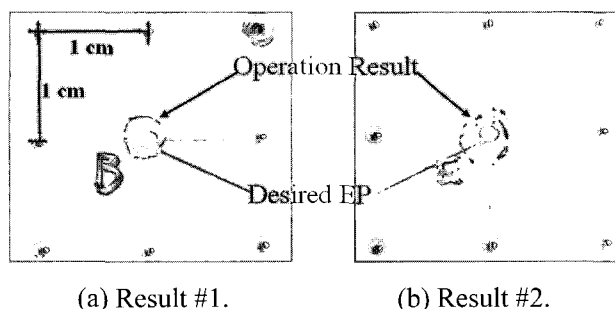


Fig. 28. Entry point deviation in drilling by SPINEBOT with high-speed drill.

reconstructed as a 3-D volume data, and using this data, the boring results are obtained as Figs. 25 and 26. It is observed from these figures that the directions of the operation results, which are wide black lines, are almost the same as the desired paths, which are dotted lines, in the two cases. But there are little offset between the desired paths and the operation results.

Figs. 27 and 28 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 centre of the bored hole, though the performance of robot is slightly better than the human performance. This deviation may come from the registration error, the tracking system error, and the manufacturing error of the robot, etc. One of causes is the limited precision of the OTS, which was used in the registration and tracking processes. Thus, the error larger than that of the tracking system itself may occur. We believe that if the OTS is replaced with the high-quality tracking system, the deviation error could be reduced. Better calibration methods with repeated experiments can reduce the error, too.

According to the experimental data, eventually, we conclude that the robot system is able to achieve more accurate performance than that of the human operation.

6. CONCLUSIONS

In this paper, a spine surgical robot, named as

SPINEBOT, is developed to assist surgeons in the spine surgical operation. Preliminary experiments have been conducted to see that the system is suitable for a real spinal surgery operation. It turns out from the experiments that SPINEBOT and its integrated system meet the desired specifications well for spinal operation.

After then, the developed robot has been employed to perform an image-guided robot surgery for spinal fusion. Two different experiments are conducted: a task of holding a surgical tool guider and a task of boring a hole into the phantom emulating a spinal surgical operation. In the first experiment, the system provided the surgeon with useful information successively by guiding him to the target position and orientation for boring. Also, in the second experiment, the system conducted an automatic boring task by the robot. From these experiments, we could arrive at the conclusion that the developed surgical robot system is able to guide the surgical instruments successfully and to bore a hole into the vertebra directly.

As the future work, cadaver experimentation for spinal fusion will be conducted before applying the system to actual spinal operation. As other ongoing effort, system integration with other sub-systems such as a haptic device is in progress. Safety issues and sterilization problems related to surgical operations are also under investigation.

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