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A Noble Bilateral Teleoperation System for Human Guided Spinal Fusion

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Abstract— **In order to provide improved convenience for a surgeon in spinal fusion surgery, a robot system should i) closely engage in surgeon's operation using an end effector, and ii) protect the surgeon from being exposed to harmful radiation due to repeated shootings of fluoroscope. This paper proposes a bilateral teleoperation system for spinal fusion, BiTESS-II, to accomplish the goals. We developed an end effector that can substitute the surgeon's manual operation and a novel closed-loop type slave robot that can exert strong reaction force to complete gimleting and screwing tasks. Master devices are used to control the position and orientation of the slave robot and to generate haptic information identical to that of the slave side. A novel force reflection method without force sensors allowed to design the end effector simple and light. BiTESS-II is among the first human guided teleoperation system for spinal fusion with an adequate end effector. The performance of the BiTESS-II was verified by experiments.**

I. INTRODUCTION

Since surgeons depend only on their visual and tactile information using fluoroscope images in spinal fusion, their experiences and intuition are dominant factors that determine success rates. However, even if the surgeon is a medical specialist who has abundant experiences in spinal fusion, he can still make a mistake during the whole operation. Since the operation task relates to the human's spine, a minor mistake might cause a critical injury to a patient. This is the reason why robotic system is needed in spinal fusion.

As shown in Fig.1, unstable vertebra due to the loss of disc makes the patient suffer from pain. Screws are inserted into the spine bone, and fixed together by connecting rods, which can restrict relative motions between the two vertebra bodies. Prior to the operation, surgeons examine MRI and/or CT scan images and plan how to perform the operation. Surgeons incise the skin and make a hole for the operation using K-wire and dilators. They break the protective outer shell (cortical bone) by gimleting with a hammer, and then insert screws into the spine bones observing the status of screws using the fluoroscope. After fixing process by connecting the rods, surgeons suture the wound, and the operation completes.

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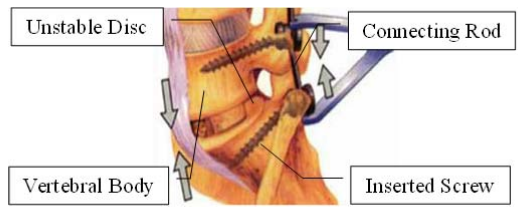

Fig. 1. Illustration of spinal fusion [7]

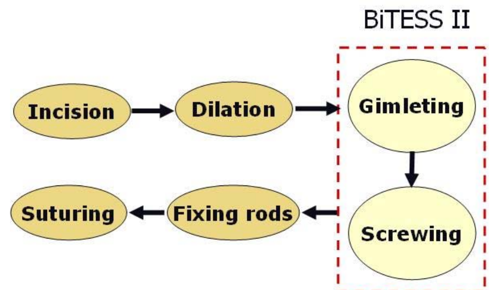

Fig. 2. Steps of spinal fusion and the roles that BiTESS II is in charge of.

In this procedure, there are three main difficulties; i) limited manipulation power needed to maintain accurate insertion pose, ii) the surgeon's overexposure to radioactive contamination, and iii) intensive labor during operation [1]. Spinal fusion is one of the most difficult operations requiring extreme caution among various medical treatments of disc illness. They should insert a screw with diameter of 3 or 4 mm into pedicle of the spine bone that has the diameter of 6 mm. If a surgeon fails to control the insertion direction by mistake, a screw can touch the spinal cord. In real operation, the screw misplacements take place in the ratio of 10%, and the half of them cause critical injury to patients. Fluoroscope images are required to check whether screws are inserted well or not during the operation. Since total four screws are inserted in the whole operation, at least four fluoroscope images are needed in each operation. Surgeons are exposed to radioactive rays repeatedly.

In order to overcome those problems, many spine surgery robots were developed such as MASOR by Shoham et al. [1], SPINEBOT by Hanyang University [2] [3], and PAKY/RCM needle module by Georgetown University [4]. They have common characteristics, guiding the desired insertion direction of a screw to the surgeon. These robotic systems can suggest a solution to rectify the first and third problems.

