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Human-Guided Surgical Robot System for Spinal Fusion Surgery: CoRASS

Jongwon Lee, Keehoon Kim, Wan Kyun Chung, Seungmoon Choi and Young Soo Kim

Abstract— **There are two main limitations in the conventional robot-assisted spinal fusion surgery. Since the end effector in the state of art has a role of guiding the insertion pose of a screw only, i) convenience that can be obtained when the robot intervenes in the surgery more actively could be limited. ii) The insertion pose of a screw provided by the robots could be deteriorated by surgeon's resisting force since he should insert a screw with his own hand withstanding the large reaction force transmitted through the drilling handle. To overcome those limitations, this paper proposes a novel approach for spinal fusion, wherein the robot performs the spinal fusion using the equipped end effector following surgeon's guide. We developed a dexterous small-sized the end effector that can perform previous gimleting and screwing tasks into the vertebrae. A five-DOF robot body that has kinematically-closed structure guides the insertion pose of a screw and resists strong reaction force firmly during the screwing process. Based on admittance control framework, the surgeon controls the pose of the end effector precisely to compensate induced static/dynamic errors during the operation. A torque feedback method without torque sensor that suggests the haptic information about the status of drilling is also included. The performance of the CoRASS was verified by experiments.**

I. INTRODUCTION

The herniated disc occurs when the disc is damaged by sudden strain on the back or degeneration from aging. When the disc is damaged, the center of the disc squeezes out through a weak point in the fibrous out-layer. Since this bulge often presses on nerves, the patient feels the back pain or sciatica [1]. The spinal fusion surgery is one of the treatments that requires extreme caution among various treatments of disc illness. However, in many cases, it was demonstrated that convalescence after spinal fusion is most favorable when we compared it with that of other surgical treatments such as endoscope surgery or microscope surgery, once the operation is successfully performed.

Fig.1 shows fluoroscopic images of two unstable vertebrae that were successfully "fused" after spinal fusion. Screws are inserted into the vertebrae, and fixed together by connecting rods. It can restrict relative motions between two vertebrae, so, the pain can be cured. The procedures of conventional surgeon-operated spinal fusion follows 1) preoperative planning using MRI and/or CT scan images, 2) skin incision, 3) dilation of an aperture using K-wire and dilators 4) gimleting the cortical layer (protective outer shell) with a hammer, 5) insertion of screws into the vertebrae, 6) interlocking using connecting rods and 7) suturing the wound.

In this procedure, the main difficulty is the surgeon's limited manipulation capability needed to maintain the accurate insertion pose of screws. Surgeons should insert a screw with the diameter of 3 or 4mm into the pedicle of the vertebra that has the diameter of 6mm. If the surgeon fails to control the insertion direction of a screw by mistake, the screw can touch the spinal cord. It can cause serious injuries to the patient. In the real operation, screw misplacement occurs in the ratio of 10%. And half of them affects as critical injuries to patients [2] [3].

In order to improve the limitations of the present spinal fusion surgery, many robotic surgical systems have been developed. A focus has been on complementing surgeon's limited capabilities of precisely controlling the insertion pose of a screw with the robot manipulator. Santos-Munn et al. introduced a surgeon helper robot that integrated the C-arm fluoroscope with the industrial PUMA-560 manipulator, wherein the robot guides the insertion pose of a screw during spinal fusion [4]. However, it is somewhat inconvenient to surgeons since determination of insertion angles (transverse angle and sagittal angle) are divided in pre-operative and intra-operative step, individually. Cleary et al. also developed guiding-assist robot based on minimally invasive surgery (MIS) paradigm. They integrated MRI, a 3-D reconstruction algorithm, an optical tracking system and a serial-type manipulator to guide the insertion pose of a screw during screwing [5]. Since they used the mobile CT as an intra-operative imaging device instead of fluoroscope, the intra-operative planning that determines the insertion angles can be done more accurately and conveniently. Shoham et al. devel-

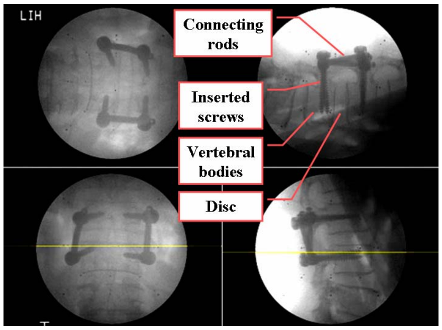

Fig. 1. Fluoroscopic images of two vertebrae fused by spinal fusion.

