Cooperative Robotic Assistant with Drill-By-Wire End-Effector for Spinal Fusion Surgery

Jongwon Lee*, Inwook Hwang**, Keehoon Kim***, Seungmoon Choi**, Wan Kyun Chung*, Young Soo Kim****

* Robotics Laboratory, Mechanical Engineering, POSTECH, Pohang, Korea
{samjong2, wkchung}@postech.ac.kr
** Haptics and Virtual Reality Laboratory, Computer Science and Engineering, POSTECH, Pohang, Korea
{inux, choism}@postech.ac.kr
*** Intelligent Mechanical Systems Laboratory, Mechanical Engineering, Northwestern University, USA
keehoon-kim@northwestern.edu
**** Center for Intelligent Surgery System, School of Medicine, Hanyang University, Korea
ksy8498@hanyang.ac.kr

Correspondance to: Seungmoon Choi

Abstract

- **Purpose:** This research is aimed at developing a surgical robot for spinal fusion and its control framework that provides higher operation accuracy, greater flexibility of robot position control, and improved ergonomics.
- **Design/Methodology/Approach:** A human-guided robot for the spinal fusion surgery has been developed with a dexterous end-effector that is capable of high-speed drilling for cortical layer gimleting and tele-operated insertion of screws into the vertebrae. The end-effector is position-controlled by a five degrees-of-freedom robot body that has a kinematically closed structure to withstand strong reaction force occurring in the
surgery. The robot also allows the surgeon to control cooperatively the position and orientation of the end-effector in order to provide maximum flexibility in exploiting his or her expertise. Also incorporated for improved safety is a “drill-by-wire” mechanism wherein a screw is tele-drilled by the surgeon in a mechanically decoupled master/slave system. Finally, a torque rendering algorithm that adds synthetic open-loop high-frequency components on feedback torque increases the realism of tele-drilling in the screw-by-wire mechanism.

**Findings:** Experimental results indicated that our assistive robot for spinal fusion performs drilling tasks within the static regulation errors less than 0.1 μm for position control and less than 0.05° for orientation control. The users of the tele-drilling reported subjectively that they experienced torque feedback similar to that of direct screw insertion.

**Research limitations/implications:** Although the robotic surgery system itself has been developed, integration with surgery planning and tracking systems is ongoing. Thus, the screw insertion accuracy of a whole surgery system with our assistive robot is to be investigated in the near future.

**Originality/value:** The originality of the present article lies in the dexterous end-effector appropriately designed for spinal fusion, the cooperative robot position-control algorithm, the screw-by-wire mechanism for indirect screw insertion, and the torque rendering algorithm for more realistic torque feedback. In particular, the system has the potential of circumventing the screw loosening problem, a common defect in the conventional surgeon-operated or robot-assisted spinal fusion surgery.

**Keywords:** Robot-assisted surgery, spinal fusion, cooperative manipulation, admittance control, torque feedback.

**Classifications:** Research paper.

1 **Introduction**

In the last few decades, robotic systems have been applied to a number of surgeries for many expected benefits such as higher operation precision, faster patient recovery, safer surgery environment, and improved ergonomics for a surgeon. In this article, we report an assistive robot named *Cooperative Robotic Assistant (CoRA)* for spinal fusion, an effective surgical
treatment for spine disc illnesses. The CoRA features with a specially designed small and light end-effector module, a rigid kinematically-closed six degree-of-freedom (DOF) robot that manipulates the end-effector under the cooperative control, a “drill-by-wire” capability using a mechanically decoupled master/slave drilling system for improving the safety of the operation and the control accuracy of the end effector, and a realistic torque-rendering algorithm for the tele-drilling.

1.1 Backgrounds on Spinal Fusion

Spinal fusion is a surgical technique used to combine two or more vertebrae (the individual bones that consist of the spinal column) and can effectively cure some critical spinal conditions that accompany serious pain, e.g., degenerative disc disease and spinal disc herniation (Kim et al., 2005). Figure 1 shows the fluoroscope images of two unstable vertebrae that were successfully “fused” through spinal fusion. The two vertebrae that would otherwise have caused severe pain to the patient are stabilized by virtue of the four screws inserted into the vertebrae and the metal rods that restrict relative motions between the screws. Spinal fusion also results in more favorable convalescence than other surgical treatments such as endoscope or microscope surgeries.

[Figure 1 about here]

A surgery for spinal fusion, however, requires extreme caution for the surgeon due to the complexity and delicacy of required operations. In its procedures, clinically relevant screws with the diameters of 3.5 mm (cervical), 5.0 mm (thoracic), and 6.5 mm (thoracolumbar) should be inserted into the pedicle of the vertebra that has only about 6 – 7 mm diameter, following a carefully preplanned path as precisely as possible. Rampersaud et al. (2001) showed that the desired accuracy for the spinal pedicle screw placement varies in 0.0 – 3.8 mm depending on the implant site. A failure of doing so may cause damage to the spinal cord, leading to a serious injury to the patient. In practice, the occurrence rate of inappropriate screw insertion reaches up to 10%, and the half of them leave critical injuries to the patient (Castro et al., 1996; Schulze et al., 1998).