[1]It takes 2∼2.5 hours for spine bone fusion surgery

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TABLE I
BiTESS II SPECIFICATION

Position/orientation accuracy		1mm/0.1°,
Torque range for screwing		20 Nm
Master DOF	Motion	6
	Force reflection	6
Slave DOF	Motion	4
Force sensor		Not used

In spite of these efforts, their functions are still limited in the sense that they cannot provide capabilities that can be obtained when a robot assists the surgery more directly, for example, inserting a screw using the robot. Moreover, the radioactive contamination problem still remains unsolved.

In this paper, we propose a bilateral teleoperation system for spinal fusion, BiTESS-II with the specification shown in TABLE I to alleviate the three problems. Though da Vinci by Institutive Surgical (6 DOF master-slave system) [5] is also a teleoperation system used for cardiac operation, the conditions for spinal fusion are different from those of cardiac operation. Force and torque needed to complete gimleting and screwing tasks in spinal fusion are about 1200 N and 3.2 Nm, respectively (see Section II for our measurements). These values are about one hundred times larger than those of cardiac operation. If a surgeon performs spinal fusion using da Vinci system which has a open-loop type structure, the system cannot bear the gimleting force. Even if high speed drill is used instead of gimleting process to avoid the strong reaction force, it is also impossible to resist such torque and reaction force generated between a screw and the human's spine during the screwing process.

Therefore, other existing robot systems cannot complete gimleting and screwing process in spinal fusion. For BiTESS-II, we first developed an end effector that can substitute the surgeon's manual operation in spinal fusion and then a closed-loop type slave robot to use the end effector robustly. The developed bilateral teleoperation system is a viable solution for the difficulties that the conventional operation method has and that other surgical robots might not handle when they are applied to spinal fusion.

BiTESS-II consists of a haptic console with two master devices operated by a surgeon and a slave robot which follows the surgeon's command for spinal fusion. A surgeon can perform spinal fusion apart from fluoroscopes remotely, using visual and tactile information identical to that of the slave side. Fig.2 shows the whole procedure for spinal fusion. BiTESS-II covers the process of gimleting the spine cortical bone and inserting screws into the human's spine. Integrating BiTESS-II with a surgery navigation system is undergoing. The characteristics and performance of the navigation system are described in [6].

Section II explains our force and torque data acquisition system used to measure spine bone properties. The properties were needed to determine specifications to design BiTESS-II. In Section III, the end effector, slave robot, and master devices in BiTESS-II are described. Section IV introduces

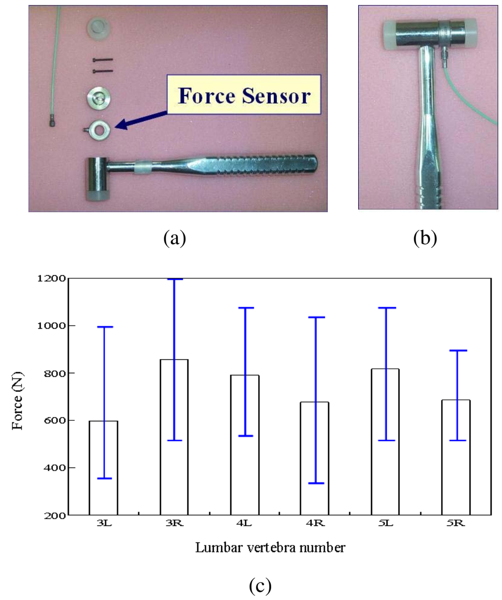


Fig. 3. Data Acquisition Experiment: (a) Parts of shock data acquisition system (b) Complete unit of shock data acquisition system (c) Force signal during hammering(L: left, R: right).

two novel methods, i.e., current monitoring method and Restriction Space Projection (RSP) method, used to generate reflecting force without force sensors. In Section V, the function and performance of BiTESS-II is verified through experiments, followed by conclusion in Section VI.

