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Deformation Analysis and Active Compensation of Surgical Milling Robot Based on System Error Evaluation

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Abstract— **The increase of precision and minimal invasiveness is an important current issue in orthopedic surgery. The femur and the tibia must be shaped to fit an artificial joint for successful knee arthroplasty. The recent trend towards MIS (Minimally Invasive Surgery) to decrease the length of the required incision has increased surgical difficulty, since the open access area is small. In this paper, registration and cutting error were analyzed with a robotic surgery system being developed first as an example, and a method of active compensation of robot deformation by gravity and cutting force was proposed and tried based on the error map with the expectation that the precision will increase.**

I. INTRODUCTION

A. Background

Total knee arthroplasty (TKA) and unicondylar knee arthroplasty (UKA) are orthopedic surgeries performed to reduce pain caused by the destruction of a joint by osteoarthritis or rheumatoid arthritis and to enhance the QOL (Quality of Life) of the patient. In the surgical operation, the damaged articular portion of the bone is excised to fit the shape of the setting plane of the artificial joint, and the original joint is replaced by the artificial joint. The number of patients suffering from osteoarthritis is from 12 to 20 % of the total population. This number is expected to increase rapidly due to the aging trend seen in developed countries.

In TKA/UKA, the setting position and orientation of the artificial joint affect the inferior limb position after the operation. Therefore, postoperative pain and reduction in the useful lifespan of the artificial joint will occur if the artificial joint is not properly fixed; high accuracy of the cut surface is required. However, the accuracy of the cut typically depends on the surgeon's skill, since the bone is shaped by hand. Therefore, the authors have been developing a system to assist in TKA/UKA and to increase the accuracy of the bone cutting.

The paper describes the registration and machining precision of the robotic surgery system, focusing on compensation of the deformational error of the bone cutting robot. The targeted surgical system consists of (1) a preplanning system providing a CAD function, (2) an intraoperative system, including registration function and CAM system, and (3) a machine tool to cut the bone.

B. Related Works

ROBODOC is the most famous robotic surgery system in the orthopedic field [1]. The system has been used in numerous clinical operations. Newer orthopedic robots display unique features. Some work passively to support the surgeon; others are downsized and mounted directly on bone. For example, "ACROBOT," developed by Davies et al., passively supports the surgeon and is used clinically [2]. Dombre et al. developed "BRIGHT," which has a guide jig for a bone saw implemented on the tip of a robot arm [3]. "ARTHROBOT" by Kwon et al. is intended for minimally invasive joint replacement [4], and the robot by Plaskos can be set on bone directly [5]. The recent tendency has been to focus on minimal invasiveness of the surgical procedure in addition to high accuracy. Pritschow et al. presented the design of and test results for a fail-safe numerical control (NC) for robotic surgery, which has assisted in a wide range of surgical treatments [6]. In the situation described above, the features of the developed system are as follows: (1) The authors developed a multi-axis bone cutting machine tool for knee surgery in which the cutting tool is surrounded by soft tissues. (2) The system performs minimally invasive surgery with a small incision. (3) A medical CAD/CAM system that provides safety, irrigation, and sterilization was developed [7].

In this paper, our surgical system and milling robot were used as an example, and the precision of each function, such as preplan, registration, and machining, was analyzed. The deformation of the milling robot by gravity and cutting force was analyzed by the finite elemental method and was actually measured by the 3-dimensional position sensor. This allowed us to make an error map at some robot postures. Likewise, a method of active compensation of robot deformation was proposed and tried based on the error map.

II. ANALYSIS OF SYSTEM ERROR

A. System Configuration

The authors have been developing a system to assist in orthopedic surgery (Fig.1). The developed system recognizes the position of the soft tissue accurately during surgery, and the toolpath is generated using this information.

1) Preoperative system as a CAD system: The shape of the bone is obtained by taking a CT image of each patient and reconstructing the 3D shape of the target bone from the sliced data. The position and size of the artificial knee joint are determined based on the clinical knowledge incorporated in the preoperative planning system.