Another issue, called the loosening problem, is related to how long the screws will stay stably in the bones after a surgery. During insertion, a manually drilled screw advances rather in a spiral fashion, exerting excessive force/torque on the surrounding bone tissues. Thus, a small gap may be resulted between the bone and the inserted screw and grow over a
prolonged period, often leading to the need of a reoperation to replace the original screws with larger ones. For instance, Pihlajamaki et al. (1997) investigated the cases regarding the complications and reoperations after posterolateral lumbosacral fusion with transpedicular screw-rod fixation for a non-traumatic disorder in 102 patients. Patients more than 17% encountered the loosening problem, and 78% of them had to have a reoperation.

1.2 Related Work

In order to improve the drawbacks of the present surgical techniques for spinal fusion, many robotic surgical systems have been developed, mostly focusing on complementing the surgeon’s limited capability of precisely controlling the insertion pose (position and orientation) of a screw during drilling. An early surgical robot system for spinal fusion by Santos-Munn et al. (1995) integrated the C-arm fluoroscope with the industrial PUMA-560 manipulator to guide screw insertion direction. The system, however, was somewhat inconvenient since the transverse and sagittal angles for screw insertion were determined before and during the operation, respectively, not in one step. Cleary et al. (2002) also developed an assistive robot for spinal fusion under the minimally invasive surgery (MIS) paradigm that can substantially reduce the trauma and recovery time of the patient. They integrated MRI, 3D model reconstruction, an optical tracking system, and a serial-type manipulator for guiding screw insertion. In particular, the use of mobile CT for intraoperative imaging, instead of the fluoroscope or ultrasound devices that are more frequently used, allowed easier and safer examination of screw insertion angles during the surgery.

Shoham et al. (2003) developed a parallel-type miniature bone-mounted robot (MARS) to position surgical tools accurately. In this system, a tracking system for compensating the patient’s movements (e.g., the respiratory motion) was not necessary since the guiding robot MARS was connected to a fixture (called Spinous Process Clamp) directly mounted on the patient’s spine. However, relatively large incision was required for that, prolonging the patient’s recovery time than MIS systems. To resolve the limitation, Mazor Surgical Technologies (Caesarea, Israel) developed an improved fixture, Hover-T Frame, through which the MARS can be mounted to the bony anatomy of the patient supporting the MIS scheme. The whole surgery system, named SpineAssist, was approved by FDA, and has been subsequently tested in clinical experiments by a few groups. For example, Lieberman et al. (2006) reported that, for lumbar spinal fusion in the cadaver using the SpineAssist, four screws were successfully implanted into the spine with average deviation less than 1.5 mm.
Sukovich et al. (2006) tested the SpineAssist in a clinical demonstration with 14 patients during six months, and reported that using the SpineAssist was fully or partially effective in 13 cases, and the 96% of screws were inserted within 1-mm accuracy. It was also pointed out that the registration incompleteness was mainly responsible for the operation failures. Barzilay et al. (2006) also performed clinical experiments with nine patients using the SpineAssist, and accomplished accurate screw insertion in six cases. Causes for the three failed cases were analyzed to be the registration error, excessive pressure on the guiding arm exerted by surrounding soft tissues, and/or the surgeon’s excessive force during screw insertion on the tool guide. Recently, Togawa et al. (2007) inserted K-wires, instead of actual screws, to precisely measure the deviation from the pre-operative plan to evaluate the system accuracy of the SpineAssist. They tested with 31 K-wires and four screws in 10 cadavers. 28 K-wires and four screws were inserted with less than 1.5-mm deviation. The rest were broken, bent, or misplaced by more than 4 mm, mostly caused by guide slipping.

Another research group developed a 5 DOF serial-type manipulator called SPINEBOT for the same purpose (screwing guidance) supporting the MIS scheme (Chung et al., 2004). The SPINEBOT is a robot grounded beside the operation bed and does not require any incisions except for those for screw insertion. This is advantageous to the patient compared to the Hover-T Frame in the SpineAssist that needs to be fastened on the patient’s vertebrae with one K-wire and two Steinmann pins. The SPINEBOT was integrated into a whole surgical system including a pre-operative planning system and an optical tracking system, and approved by KFDA (Chung et al., 2006). This surgical system used a surgical planning system (called HexaView) that provides the six different views of a surgical area based on the CT data to improve the accuracy of pedicle screw placement, and an optical tracking system (NDI Co. Ltd, Canada) that performs registration and tracks the patient’s motion with the accuracy less than 0.35mm. The reported accuracy of the whole system was bounded in 1 – 2 mm for screw insertion. Our research team has been collaborating with the SPINEBOT team to upgrade the capabilities of the SPINEBOT in several aspects, and the outcome, CoRA, is presented in this article.