II. Measurement of Spine Bone Property

In order to find the appropriate specification of a robot system for spinal fusion and determine whether other existing surgical robots satisfy the specification, we needed to know how strong force and torque are needed to complete the tasks of spinal fusion. Unfortunately, to the best of the authors' knowledge, there have been no studies about the human's spine property during spinal fusion. This section shows how we measured bone properties using a newly developed hammering and screwing system.

A. Force data acquisition to break cortical bone

Fig.3(a) shows the developed hammering system. A ring type force sensor is included to obtain force data. The bandwidth of the system is 10 kHz, and the permissible force

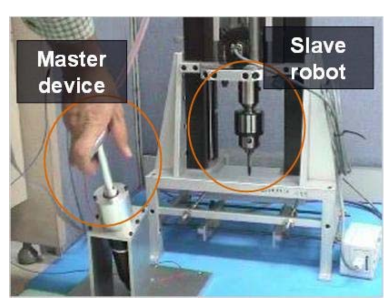


Fig. 4. 1-DOF drilling bilateral operation system.

TABLE II

Pig bone properties (Unit:N)

Subject	3L		3R		4L		4R		5L		5R	
	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.
1	599	1000	855.62	1172	789	1080	678	1057	817	1130	686	900

TABLE III

Human bone properties of female 56years old (subject 1), male 55years old (subject 2), male 79years old (subject 3), female 54years old (subject 4) and female 42years old (subject 5)(Unit: N).

Subject	3L		3R		4L		4R		5L		5R	
	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.	Av.	Max.
1	N/A	N/A	N/A	N/A	759	956	841	1088	1062	1394	919	1078
2	297	427	293	422	394	428	N/A	N/A	220	336	265	338
3	N/A	N/A	N/A	N/A	725	1030	918	1155	524	604	793	965
4	N/A	N/A	N/A	N/A	813	891	951	1107	730	1096	798	893
5	877	1175	777	1351	739	1010	650	1010	682	1358	714	1059

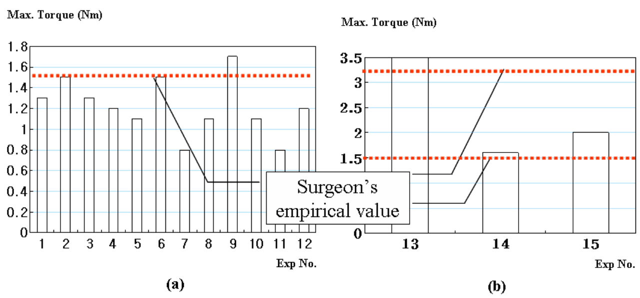


Fig. 5. Maximum torques to insert a screw: (a) Maximum torques into the sponge bone (b) Maximum torques into the sponge bone through the cortical bone.

range is 15 kN . The system was applied to measure the pig spine bone and human spine bone properties.

For the measurement, surgeons performed spinal fusion with the pig spine bone. During the operation, we measured force data needed to break the cortical bone. Fig.3(c) and Table II show that the force range for gimleting is between 500 N and 1200 N. The system is also applied to the human spine bones in real spine surgery. Table III shows the force range of 5 subjects. Although the values for gimleting depend on their age and gender, maximum values lie between 400 N and 1200 N. We can thus conclude that the force larger than 1200 N is needed to gimlet a human spine bone.

B. Torque data acquisition to insert a screw

In spinal fusion, the next procedure after gimleting is the insertion of screws. In order to know torque required for screwing, we developed a 1-DOF drilling bilateral teleoperation system shown in Fig.4. A torque sensor is equipped in the slave side to measure torque during the operation. The model is SENSOTEC UV-10, with the permissible frequency range of 3000 Hz.