Jongwon Lee and Wan Kyun Chung are with the Robotics Laboratory at POSTECH, KOREA {samjong2, wkchung}@postech.ac.kr

Keehoon Kim is with the Laboratory for Intelligent Mechanical Systems, Northwestern Univ., USA keehoon-kim@northwestern.edu

Seoungmoon Choi is with the Haptics and Virtual Reality Laboratory at POSTECH, KOREA choism@postech.ac.kr

Young Soo Kim is with the Center for Intelligent Surgery System, School of Medicine, Hanyang University, KOREA ksy8498 @hanyang.ac.kr

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oped a parallel-type miniature bone mounted robot (MARS) to accurately position surgical tools [6] [7]. Since the robot is mounted on the patient's vertebrae, a tracking system for compensating patient's movement (e.g., respiratory motions) is not necessary. However, due to relatively large incision, the patient's recovery time is longer than that of the MIS system. Chung et al. also developed a serial-type manipulator (SPINEBOT) for the same purpose [8] [9]. Since it supports MIS scheme, the trauma and recovery time to the patient could be reduced. In conclusion, these robotic systems have common characteristics that they are surgeon helper robots to provide the desired insertion pose of a screw to a surgeon, so, they can suggest a solution to rectify the predefined difficulty of the conventional surgeon-operated spinal fusion surgery.

However, there are two main limitations in the conventional robot-assisted spinal fusion surgery. 1) Convenience that can be obtained when the robot intervenes in the surgery more actively could be limited since the end effector in the state of art for spinal fusion has a role of guiding the insertion pose of a screw only. 2) Since conventional robot systems provide a fixture only for guiding the desired pose of a screw, the surgeon himself should insert the screw into the bone with his own hand withstanding the large reaction force transmitted through the drilling handle. In this procedure, the insertion direction of a screw provided by the robot could be deteriorated by surgeon's resisting force during screwing, resulting in small gap between the bone and the inserted screw. As time goes, this gap extends, so, re-operation is needed to replace the screw with the larger ones.

These two limitations can be solved when the robot intervenes in the surgery more actively. If screw insertion can be performed by the end effector of the robot, surgeon's laborious screwing that leads to inaccurate operation results does not be required anymore. Moreover, we can always make the insertion pose of a screw provided by the robot identical to that of the preplanned path since the surgeon does not need to apply the resisting force to the robot.

Then, to use the end effector that can perform the spinal fusion surgery, what should be considered? First, the robot should be able to move the pose of the end effector precisely withstanding large reaction force/torque occurring in the surgery. The force and torque needed to complete gimleting and screwing tasks in spinal fusion are about 1200N and 3.2Nm, respectively in [10]. Since these values are about one hundred times larger than those of cardiac operation, if a surgeon performs the spinal fusion with the robot that has kinematically-open structure (e.g., da Vinci by Institutive Surgical or SPINEBOT by Hanyang Univ.), the system cannot bear the gimleting force and insertion torque. Second, the mechanisms to compensate induced static/dynamic errors during the operation should be considered. If the robot system cannot compensate such errors (e.g., the registration and manufacturing errors and deviations of the actual pose induced by the strong reaction force between the vertebrae and the tools), the end effector might insert a screw with the wrong pose. Third, a master/slave drilling system and a torque feedback algorithm for screwing should be incorporated. Since screw insertion is a very delicate and cautious procedure, the screwing task performed by the end effector should be progressed under the surgeon's supervision. By using the master/slave drilling system, surgeon's expertise can be exploited during screwing. To suggest the status of a screw to the surgeon, a torque feedback method is also required.