The assistive robots used in all of these surgical systems concentrate on the precise guidance of screwing position and orientation for the surgeon. The pilot holes that need to be made on the cortical layer of the vertebrae before screw insertion are produced manually, using either a high-speed drill (in the SpineAssist only) or a hammer (in the other systems). Recently, efforts have arisen to endow the assistive robot with the capability of high-speed
drilling for making pilot holes for improved convenience of the surgery. Ortmaier et al. (2006) developed the Hand-On-Robot that had a high-speed drill as an end effector. The robot maintains an insertion pose so that the surgeon can complete the pilot drilling using the high-speed drill. However, no experimental results on the system performance were reported. In the system by Boschetti et al. (2005), the same task can be undertaken using a teleoperation system. The surgeon controls the pen-type master device to control the insertion pose of the high-speed drill on the slave slide. A contact force between the drill bit and the bone is fed back to the surgeon through teleoperation.

In all of the surgical systems introduced in this section, the assistive robots only guide the insertion path. Moreover, since the screws are manually inserted by the surgeon who may exert excessive force/torque, the robots may not be free from the loosening problem. In our CoRA, the screws are inserted by teleoperation using the drive-by-wire mechanism, which provides computer-controlled torque for screw insertion in the continuous manner with greater accuracy and repeatability.

1.3 Overview of Cooperative Robotic Assistant for Spinal Fusion

In general, the conventional surgery for spinal fusion proceeds in the following steps: 1) Preoperative planning using CT scan images, 2) Skin incision, 3) Dilation of an aperture using the K-wire and dilators, 4) Gimletting the cortical layer (the protective outer shell) of vertebrae with a hammer, 5) Insertion of screws into the vertebrae penetrating the sponge bone, 6) Interlocking the screws with connecting rods, and 7) Suturing the wound. The previous robotic systems for spinal fusion primarily contributed to increasing the accuracy of screw insertion (step 5) by providing a firmer fixture for screw alignment. In addition to this, the CoRA (its overall structure is depicted in Figure 2 and performance specifications are summarized in Table 1) provides extended capabilities for steps 4 and 5, such as:

- Robot-actuated cortical-layer gimletting and screw insertion: A small, lightweight, multifunctional end-effector controlled by the surgeon performs high-speed drilling (as an alternative to gimletting the cortical bone with a hammer) and screw insertion with haptic feedback. To our knowledge, no previously developed assistive robots for spinal fusion had such a dexterous end-effector. The excellent accuracy and repeatability of robotic drilling may mitigate the screw-loosening problem.

- Precise screw pose control: A kinematically closed, structurally stiff, 6-DOF robot precisely controls the end-effector to be fixed at an insertion position along a desired
orientation. The robot can be controlled either autonomously by a preoperative surgery planner or manually by the surgeon under the admittance control, thereby maximizing the flexibility of end-effector positioning. The closed kinematic-loop structure can accommodate very high reaction force and torque as large as 1200 N and 3.2 Nm, respectively, observed in a spinal fusion surgery (Kim et al., 2007).

- **“Drill-by-wire” with realistic torque feedback:** In the end-effector of the CoRA, a master handle rotated by the surgeon controls a mechanically decoupled slave drill that inserts screws on the vertebrae. This drill-by-wire mechanism (analogous to the drive-by-wire steering wheel in the automobile) is expected to alleviate the screw loosening problem by exerting well-controlled torque to the spine bone during drilling. It also allows additional safety features, e.g., by detecting anomalies in the surgeon’s drilling behavior and preventing their delivery to the slave drill. The haptic feeling of drilling that the surgeon would experience during direct screwing is also recreated at the master side by integrating a torque rendering algorithm designed using the sensation matching (Okamura and Cutkosky, 2001).

The rest of this article is organized as follows. To begin with, the design and functionality of the end-effector is described in details in Section 2. Section 3 presents the closed kinematic-loop 6-DOF robot that houses the end-effector and the patient, along with its dual-mode control schemes including the cooperative position control. The torque feedback method during the screwing process is elaborated in Section 4. The performance of the CoRA is evaluated in Section 5 through experiments, followed by discussions and conclusions in Sections 6 and 7, respectively.

## 2 End-Effector

The end-effector is responsible for high-precision gimleting and screw insertion under the surgeon’s supervision. Thus, the end-effector should be designed carefully to meet the specifications fulfilling spinal fusion. In addition, the compact design is required for the dexterous motion by the robot body of the CoRA. This section describes our approaches to solve the challenging design problems.
2.1 Design
The end-effector weighs 1.5 kg with the compact package of a master motor, a stroke motor, a tool-change motor, a main ball screw, a high-speed drill, four screws, and several connection adapters, in and beneath a cylindrical case with 50-mm radius and 300-mm height, as illustrated in Figure 3 (also see Table 1 for the further design specifications). The high-speed drilling (at 20,000 rpm) is in charge of the gimleting process wherein the stiff cortical bone is penetrated to make initial guiding holes for the subsequent screw insertion. In the conventional surgery, the surgeon uses a hammer for this process, which produces impulse force as high as 1200 N (Kim et al., 2007). Emulating the same with a robotic actuator is not only technically intimidating, but also hazardous to the surgery staff and the patient. We therefore employed a much safer option, that is, the high-speed drill mainly used for dental treatments.