2) Registration and CAM system: The position and the orientation of the bone are described with reference to the bone cutting machine tool coordinate system using the information from the registration process. A minimally invasive

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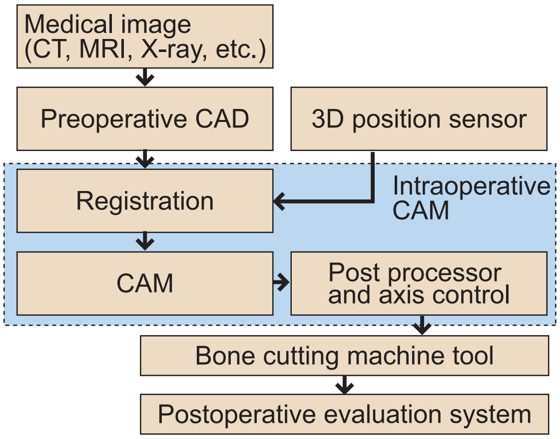


Fig. 1. System configuration

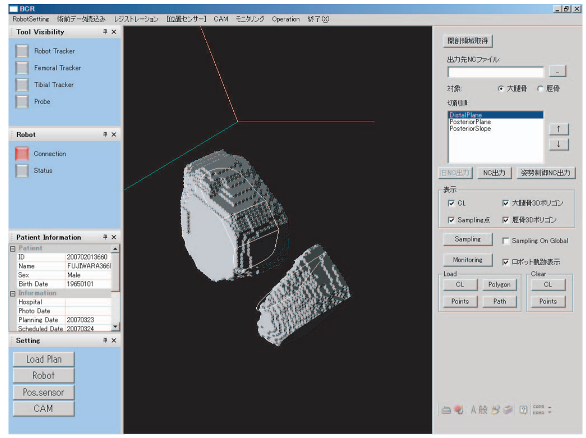


Fig. 3. Intraoperative system

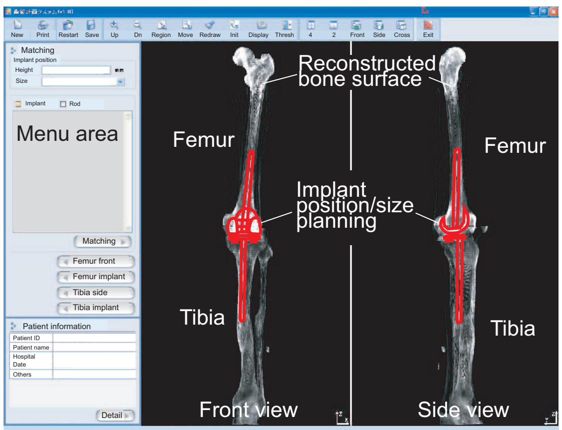


Fig. 2. Preoperative system

toolpath that considers the actual size and location of the entry incision is generated in the CAM system, based on the configuration and the shape of femur and tibia.

The surgical protocol used for the bone cutting machine tool in knee arthroplasty is as follows: skin cut, preoperative planned data reading, registration, fixture of the target bones, skin cut area measurement, toolpath generation, and bone cutting. Each surgical process is guided by the user interface. In the developed user interface, the surgeon is asked to confirm the preplanned data with the actual position by displaying the patient information at any time to increase the safety of the total system. Furthermore, a wizard format is adopted for the user interface to avoid mistakes during the actual surgical procedure. The shape of the bone, as well as the necessary numerical data needed to confirm it intuitively, is displayed on the screen.

3) Bone cutting robot: Fig.4 shows the developed bone cutting machine tool. The machine has the following features to cut the bone precisely and safely with minimal invasiveness.

(1) The machine has a C-arm type structure. It provides adequate workspace and a view for a surgeon.
(2) 3 translational axes (U, V, and W axes) and 3 rotational axes (A, B, and C axes) are implemented in the machine. The machine can set an arbitrary attitude of a cutting tool with the 3 rotational axes. This avoids collisions with the surrounding tissues during the surgical operation and minimizes invasiveness.
(3) The axes of all rotational degrees of freedom intersect at the same point. Therefore, even when a posture change of the cutting tool is required, the other axes do not move. Consequently, bone cutting is performed safely and precisely.
(4) The spindle is covered with a sleeve so that only the cutting tool tip touches the bone surface. This avoids damage to the soft tissues when the cutting tool interferes with the surrounding tissues. The spindle mechanism also satisfies the requirements for irrigation and sterility.
(5) The elevation axis (Z-axis) is implemented beneath the C-arm. This makes it possible to approach the patient with the cutting tool from an arbitrary bed height. This axis minimizes the required range of motion of the other axes, reduces the total machine weight, and improves the machine handling in the operation room.