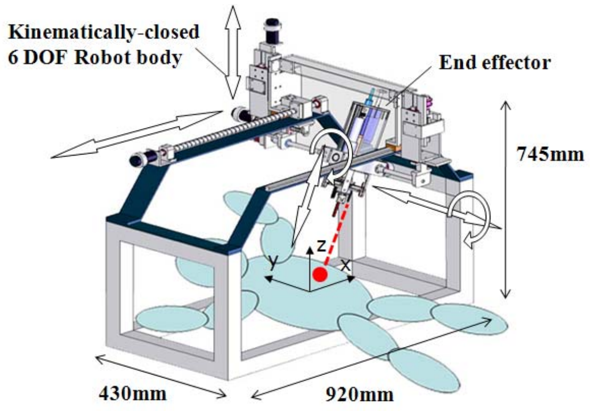


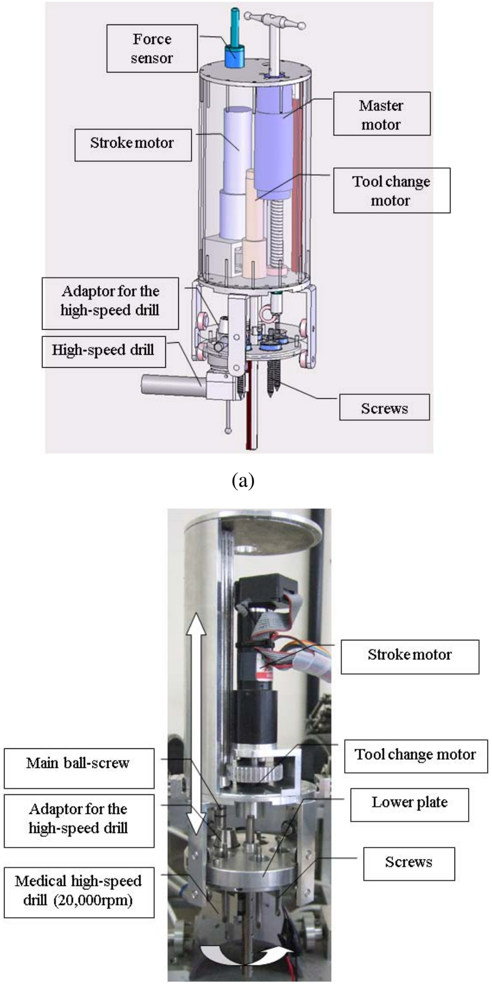
Fig. 2. Overall structure of the CoRASS.

In this paper, to accomplish the goals, we proposed a cooperative robot-assisted surgery system (CoRASS) for spinal fusion as shown in Fig.2. As implied in its name, the CoRASS is the surgical robot, featuring with a dexterous small-sized end effector that can perform previous gimleting and screwing tasks with greater accuracy, a rigid six-DOF robot that has kinematically-closed structure specialized to spinal fusion, cooperative manipulation framework that augments surgeon's judgment and sensory integration into the operation for compensating the mentioned errors, mechanically decoupled master/slave drilling system in the end effector for improved safety during screwing, and a torque feedback method for suggesting the status of a screw to the surgeon. Integrating CoRASS with a surgery navigation system is in progress. The characteristics and performance of the navigation system are described in [11].

This paper is organized as follows. The design and functionality of the end-effector is described in details in Section II. Section III presents five-DOF robot body that has kinematically-closed structure, along with the measurement of its dynamic tracking errors. The control schemes for the cooperative position control and the torque feedback method during the screwing process is elaborated in Section IV. The performance of the CoRASS is evaluated through experiments in Section V, followed by conclusions in Section VI.

II. END EFFECTOR OF CORASS

Since the capability of the robot depends on the function of the end effector, the end effector design is one of the most important considerations during the robot system development. The goal of the design is to make a dexterous end effector which can perform the conventional gimleting and



(a)

(b)

Fig. 3. Developed end effector : (a) CAD model of the design (b) Prototype of the end effector.

screwing procedures that need extreme caution with greater accuracy. And, the end effector should be small and lightweight to be moved dexterously by the robot body.

A. Description

As shown in Fig.3, the end effector equips a master motor, a stroke motor, a tool-changing motor, a main ball-screw, a high-speed drill, four screws and several connection adaptors in the cylindrical case. The end effector has 50-mm radius and 300-mm height, and weighs only 1.5kg. The high-speed drill is used to remove the cortical layer of the vertebra for the subsequent screw insertion. In conventional surgery, the surgeon performs gimleting with a hammer, wherein the gimleting force to penetrate the cortical layer is as high as 1200N. However, since the size of the actuator and system breakdown by repeated shocks may cause problems to the CoRASS, we apply the high-speed drilling as an alternative.

Operation of the end effector proceeds in the following steps: 1) The tool-changing motor makes the lower plate rotate for matching the center lines between a tool (high-speed drill or screws equipped on the lower plate) and an adaptor of the main ball-screw. 2) The surgeon grasps and turns the drilling handle of the master motor by his hand. 3) The rotation angle of the master motor is given as an angle command to a PID position controller that controls the stroke motor. 4) The stroke motor makes the main ball-screw act screwing motion. 5) The main ball-screw is joined with a selected tool using the connection mechanism explained in Section II-B. 6) The end effector performs the high-speed drilling or screw insertion under the surgeon's supervision with the master/slave (master motor/stroke motor) drilling system. By using those automatic tool-changing function embodied on the end effector, the surgeon can perform the spinal fusion surgery with the minimum number of actuators.