When surgeons insert a screw into the spine bone, they estimate the position and orientation of the screw using a fluoroscope. However, due to the radioactive exposure, concurrent fluoroscope images may not be provided to the surgeon. Therefore, it is inevitable to depend on tactile sensing to know the status of the screw. The spine bone is composed with two layer: cortical bone (protective outer shell) and sponge bone (inner soft region). The cortical bone and the sponge bone have different characteristics, and thus the surgeon can feel the relative position of a screw during insertion by tactile sensing.

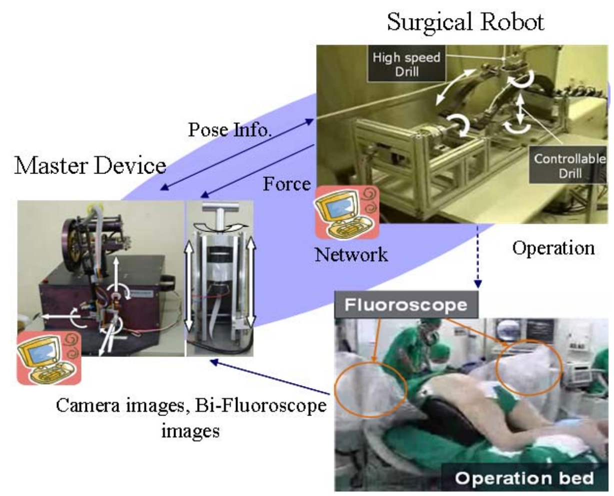


Fig. 6. Architecture of BiTESS-II

In order to develop a novel system, we should determine the torque resolution needed for the surgeons to distinguish the cortical bone from the sponge bone via haptic interface, as well as the maximum torque required to insert a screw into the spine bone. Fig.5(a) shows the maximum torque to insert a screw into the sponge bone of the pig spine. The value is less than 1.5 Nm with the average value of 1.06 Nm. Fig.5(b) shows the maximum torque to insert a screw into the sponge bone through the cortical bone of the pig spine. The value is between 1.5 Nm and 3.2 Nm with the average value of 2.3 Nm. In case of the human spine bone, it is impossible to apply the system to real humans because it is not permitted by KFDA, yet. Instead,

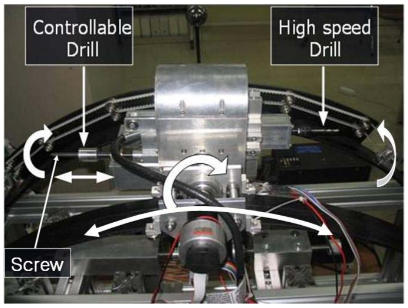


Fig. 7. End effector of BiTESS-II

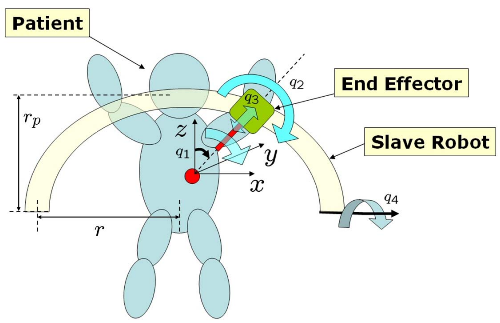


Fig. 8. The structure of BiTESS-II.

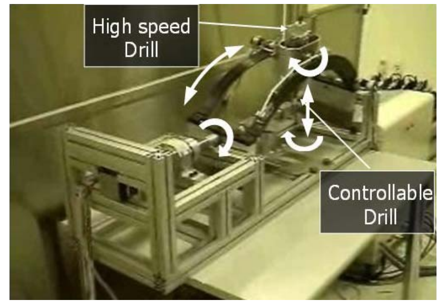
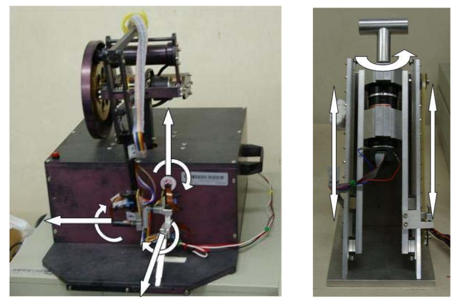


Fig. 9. Slave robot of BiTESS-II.