[Figure 3 about here]

The high-speed drilling proceeds as follows. The surgeon grasps and turns the drilling handle on top of the end-effector. The drilling handle is connected to the master motor for torque feedback to the surgeon. The rotation angle detected by an optical encoder mounted on the master motor is used as an angle command to a PID controller that controls the stroke motor, constituting the drill-by-wire system. The stroke motor actuates the main ball screw that is coupled to the high-speed drill via the connection mechanism that will be explained in Section 2.2. As a consequence, the circular motion of the drilling handle grasped by the surgeon is converted to the normal stroke motion of the high-speed drill that is rotated at 20,000 rpm by its own motor. After making the pilot holes, the high-speed drill is detached from the main ball screw and retreated to the neutral position. This mechanism successfully replaces the traditional gimleting using a hammer, as will be demonstrated in Section 5.

The next step is to insert screws to the guiding holes. For this, the lower plate to which four screws are fastened is rotated by 72°, and the target screw is aligned and connected to the main ball screw, all automatically. This connection mechanism is fully explained in Section 2.2. Then, the surgeon rotates the drilling handle, and this is turned into a screw insertion along the longitudinal direction via the drill-by-wire system. When the screw insertion is completed, the screw is released from the main ball screw, and the lower plate is turned by another 72° to continue with the next screw. The automatic tool-changing function is one of the primary achievements that have enabled the compact and dexterous end-effector.
Note that the four screws are to be manually installed to the end-effector prior to the surgery.

2.2 Connection Mechanisms for Automatic Tool Changing

The end-effector incorporates two functions, including the high speed drilling and screw inserting. Both are powered by the stroke motor through the main ball screw. This compact design requires sophisticated connection mechanisms for automatic tool changing illustrated in Figure 4. First, in order to connect the main ball screw to the high-speed drill, we have designed a one-touch joining mechanism utilizing the elasticity of a metal C-clip (see Figure 4(a)). The diameter of the C-clip is slightly larger than the internal diameter of the adapter opening of the high-speed drill. It follows that the clip, once inserted, rests in the adaptor and strongly joins the main ball screw and high-speed drill. The connection force is as large as 18 N. For insertion, the two electromagnets and a shock absorber attached on the lower plate are activated and attract the main ball screw with the force of 45 N into the adapter. This easily overcomes the resisting force of the C-clip, leading to a reliable insertion mechanism. For detachment, the main ball screw is retreated, and the high-speed drill adapter becomes “stuck” in the lower plate owing to the asymmetric slants of the dent in the adapter and stays in the original position for a next use.

[Figure 4 about here]

The connection mechanism for screws is simpler. A different requirement from the high-speed drilling is that after screw insertion is completed, the screw must remain in a target vertebra. For this, we use the spiral connection mechanism shown in Figure 4(b). When the surgeon turns the drilling handle in the positive direction (clockwise) for screw insertion, the ball screw and the screw are joined together. The screw is soon separated from the lower plate and then inserted into the vertebra. After the insertion is completed, the surgeon rotates the drilling handle in the opposite direction (counter-clockwise), unfastening the main ball screw from the screw to leave it in the vertebra. Test results have consistently shown that the tool-changing is extremely reliable with our connection mechanisms (99% success rate).

3 Robot Body

The robot body of the CoRA controls the position and orientation of the end effector during high-speed drilling and screw insertion. Since the robot body must be able to stably withstand the strong reaction force during the surgery, we designed the robot body to be inherently stiff
in a kinematically closed structure. The CoRA also can be operated under an admittance-control scheme, so that cooperative manipulation is available with the surgeon's manual control of the end effector.

3.1 Design
As shown in Figure 5, the CoRA has a closed-loop structure with a six-DOF motion space including the stroke movement of the end effector. The robot body in Figure 5(a) is in charge of 5 DOFs, three for translations along $x$, $y$, and $z$ axes powered by the motors $T_x$, $T_y$, and $T_z$, and two for rotations around $x$ and $y$ axes powered by the motors $R_x$ and $R_y$. The end-effector provides the remaining one DOF for drilling. For the translational motions of the end effector, the rotary motions of common electromagnetic motors are converted into linear motions by ball screws and linear guides. Detailed performance specifications of the robot body can be found in Table 1. The workspace of the CoRA is $100 \times 100 \times 70$ mm$^3$, and large enough for the spinal fusion surgery that requires a free space of approximately $50 \times 50 \times 50$ mm$^3$. [Figure 5 about here]