Based on human bone properties [10], we choose the specification of the system actuators. For the screwing task, stroke motor, Maxon RE 25 (maximum torque; 3.84Nm) with 128:1 reduction ratio, is used. For the tool-changing task, tool-changing motor, Maxon EC 16 (maximum torque; 1.12Nm) with 84:1 reduction ratio, is used. The stroke of the end effector is about 150mm.

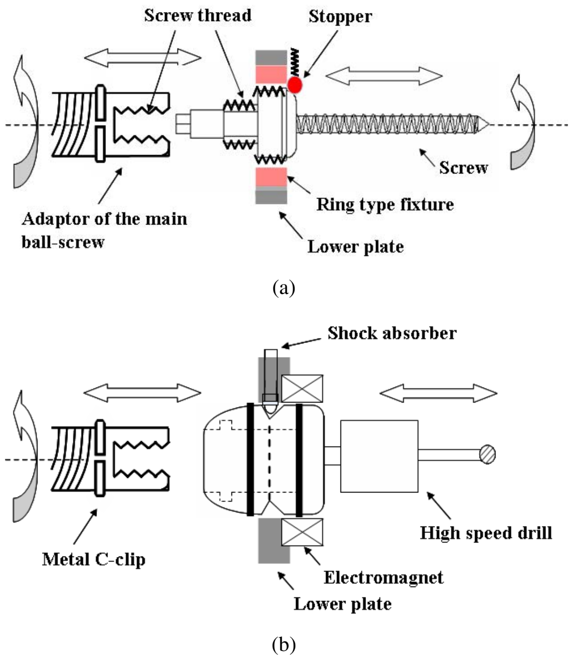
B. Connection mechanisms

During the design of the connection mechanism between the main ball-screw and tools, main design objective is to minimize the dimension of the adaptor and to simplify its mechanism since the tools and the manipulator works inside a patient through a small port, while still satisfying high connection success rates. As shown in Fig.4, two connection mechanisms are implemented to the end effector of the CoRASS. Fig.4(a) and Fig.4(b) represent the connection mechanisms between the main ball-screw and inserted screws, and between the main ball-screw and the high speed drill, respectively.

1) Connection mechanism between the main ball-screw and screws: After the insertion process is completed, the screw should be remained into the vertebra. In other words, to satisfy the condition of connection mechanism with a screw, the delivered torque should be transmitted to a screw only when the ball-screw turns in the positive direction (clockwise). When it turns in the opposite direction (counter-clockwise), joining should be unfastened.

Developed the spiral connection mechanism is the kernel of the idea. As shown in Fig.4(a), there are screw threads of 2mm in lead, 8mm in diameter at the upper part of a screw and the inside of the adaptor of the main ball-screw. When the surgeon turns the drilling handle in the positive direction (clockwise), the main ball-screw and the screw can be joined together. The screw is soon separated from the lower plate and then inserted into the vertebra following the surgeon' guide. After the insertion process is completed, the ball-screw turns in the opposite direction (counter-clockwise). The joining is unfastened since the torque is transmitted to the screw during the positive direction only.

2) Connection mechanism between the main ball-screw and high-speed drill: Since total four screws are inserted during the whole operation, at least four high-speed drilling



(a)

(b)

Fig. 4. Connection mechanisms between the main ball-screw and surgical tools: (a) Joining between the main ball-screw and a screw (b) Joining between the main ball-screw and a high-speed drill.