(a) (b)

Fig. 10. Master Devices: (a) 6 D.O.F master device (b) 2 D.O.F master device.

we measured the surgeons' empirical values using the 1-DOF haptic device. 4 expert surgeons who have prolonged experiences on spinal fusion compared the virtual torque with their empirical values. The range of the empirical values is between 1.5(Nm) and 3.2(Nm) as the red dotted line in Fig.5. We can conclude the screwing forces of the pig spine bone well coincides with the surgeons' empirical values. Moreover, in order to generate different haptic information for the sponge bone and cortical bone, BiTESS-II is designed to have relative torque sensing resolution less than 0.5 Nm.

III. System Development

Based on the human bone properties discussed in Section II, we developed a new bilateral teleoperation system, BiTESS-II, which can substitute the traditional gimleting and inserting process. It consists of an end effector, a slave robot, two master devices and controller. As shown in Fig.6, a surgeon operates the slave robot via the two master devices at the remote side and feels kinesthetic haptic information reflected from interactions between the slave robot and the human spine bone. The operation is aided by camera and fluoroscope images transmitted to master side.

A. End Effector

The end effector enables the robot system to substitute surgeon's manual operations. Using the developed end effector, more active assistance can be provided during the operation. This is the major difference between BiTESS-II and other spine surgery robots. Since the objective of BiTESS-II is gimleting and screwing, the end effector should be designed to complete the tasks considering the human spine bone properties. We showed that force larger than 1200 N is needed to break the cortical bone in Section II. However, if we apply gimleting in spinal fusion using a surgical robot, the size of actuator and the possibility of system breakdown by repeated shocks might be problems. We thus changed the previous gimleting process with a high speed drilling process. The end effector includes one high speed drill (20,000rpm) and one controllable drill. The high speed drill is used to remove the cortical bone. After high speed drilling, the end effector automatically rotates $180°$ to change tools. The screw is located at the end of the controllable drill for screw insertion. When insertion process is completed, the screw detaches from the end effector. Since only one motor is used to control the stroke motion and screwing motions shown in Fig.7, the end effector can be simple and light. For screwing task, Maxon RE-max 24 (20 Watt) with 86:1 gear ratio is used. Its stall torque is 20 Nm.

B. Slave Robot

The objective of a slave robot is to aline the end effector at a preplanned position with a specified orientation. Since the task point of a patient's spine bone is on the medial plane as shown in Fig.8, 4-DOF is needed to complete the task. The developed slave robot with the end effector has 4-DOFs except for the drilling motion. Since the task is to manage hard material, i.e., the spine bone, strong reaction force is imposed to the slave robot during the drilling process. This requires the robot to be inherently stiff and thus a closed-loop type design is more suitable than the open-loop type. The forward kinematics of the developed slave robot can be described as:

$$H = R_x(q_4) \cdot T_z(r_p - r) \cdot R_y(q_1) \cdot T_z(r) \cdot R_y(q_2) \cdot T_z(q_3) \quad (1)$$

q_1, q_2, q_3, and q_4 are joint angles represented in Fig.8. T and R are the homogeneous transform for translation and rotation, respectively. T_x means translation in the x direction and R_x rotation about the x axis. r and r_p are the radius and height of the slave robot.

C. Master Devices

A surgeon operates the slave robot and receives haptic feedback via the master devices. We developed two master devices. One is used to move the slave robot and end effector to a desired configuration. Another is used to control the high speed drill (gimleting) and controllable drill (screw insertion) at the end effector. Developed master devices are shown in Fig.10. Master-I in Fig.10(a) is an extended version of 4D4M [8]. It has 6-DOF motion space and 6-DOF force reflection. Master-II in Fig.10(b) has 2-DOF screw motion space and 2-DOF force reflection. The system can also visualize the insertion depth of a screw during spinal fusion.