3.2 Dual-Mode Position Control
In order to insert screws at preplanned configurations, two control schemes are introduced enhancing the accuracy and the robustness of the motion of the end effector. Basically, the CoRA has a built-in position controller based on the PID control. This controller is used to move the end-effector to a desired preplanned configuration. However, no matter how accurate and robust the position control is, some errors may occur in actual operations due to multiple reasons. They include static errors such as the registration and manufacturing errors and dynamic errors such as those induced by the strong reaction force between the vertebrae and the tools and by the patient’s respiration. An effective remedy for this problem is the cooperative manipulation framework where a robot position is controlled by external force exerted by the operator (Taylor et al., 1999).

The CoRA provides the cooperative control mode in which the surgeon can translate and rotate the end-effector by manipulating the linear handle on top of the end-effector with his hand (see Figure 6). In this mode, the surgeon may compensate any errors that can be encountered during a surgery based on his experiences and judgments. For this capability, a 6-DOF force/torque sensor (ATI automation; model Nano 17) is installed between the handle
and the upper plate of the end-effector. The force applied by the surgeon is converted to a position command that moves the end-effector via the admittance control algorithm shown in Figure 7. In the figure, $F_h$ represents the surgeon’s force command detected by the force sensor. $F'_h$ is the low-pass filtered force command that removes the surgeon’s hand tremor from $F_h$. Then, $F'_h$ is used as an input to the virtual mass-damper model. The output of the model is the desired pose of the end effector, $p_{ds}$. $p_e$ is the actual pose of the end effector. $p_s$ is the mechanical admittance of the robot body, $Z_h$ is the impedance of the surgeon, and $K_s$ is a control gain. The parameters of a virtual mass-damper model were manually tuned, and chosen to be conservative values to guarantee the system stability during operations.

3.3 Position Control Performance
Dynamic tracking errors were measured for each joint of the CoRA in the PID control mode to evaluate tracking performance. An example is provided in Figure 8. Given a sinusoidal input trajectory shown in Figure 8(a), the measured tracking errors in the three translation joints are shown in Figure 8(b). Similar data for the two revolute joints are given in Figure 8(c) and Figure 8(d), respectively. Through extensive testing, we confirmed that the dynamic tracking errors are less than 0.1 mm for translation and 1.0° for rotation. Static regulation errors of each joint were measured to be less than 0.5 μm for translation and 0.05° for rotation. Assuming manufacturing error in 10-μm order, the static regulation error of the CoRA can be better rather than those of the assistive robots used in the commercialized surgery system (SPINEBOT or SpineAssist, as described in Section 1.2; The accuracy of the robot in the SpineAssist is about 100 μm). Therefore, we can conclude that the control performance of the CoRA is sufficient to be used in robotic spinal fusion surgery.

Note that the cooperative control mode is mainly to allow the surgeon to transfer the end-effector by holding and moving it with the hand to a desired pose. During high-speed drilling or screw insertion, the end-effector is controlled by the PID control.

4 Torque Feedback for Drill-By-Wire
As explained earlier, the CoRA has the drill-by-wire capability to insert screws into the
vertebrae. A surgeon rotates the master drill mounted on the end-effector (see Figure 6), and then the position of the master drill is used to control the rotation angle of a screw. In this system, the surgeon’s undesired or abnormal behaviors may be detected and prevented during screw insertion. A drawback, however, is also present, especially the lack of haptic sensations (e.g., apparent friction between the vertebra and a screw) that would have existed with direct drilling. Since such haptic information suggests the status of drilling (e.g., insertion depth) to the surgeon, it is desirable for the drill-by-wire system to provide the information. This would allow the surgeon to make decisions and actions based on the same haptic sensations available in the conventional spinal fusion surgery. For this purpose, we included in the CoRA a torque rendering algorithm for realistic torque feedback during drilling the screws.

For the study of torque rendering algorithms, we constructed a 1-DOF teleoperation system (see Figure 9) that consists of a master handle and a slave screw with a rotary shaft torque sensor (Sensor Developments Inc.; model 01324-012). The slave screw can be actuated with either a direct handle (for direct drilling) or a slave motor (for tele-drilling). Figure 10 shows torque signals measured with the slave system during direct drilling using the pig vertebra that is known to have the most similar characteristics to the human vertebra (McLain et al., 2002). In a typical torque signal, smooth torque components such as one in Figure 10(a) are irregularly interwoven with “crisp” high-frequency torque components such as one shown in Figure 10(b). The abrupt torque changes in Figure 10(b) are likely to be caused by the uneven density of the sponge bone.