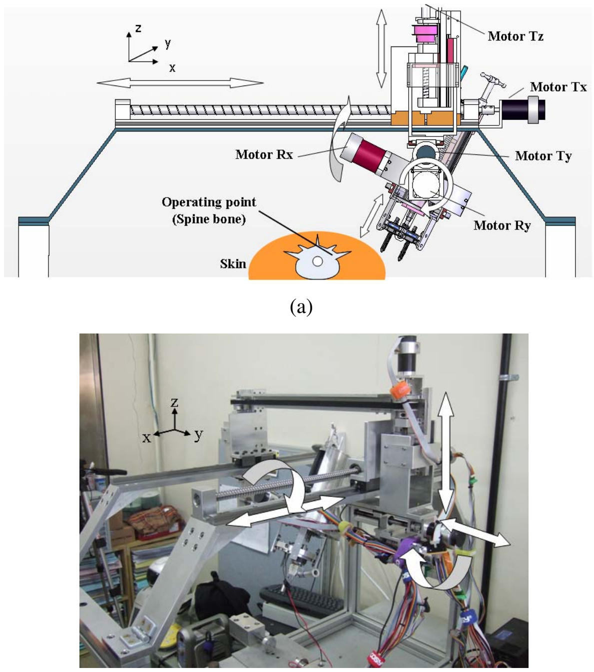
processes are needed to complete the spinal fusion. The high-speed drill should be carried back to its original place for the next use. We apply one-touch joining mechanism utilizing the elasticity of a metal C-clip. As shown in Fig.4(b), the diameter of the C-clip is slightly lager than the internal diameter of the adaptor opening of the high-speed drill. The clip is relaxed at the inside of the adaptor, once the clip is inserted. It induces the joining force as large as 18N between main ball-screw and high speed drill. However, in order to insert the C-clip into the adaptor, same amount of attraction force is also required during joining process. An electromagnet and shock absorber equipped in the lower plate generate the attraction force of 45N between the adaptor and the ball-screw. Asymmetric shape of the adapter also makes the disparity of the interaction force between the attaching and detaching step. The connection success rate reaches about 98%.

III. ROBOT BODY OF CORASS

In section II, we discussed the design of the dexterous small-sized end effector that can perform existing gimleting and screwing tasks. Then, the remained objective of a robot system is to align the end effector at a preplanned position with specified orientation accurately. However, since the task is to manage the vertebrae, the strong reaction force as high as 200N imposed to the robot system makes their joints be lifted during screw insertion. We thus designed the robot body to be inherently stiff in kinematically-closed structure.

A. Description

As shown in Fig.5, the CoRASS has kinematically-closed structure that has six-DOF motion space including the stroke motion of the end effector. To provide the accurate desired insertion pose of a screw, the robot should have at least five-DOFs, i.e., three translation (XYZ) and two rotation axes (Rx, Ry). Ball-screws and linear motion guides are used to transform the rotational motion into the linear motion. Maxon EC 45 motor (maximum torque; 1.52Nm) with 18: 1 reduction ratio is used in each translation part. For the rotational motion, Maxon EC 45 (maximum torque; 8.45Nm) and harmonic drive with 100:1 reduction ratio are used. Since needed workspace of the end tip to complete the spinal fusion is about 50×50×50mm^3, the CoRASS is designed to provide 100×100×70mm^3 workspace considering the insertion angles of a screw.



(a)

(b)

Fig. 5. Robot body of CoRASS: (a) CAD model (b) Prototype.

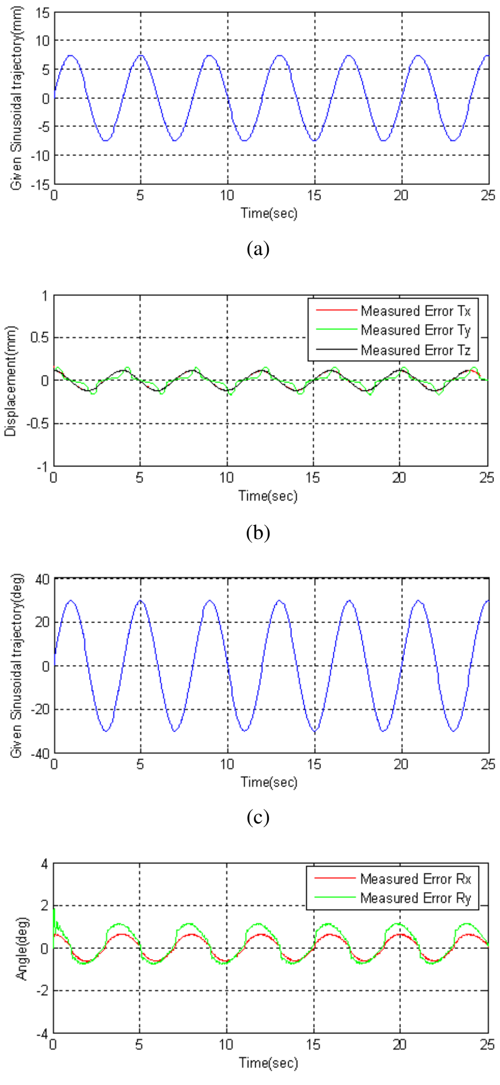
B. Performance Test of the CoRASS

Each joint is controlled by a PID position controller that has 1kHz update rate. Dynamic tracking errors were measured for each joint of the CoRASS. Given sinusoidal trajectory in the three translation joints is shown in Fig.6(a). Similar data for the two revolute joints is shown in Fig. 6(c). Fig.6(b)6(d) show the tracking errors in the translation and orientation parts, respectively. Tracking errors are bounded below 0.1mm and 1.0°. Static errors of the CoRASS were also measured to be bounded below 0.5μm for translation and 0.05° for rotation.