IV. Force Reflection method without a Force Sensor

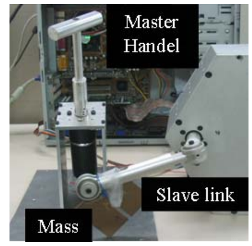
Though kinesthetic sensation is an important information during spinal fusion, an end effector with a force sensor attached becomes heavy and bulky. Since our design goal for the end effector is to make it adaptable to any kind of surgical robots, the end effector needs to be simple and light. This section discusses a force reflection method that does not require a force sensor and a current monitoring method used to calculate interaction torque for the screwing motion during the high speed drilling and screws insertion processes. Also, Restriction Space Projection (RSP) method [10] to calculate interaction force caused by collisions with unexpected obstacles or the limitations of workspace at slave side is explained.

A. Current Monitoring Method

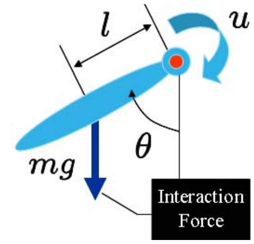
The idea to calculate drilling torque without torque sensors is to use the current signal of the amplifier since the monitoring current is proportional to the load at the motor. Fig.11(a) shows the 1-DOF experimental setup to demonstrate the performance of the current monitoring method. Since we know the mass and inertia of the slave link, the applied torque can be calculated as follows.

$$\begin{aligned} \tau_e &= mgl\sin\theta + u + I\ddot{\theta} \\ &\simeq mgl\sin\theta + u \quad (2) \\ u &= K_p e + K_v \dot{e} \quad (3) \end{aligned}$$

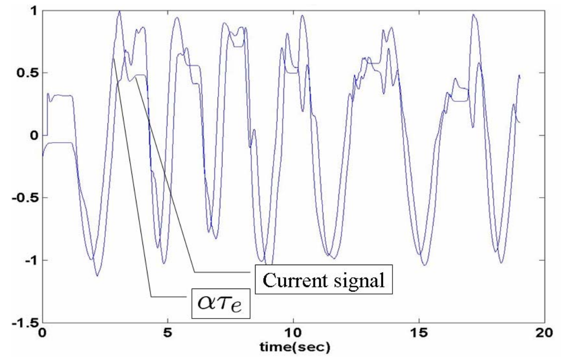
m and l are the mass and length of the slave link. θ and e mean the angle and error, respectively. g is the gravitational constant. u is the control input. After K_p and K_v are well tuned, the current monitoring signal is matched with the real torque in low frequency region. Fig.11(c) shows that an example of current signal and calculated torque values.



(a)



(b)



(c)

Fig. 11. Current monitoring method: (a) Experimental setup (b) Simplification of experimental setup. (c) Current monitoring Signal and calculated torque(scaled).

B. Restriction Space Projection Method

In teleoperation, the operator cannot see the whole situation at the slave side, so that collisions between links or with unexpected obstacles can occur. Therefore, the interaction force and its direction should be accurately transmitted to the human operator. Our slave robot has no force sensor, so, position-position (p-p) architecture should be used. However, the conventional p-p architecture has a limitation when the master and slave robots are not kinematically similar. The limitation is explained in details in [9]. Since this is the case with BiTESS-II, Restriction Space Projection (RSP) method [10] was implemented. RSP method using the concept of Instantaneous Restriction Space (IRS) is especially useful to calculate the accurate direction of reflecting force when the slave robot collides with unexpected obstacles. In spinal fusion, unexpected obstacles can be other bones or organs.