Our torque feedback algorithm is based on the amount of current that flows to the stroke motor of the end-effector (represented by the slave motor in the 1-D teleoperation system in Figure 9). Since this current is proportional to the load of the motor and can be easily monitored from the motor amplifier, we rely on this signal to determine feedback torque for the master motor. The computational details and its performance of the monitoring current method can be found in our previous work (Kim et al., 2007). An alternative is to use an additional torque sensor at the stroke motor, but it is costly and gives rise to complicated design issues such as cabling around the rotating main ball screw.

A downside of using the slave motor current is that the method fails to carry the crisp and realistic haptic sensations to the operator at the master side due to the limited accuracy and bandwidth of the current monitoring circuit. In order to revive the realism, we add a synthetic
open-loop torque-shaping signal that resembles the sawtooth function (see Figure 11) such that:

\[
\tau_{\text{add}}(t) = b \cdot \tau_{\text{slave}}(t) \tan \left( \omega \left( \frac{\pi}{4} - \theta(t) \mod \frac{\pi}{2} \right) \right),
\]

where \( \tau_{\text{slave}}(t) \) is the torque converted the monitoring current at the slave side, \( \tau_{\text{add}}(t) \) is the synthetic torque to be added to \( \tau_{\text{slave}}(t) \) for torque feedback at the master motor, \( \theta(t) \) is the master motor angle, and \( b \) and \( \omega \) are the amplitude and frequency of torque ripples to be created by the addition of \( \tau_{\text{add}}(t) \). This function was chosen among many other tested candidates (e.g., the sinusoidal function, because it is simple and well matches with the feeling of direct bone screwing that contains the high-frequency crisp sensation. The parameters of the shaping function were determined by the sensation matching (Okamura et al., 2001).

[Figure 11 about here]

This torque-feedback algorithm is further illustrated in Figure 12 where \( \tau_h \) represents the surgeon-exerted torque and \( F_e \) the external friction force between the bone and the screw. \( \theta_{\text{des}} \) and \( \theta_e \) are the desired and actual angles of the stroke motor in the end-effector, respectively. The dynamics of the master and stroke motors in the end-effector are denoted by \( P_m \) and \( P_s \), respectively. Note that we let the additional friction torque increase with the measured torque because real friction force grows with the insertion depth of a screw, and that the torque shaping function is not used during high-speed drilling.

[Figure 12 about here]

The values of \( b \) and \( \omega \) were determined using the sensation matching such that the most similar sensations to that of direct drilling are resulted from the parameter values. \( b = 0.03 \) and \( \omega = 100 \) are used to compute \( \tau_{\text{add}}(t) \) in our system. Figure 13 provides the motor currents fed back to the master motor when the torque shaping function was not used (Figure 13(a)) and was used (Figure 13(b)). Apparently, the shaping function added more spiky current components that would create the sensation of more irregular friction. Note that the motor current shown in Figure 13(b) is mechanically filtered through the master motor dynamics, resulting in torques similar to that shown in Figure 10(b). The power spectrums of the currents in Figure 13 are also shown in Figure 14 and indicate that the torque shaping function slightly increased the signal power in 20 – 40 Hz.

[Figure 13 about here]

[Figure 14 about here]
5 Performance Evaluation

In this section, we demonstrate the accurate and robust performance of the CoRA in two experiments, one for the high-speed drilling and the other for the whole screw insertion process.

5.1 Accuracy of High-Speed Drilling

The acryl and engineering plastic specimens were used for this experiment. Note that engineering plastic is stiffer than the cortical bone, representing a more difficult condition for high-speed drilling. For the experiment, the bottom of the specimen was tightly fastened on the holder surface in the CoRA. We then marked drilling points on the specimen, which allows us to measure the performance of the robot only, without any errors originated from a registration system. A human operator was instructed to control the position and orientation of the end-effector considering the marked insertion points and the target direction (= 60°; in real spinal fusion, the insertion angle of a screw is about 60° from the horizon.) using the cooperative manipulation scheme and to make a hole using the high-speed drill. The drilled specimen was CT-scanned with the bottom side of the specimen firmly fixed to the surface in order to minimize the setting difference between drilling and measurement.

Experimental results are shown in Figure 15. The left images are the bird’s-eye views taken with a camera, and the right images are CT-scanned images showing the cross-sections of pilot holes made with the CoRA. From the figure, we can observe that the high-speed drilling worked out successfully with the two materials; the guiding holes were accurately drilled at the preplanned positions with the desired 60° orientation (see the orange triangles of the right images).

[Figure 15 about here]

5.2 Screw Insertion into the Pig Vertebrae

In this experiment, screws were inserted using the CoRA into the pig vertebrae. The experimental procedure was: 1) A human operator controls the pose of the end effector to a desired pose under the cooperative control mode. 2) The main ball screw is connected to the high speed drill under the automatic tool changing procedure. 3) The operator turns the drilling handle until the high speed drill perforates the cortical bone to the predefined
penetration depth. 4) The high speed drill is retreated for the next use. 5) The tool changing motor rotates the lower plate of the end effector by 72°. 6) The main ball screw is connected to the aligned screw. 7) The operator rotates the drilling handle to insert the screw into the vertebra via the screw-by-wire system while perceiving the realistic torque feedback. 8) The screw is detached from the end-effector by the opposite direction rotation of the drilling handle. 9) Steps 1 to 8 are repeated for other screws. Other details about experiment setups were the same to those for the high-speed drilling.