IV. CONTROL ARCHITECTURE OF CORASS

A. Position Control

To increase the accuracy of the operation, the robot system should be able to insert a screw at the preplanned position and orientation precisely. However, no matter how we reduce



(a)

(b)

(c)

(d)

Fig. 6. Measure dynamic tracking errors: (a) Desired trajectory in translation parts (b) Tracking errors in translation X,Y,Z-axes (c) Desired trajectory in rotation parts (d) Tracking errors in Rotation X,Y-axes.

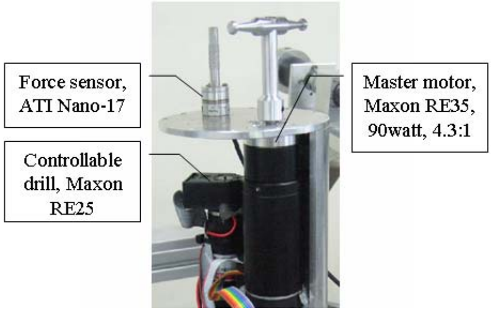
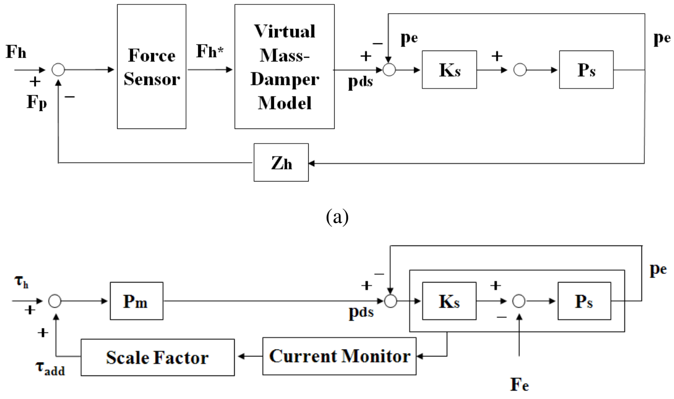


Fig. 7. Enlarged upper part of the end-effector



(a)

(b)

Fig. 8. System diagram for CoRASS: (a) Block diagram for admittance control (b) Block diagram for torque feedback in the CoRASS.

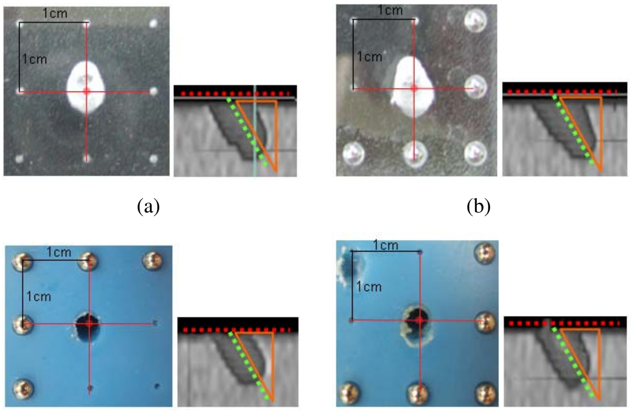
the tracking errors using the controller, system errors like registration errors and manufacturing errors cause inaccurate operation results. And, the pose of vertebrae is slightly changed during screwing since the strong reaction force is imposed the vertebrae. If these deviations can be detected using other intra-operative imaging devices like fluoroscope, mentioned problems can be easily solved. However, it is not easy to estimate such delicate errors quantitatively using the 2-D binary images obtained by fluoroscope.

To solve those problems, we apply the cooperative manipulation paradigm in spinal fusion. A practical use of the cooperative manipulation in the surgical robot was firstly introduced at the micro-surgical manipulation system for eye surgery in [12]. Cooperative manipulation means that the robot moves simultaneously with the operator's hand, while sensing forces exerted by the operator on the tool. Although the measurement of the delicate errors is difficult to obtain, it might be easier to make compensate such errors with the help of surgeon's abundant experience and intuition. Cooperative manipulation can increase the flexibility for controlling the precise surgical manipulation when the desired insertion pose of a screw needs to be slightly changed due to the system errors and/or strong reaction force during the operation.