Reflecting forces are calculated using Jacobian and joint angle errors. The Jacobian of the slave robot can be calculated as follows.

$$\boldsymbol{J}_{sr} = \begin{bmatrix} r\boldsymbol{c}(q_1) & 0 & 0 \\ r\boldsymbol{s}(q_4)\boldsymbol{s}(q_1) & 0 & -\boldsymbol{c}(q_4)[r\boldsymbol{c}(q_1) - (r - r_p)] \\ -r\boldsymbol{c}(q_4)\boldsymbol{s}(q_1) & 0 & -\boldsymbol{s}(q_4)[r\boldsymbol{c}(q_1) - (r - r_p)] \\ 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (4)$$

where $\boldsymbol{s}$ means sine, $\boldsymbol{c}$ means cosine, and $\dot{\boldsymbol{X}}_{sr} = \boldsymbol{J}_{sr}\dot{\boldsymbol{q}}_{sr}$. $\boldsymbol{X}_{sr} \in R^6$ and $\boldsymbol{q}_{sr} \in R^3$ are the pose and joint angles of

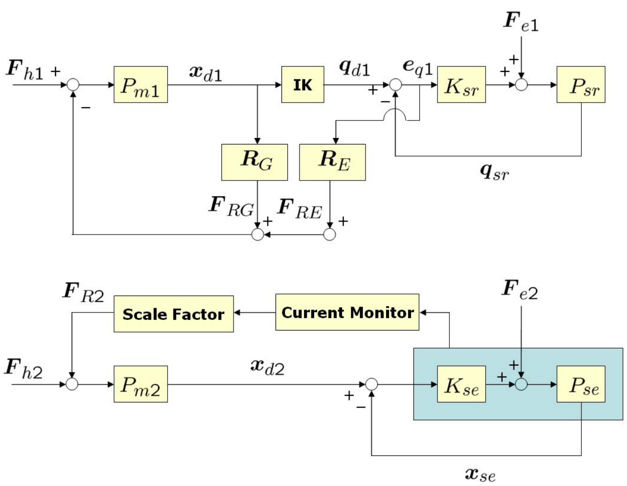


Fig. 12. Whole system diagram for BiTESS-II

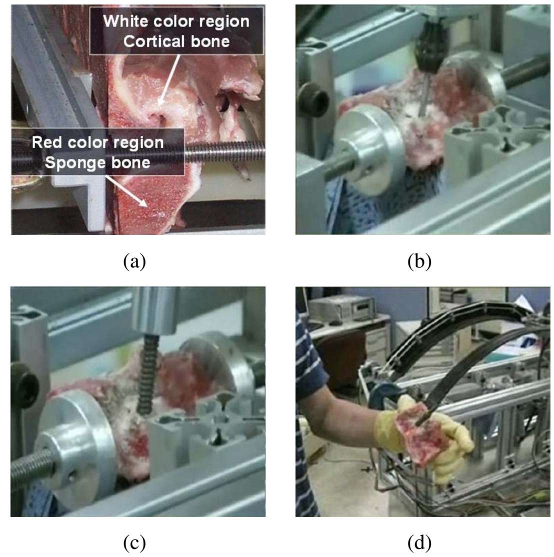


Fig. 13. Experimental results: (a) Composition of pig's spine bone (b) High speed drilling process (c) Controllable drilling process (d) End of the operation.

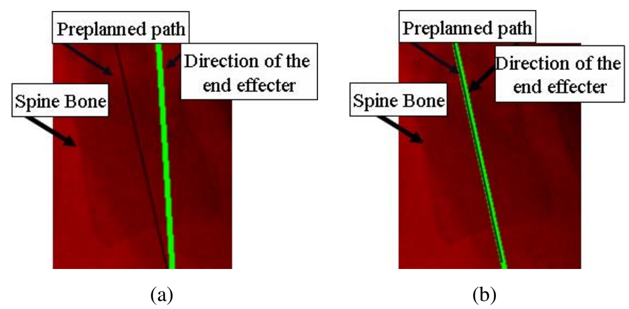


Fig. 14. Displayed images of a preplanned operation path and the direction of the end effector (the operator controls the direction of the end effector (green line) to match it to the preplanned path (black line) displayed on the spine bone image) : (a) Before operation (b) After operation.