Figure 16 illustrates step-by-step experimental results performed on the pig vertebra. It can be confirmed from the pictures that the high-speed drilling and the screw insertion were successfully completed. A CT scan image in Figure 17 shows that the actual screw insertion angle (70°; see the orange triangle) matched to the planned angle that was 70° as well. We also confirmed the excellent accuracy of the CoRA in repeated experiments.

6 Discussion

The CoRA is a cooperative surgical robot for spinal fusion with several distinctive features compared to the existing robots introduced in Section 1.2. First, the CoRA has the end-effector that supports both high-speed drilling for pilot holes and robot-actuated screw insertion, alongside the autonomous tool-changing mechanism. Although there have been attempts to install high-speed drills as an end-effector (Ortmaier et al., 2006; Boschetti et al., 2005), they were capable of high-speed drilling only. No end-effectors prior to our end-effector have had both functions. Second, the end-effector supports the paradigm of drill-by-wire, especially for screw insertion. To our knowledge, all of the previous surgical systems had the surgeon manually insert screws. This can produce excessive force and torque during screw insertion which can be a source of clinical failure as pointed out by Barzilay et al. (2006). The excellent controllability and repeatability of robotic drilling bear high potential for alleviating the loosening problem. Third, the CoRA’s body is designed in the kinematically closed structure to guarantee the sufficient structural stiffness against the payload during the operation. The payload of the CoRA is more than 300 N that is sufficiently high to withstand large reaction forces (= about 150 N) occurring during screw insertion. The payloads of the existing surgical robots such as SPINBOT, Hand-On-Robot,
and RIME are considerably smaller than that of the CoRA since they were designed for either high-speed drilling or surgeon-performed screw insertion, and cannot support robotic screw insertion. The high controlled stiffness of the CoRA also helps the precise pose regulation of the end-effector. Fourth, the admittance control framework of the CoRA can be an effective solution, especially when other system errors such as the registration and manufacturing errors disturb the operation accuracy. The cooperative mode of the CoRA allows the surgeon to control the preplanned insertion pose based on his expertise and experience to cope with the system errors. Finally, the CoRA also has an advanced realistic torque rendering algorithm for the drill-by-wire insertion of screws. Although RIME can transfer primitive haptic information about the contact between the drill tip and the patient vertebrae (Boschetti et al., 2005), this was for high-speed drilling only. Our torque rendering algorithm also works for the screw insertion based on the limited sensing information from the monitoring current, without any additional sensors. The impaired feedback realism is compensated by adding the open-loop high-frequency torque components.

At present, we are collaborating with the SPINEBOT research team at Hanyang University, Korea to integrate the CoRA with their pre-operative planning, intra-operative planning, and vision tracking systems. Assuming that all other conditions are the same, the only difference between the SPINEBOT system (Chung et al., 2006) and our new integrated surgery system will be the robot used in each system. Therefore, we expect that the final screw insertion accuracy of the new surgery system will be the same to or better than that of the SPINEBOT system (1 – 2 mm; Chung et al., 2006), considering that the CoRA has better position control accuracy.

7 Conclusions

Spinal fusion is a very effective surgical treatment that can cure a number of spine illnesses, and includes the procedures of drilling and screwing at which a robot can outperform the surgeon in terms of accuracy and repeatability. In this article, we have described a 6-DOF cooperative surgical robot for spinal fusion that enables intimate cooperation between the robot and the surgeon. The CoRA has a number of useful functionalities; its hardware is composed of the dexterous end-effector with the screw-by-wire capability and the rigid robot body, and its software supports the hybrid position control with realistic torque feedback. The high accuracy of the CoRA for screw insertion has been experimentally confirmed,
demonstrating great plausibility for decreasing the occurrence rates of undesirable clinical
results (e.g., imprecise screw insertion and loosened screws over time) for spinal fusion
surgeries when the CoRA is successfully integrated into the whole surgical system.

Acknowledgments
This study was supported by a grant of the Korea Health 21 R&D Project, Ministry of Health
& Welfare (A020603), by the IT R&D program of MIC/IITA (2005-S-033-02, Embedded
Component Technology and Standardization for URC) and by the Korea Science and
Engineering Foundation (KOSEF) grants funded by the Korea government (MOST) (No.
R0A-2003-000-10308-0 and No. R01-2006-000-10808-0), all in Republic of Korea.