A 6-axis F/T sensor (ATI; Nano-17) was used to augment surgeon's force commands to the pose of the robot in the five-DOF motion space. As shown in Fig.7, the F/T sensor is mounted on the top of the end effector. Fig.8(a) represents the admittance control diagram for the cooperative manipulation. The parameters of the virtual mass-damper model were determined to satisfy the system stability. In the figure, F_h and F_p represent the surgeon's force command and the response force due to the end-effector dynamics, respectively. p_{ds} is the desired pose of the end effector, whereas p_e is the actual. P_s is the robot plant, Z_h is the impedance of the surgeon, and K_s is a control gain.

B. Torque feedback method without torque sensor

Since screw insertion is a very delicate and cautious procedure, the screwing task performed by the CoRASS should be progressed under the surgeon's supervision. By using the master/slave drilling system, surgeon's expertise can be exploited during screwing. However, in the real operation, a friction between the vertebra and the screw



(a) (b)

(c) (d)

Fig. 9. Experimental Result of high-speed drilling with the CoRASS (Left images are upper views taken by camera, right images are CT-scan images showing the cross-section) (a) Acryl, hole 1 (b) Acryl, hole 2 (c) Engineering plastic, hole 1 (d) Engineering plastic, hole 2.

makes a tactile feedback on surgeon's drilling hand. This haptic information suggests the status of a screw to the surgeon, e.g. insertion depth, the surgeon thus can make more accurate decision that is helpful to increase the safety of the patient.

In our master/slave drilling system, we should generate the haptic information identical to that of real operation and transmit it to master motor of the robot. In our previous work, we introduced the current monitoring method to calculate drilling torque without torque sensor in [10]. The idea is to use the current signal of the amplifier since the monitoring current is proportional to the load at the motor. The current monitoring signal is well matched with the real torque in low frequency region. This method is also incorporated in the CoRASS. Using an additional torque sensor at the stroke motor is an alternative, but it is costly and gives rise to complicated design issues such as cabling around the rotating main ball screw. This torque-feedback algorithm is further illustrated in Fig. 8(b) where τ_h represents the surgeon-exerted torque and τ_{add} feedback torque. F_e is external friction forces between the bone and the screw. p_{ds} and p_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.

V. EXPERIMENT

To perform screw insertion using the end effector, the robot system should satisfy following two requirements: i) Since the pose of the inserted screw is seriously affected by the initial pose of the hole made by the high-speed drill, the robot should remove the cortical bone at the preplanned position and orientation accurately. ii) The angle of the inserted screw should be maintained withstanding the large reaction force until the insertion process is completed. To verify the mentioned requirements, following two experiments were conducted using the CoRASS.

A. Accuracy estimation of high-speed drilling process

The acryl and engineering plastic specimens were used for the experiment. Since the mechanical property of the engineering plastic is much stronger than that of the cortical bone, if the accurate high-speed drilling can be operated on the specimen successfully, we can expect the drilling performance of the CoRASS in spinal fusion. In the real operation, the insertion angle of a screw is about 60° from the horizon. We made a hole at the preplanned position with an angle of 60° using the equipped high-speed drill.

Fig.9 shows the results of the experiment. From the figure, we can observe that the high-speed drilling was successfully operated with two specimens at the preplanned position and orientation accurately. Inner angle of the orange triangle is 60°. It is well matched with the insertion angle of the high-speed drill.

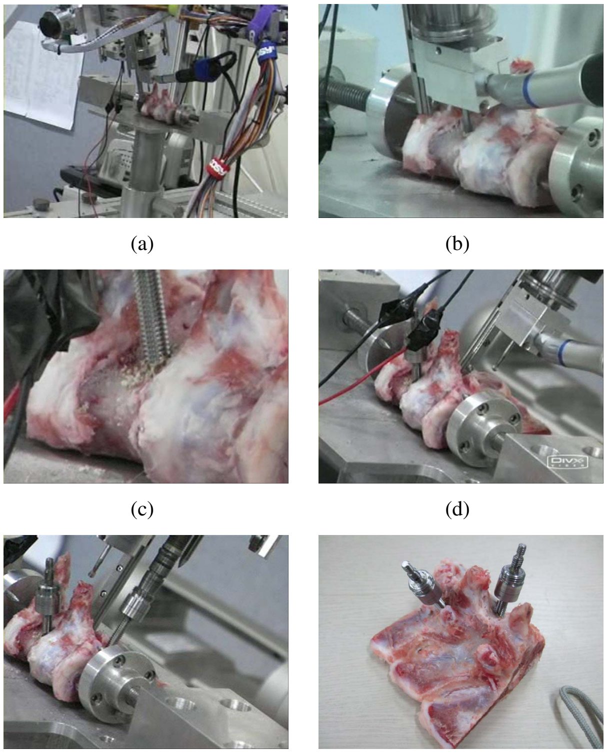
B. Screw insertion with the pig spine specimen