the slave robot, i.e.,

$$\begin{aligned} \boldsymbol{X}_{sr} &= \begin{bmatrix} x_{sr} & y_{sr} & z_{sr} & \theta_{srx} & \theta_{sry} & \theta_{srz} \end{bmatrix}^T \\ &= \begin{bmatrix} r\boldsymbol{s}(q_1) \\ -\boldsymbol{s}(q_4)[r\boldsymbol{c}(q_1) - (r - r_p)] \\ \boldsymbol{c}(q_4)[r\boldsymbol{c}(q_1) - (r - r_p)] \\ q_4 \\ q_2 \\ 0 \end{bmatrix}, \end{aligned} \tag{5}$$

$$\boldsymbol{q}_{sr} = \begin{bmatrix} q_1 & q_2 & q_4 \end{bmatrix}^T. \tag{6}$$

r and r_p mean the radius and height of the slave robot as shown in Fig.8. In this paper, we will not pursue the derivation of the IRS and the RSP matrices. The details are explained in [9].

Fig.12 shows the implemented whole system diagram. R_G and R_E are RSP matrices calculated from IRS in [9] [10]. $\boldsymbol{x}_{d1}$ is the pose of the master device and $\boldsymbol{e}_{q1}$ is joint space error at the slave side. F_{h1} and F_{h2} are human force command to control master-I and master-II, P_{m1} and P_{m2}, respectively. IK means inverse kinematics. F_{e1} and F_{e2} are external forces at the slave robot and end effector. F_{RG} and F_{RE} are reflecting forces generated by RSP method. F_{R2} is scaled reflecting force calculated from current monitoring signal at the end effector. P_{sr} and P_{se} mean the slave robot and the end effector.

V. Experiment

In this experiment, we used the spine bone of the pig to evaluate the system performance. The objective of the experiment was to insert a screw at a preplanned position and orientation, with the accuracy less than 1 mm and $0.1°$ error, respectively, using BiTESS-II. The experimental procedure was as follows :

1) Using visual information displayed on the monitor, the operator controls the master device I to coincide the position and orientation of the end effector with the desired pose, and fixes the pose of the slave robot.
2) Using the master device II, the operator controls the high speed drill to break the cortical bone while feeling haptic feedback.
3) After the high speed drilling is completed, the slave robot automatically pulls out the high speed drill and rotates the end effector $180°$ to use the controllable drill.
4) Using the master device II, the operator controls the controllable drill to insert a screw into the pig spine bone while feeling haptic information.

Fig.13 illustrates the results of the experiment. From the figure, we can observe that the process of high speed drilling was successfully performed to break the cortical bone at the desired point and along the target direction, and thus our high speed drilling can adequately replace the traditional gimleting process, successfully. After high speed drilling, the screw was accurately inserted at the preplanned position with the specified orientation as shown in Fig.14. We repeated the experiment with more than 20 pig spine specimens and obtained 95% of successful screw completions. Movie clips demonstrating the experiment can be downloaded at the website [11].

VI. Conclusions

A bilateral teleoperation system for spinal fusion, BiTESS-II was developed to solve the difficulties in i) managing strong reaction force occurring from contacts between surgical tools and the human's spine, ii) preventing the surgeon's overexposure to radioactive contamination. In BiTESS-II, we first developed an end effector for spinal fusion to increase convenience for the surgeon. A force reflection method that does not require a force sensor makes the slave robot simple and light. Surgeons can feel the interaction force during the screwing process with the aid of visual and haptic sensation on the slave side. Though BiTESS-II has not been applied to the spinal fusion with the humans yet, the experiment using the pig spine bone confirmed the capability of the developed system.

Our future work is to increase the robustness of BiTESS-II so that the system can be used in real spinal fusion. Since the environment of real operation is more dynamic due to the patient's respiration and the reaction force by surgeons, we are now developing a vision tracking system to measure the movement.

Acknowledgment

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