References
guidance for spine surgery – introduction of a novel system and analysis of challenges
encountered during the clinical development phase at two spine centres," International
Boschetti, G., Rosati, G. and Rossi, A. (2005), "A haptic system for robotic assisted spine
surgery," Proceedings of the IEEE Conference on Control Applications, Toronto, Canada,
1320-4.
International Conference on Intelligent Robots and Systems, Sendai, Japan, September
"Technology improvements for image-guided and minimally invasive spine procedures,"


### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fluoroscopic images of two vertebrae fused by spinal fusion.</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Overall structure of the CoRA.</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>End-effector of the CoRA.</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Tool connection mechanisms used in the CoRA end-effector.</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Body structure of the CoRA.</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Enlarged upper part of the end-effector.</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Block diagram for the admittance control.</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Results of an experiment that measured position tracking errors.</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>One-DOF tele-drilling system used as a test bed for the screw-by-wire.</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Torque signals measured during direct drilling.</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>Shaping function used for realistic torque rendering.</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Block diagram for realistic torque feedback in the CoRA.</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Feedback current to the master motor.</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>Power spectrum of the feedback currents in Figure 13.</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>Experimental results of high-speed drilling using the CoRA. Left images are bird’s eye views taken with a camera, and right ones are CT-scanned images showing the cross-sections.</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>Experimental results of screw insertion into the pig spine vertebra using the CoRA.</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>CT scan image of a screw inserted into the pig vertebra using the CoRA. The insertion angle (see the orange triangle) is 70°, exactly matching the plan.</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 1. Fluoroscopic images of two vertebrae fused by spinal fusion.
Figure 2. Overall structure of the CoRA.
Figure 3. End-effector of the CoRA.
Figure 4. Tool connection mechanisms used in the CoRA end-effector. 

(a) Between the main ball-screw and the high-speed drill.

(b) Between the main ball-screw and a screw.
Figure 5. Body structure of the CoRA.
Figure 6. Enlarged upper part of the end-effector.

- **Force sensor, ATI Nano-17**
- **Controllable drill, Maxon RE25**
- **Master motor, Maxon RE35, 90 watt, 4.3:1**
Figure 7. Block diagram for the admittance control.
Figure 8. Results of an experiment that measured position tracking errors.
Figure 9. One-DOF tele-drilling system used as a test bed for the screw-by-wire.
Figure 10. Torque signals measured during direct drilling.

(a) Torque signal that results in smooth sensation.
(b) Torque signal that results in “crisp” sensation.
Figure 11. Shaping function used for realistic torque rendering.
Figure 12. Block diagram for realistic torque feedback in the CoRA.
(a) Without the additional torque shaping function.

(b) With the additional torque shaping function.

Figure 13. Feedback current to the master motor.
Figure 14. Power spectrum of the feedback currents in Figure 13.
(a) Acryl, hole 1.  (b) Acryl, hole 2.  
(c) Engineering plastic, hole 1.  (d) Engineering plastic, hole 2.

Figure 15. Experimental results of high-speed drilling using the CoRA. Left images are bird’s eye views taken with a camera, and right ones are CT-scanned images showing the cross-sections.
Figure 16. Experimental results of screw insertion into the pig spine vertebra using the CoRA.
Figure 17. CT scan image of a screw inserted into the pig vertebra using the CoRA. The insertion angle (see the orange triangle) is 70°, exactly matching the plan.
List of Tables

Table 1. Specifications of the CoRA. 39
<table>
<thead>
<tr>
<th>Table 1. Specifications of the CoRA.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Robot Base – Translation</strong></td>
</tr>
<tr>
<td>DOFs</td>
</tr>
<tr>
<td>Work volume</td>
</tr>
<tr>
<td>Motor</td>
</tr>
<tr>
<td>Maximum continuous torque</td>
</tr>
<tr>
<td>Maximum speed</td>
</tr>
<tr>
<td>Position sensing resolution</td>
</tr>
<tr>
<td><strong>Robot Base – Rotation</strong></td>
</tr>
<tr>
<td>DOFs</td>
</tr>
<tr>
<td>Motor</td>
</tr>
<tr>
<td>Maximum continuous torque</td>
</tr>
<tr>
<td>Maximum speed</td>
</tr>
<tr>
<td>Orientation sensing resolution</td>
</tr>
<tr>
<td><strong>End-Effector</strong></td>
</tr>
<tr>
<td>DOFs</td>
</tr>
<tr>
<td>Equipped surgical tools</td>
</tr>
<tr>
<td>Stroke motor</td>
</tr>
<tr>
<td>Maximum continuous torque</td>
</tr>
<tr>
<td>Tool-changing motor</td>
</tr>
<tr>
<td>Maximum continuous torque</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td><strong>System</strong></td>
</tr>
<tr>
<td>Control sampling rate</td>
</tr>
<tr>
<td>Data I/O card</td>
</tr>
<tr>
<td>Motor servo amplifies</td>
</tr>
<tr>
<td>Encoders</td>
</tr>
<tr>
<td>Operating Environment</td>
</tr>
</tbody>
</table>