The objective of the experiment was to insert a screw into pig spine vertebrae at a preplanned position and orientation, with the accuracy less than 1mm and 0.1°, respectively, using the CoRASS. The procedure of the experiment was as follows: 1) Using the 6-axis F/T sensor, the operator controls the pose of the end effector to coincide with the desired ones. 2) Using the automatic tool-changing mechanism, the main ball-screw is joined to the high-speed drill. 3) Using the master motor, the operator controls the stroke motion of the high speed drill to break the cortical layer. 4) After the high-speed drilling is completed, the high-speed drill is carried back its original position for the next use. 5) The tool-changing motor rotates 72° and the main ball-screw is joined to the screw 1. 6) Using the master motor, the operator controls the stroke motor to insert the screw into the pig spine vertebrae while feeling the haptic feedback. 7) After the insertion process is completed, the screw is detached from the end effector. 8) The tool changing motor rotates -72° and the main ball-screw is connected to the high-speed drill. 9) Repeat the experiment to insert screw 2.

Fig.10 represents the procedures of the spinal fusion surgery using the CoRASS and the result of the experiment. The high-speed drilling and the screw insertion were completed, successfully. As shown in Fig.11, we measured the accuracy of the insertion angle quantitatively using the CT scan image. We set the preplanned insertion angle to be 70°. The inner angle of the orange triangle is also 70°. We confirmed that developed CoRASS satisfied the objective of the experiment sufficiently.

VI. CONCLUSIONS

This paper addressed six-DOF cooperative robot-assisted surgery system for spinal fusion, CoRASS. Many robot-assisted surgical methods were developed to guide the desired insertion pose of a screw to a surgeon. However, for the real implementation, there are two main limitations in existing spinal fusion surgery: limited capabilities provided by the robot and the loosening problem. To overcome those limitations, this paper proposes a novel surgical system that



(a) (b) (c) (d) (e) (f)

Fig. 10. Experimental Result of screw insertion into the pig spine vertebra using the CoRASS: (a) Experimental setup (b) 1st high-speed drilling (c) 1st screw insertion (d) 2nd high-speed drilling (e) 2nd screw insertion (f) Final results.

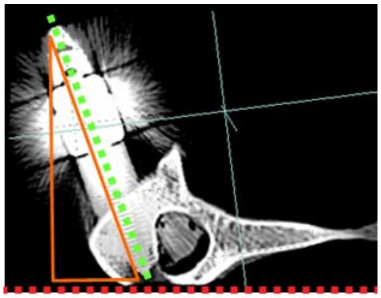


Fig. 11. Experimental Result: CT scan image

performs the spinal fusion surgery using the dexterous end effector following surgeon's guide. Since it has six-DOF kinematically-closed structure, it can perform accurate screw insertion into the spine bone withstanding strong reaction force. Based on cooperative manipulation framework, we can give the manipulation power to a surgeon to compensate the problem when delicate errors and/or deviations of the actual pose from the preplanned path occur. And, in order to exploit the surgeon's expertise during screwing, we incorporated the master/slave drilling system into the end effector. The current monitoring method for the torque feedback was also used to increase the presence of the touch during the operation.

Two experiments were performed to verify the performance of the CoRASS. It shows that the developed robot system enables accurate screw insertion into the vertebrae with the preplanned position and orientation. We validated the performance of the CoRASS using pig spine specimens.

Our future work is to increase the robustness of the CoRASS to perform the spinal fusion surgery with the animal. The animal surgery includes more dynamic motions compared with the specimen experiment. We are now integrating the robot with the vision tracking system to measure the respiration movement and/or the deviations of the pose induced by the reaction force between the screw and the vertebrae.

VII. ACKNOWLEDGMENT

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