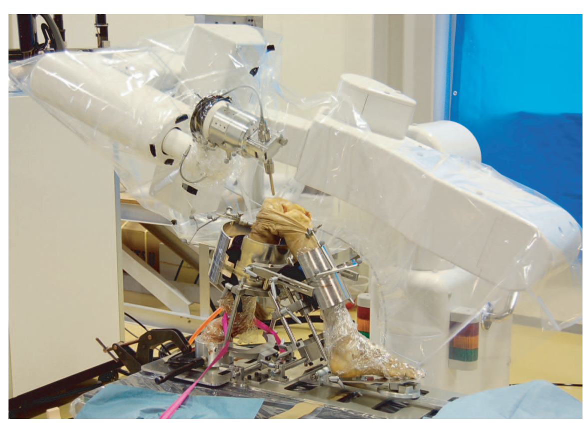


Fig. 4. Bone cutting robot

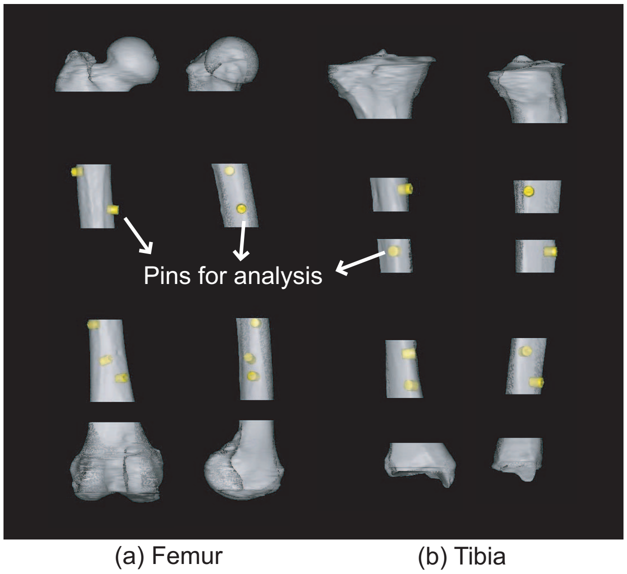


Fig. 5. Evaluation with inserted pins

B. Analysis of System Error

With the surgical system above, error of the implant position is caused by (1) preplanning error due to slice interval of computed tomography, (2) indication error of characteristic points at the registration phase, and (3) machining error due to deformation of the robot and tool by the gravity and cutting force. In this section, the precision is evaluated by the characteristic points of bone and the machined planes with the distance from the reference points inserted into the bone (Fig.5). As shown in Fig.6, 5 planes at the distal part of the femur and one plane at the proximal part of the tibia are cut accurately by the bone cutting machine tool to fit the artificial joint shape in this case.

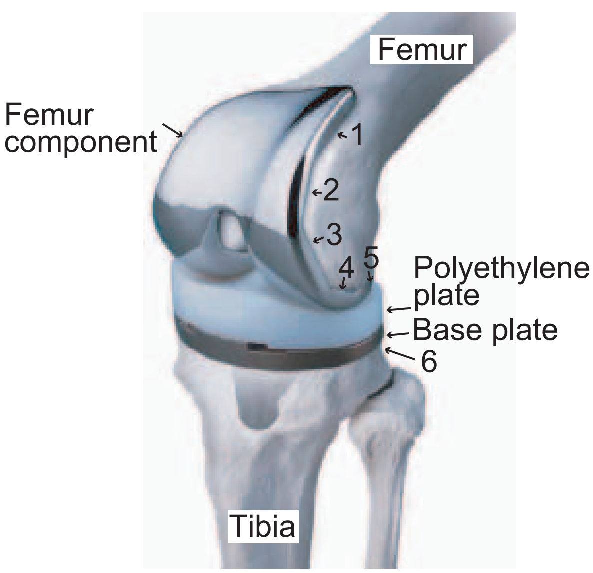


Fig. 6. Shape of an artificial knee joint(1:Anterior, 2:Anterior slope, 3:Distal, 4:Posterior slope, 5:Posterior)

Table I shows the error in the case of registration and

TABLE I

COMPARISON OF REGISTRATION AND CUTTING ERROR

Plane	Registration [mm]			After cutting [mm]			Distance ave.	Cutting/Regist error ratio
	Max.	Ave.	STDEV	Max.	Ave.	STDEV		
Anterior	6.950	4.582	1.277	6.375	3.948	1.152	-0.634	0.138
Anterior plane	5.660	3.505	1.092	5.934	3.555	0.971	0.049	0.014
Distal	0.752	0.286	0.192	0.981	0.848	0.054	0.561	1.962
Posterior slope	6.995	4.156	1.662	5.407	3.134	0.999	-1.022	0.246
Posterior	9.284	4.902	1.403	6.123	2.079	1.784	-2.822	0.576
Tibia	4.457	4.002	0.204	5.954	5.153	0.381	1.151	0.288

bone cutting, and Fig.7 shows the distribution of machining error. These errors are evaluated by the averaged distance between planned planes and ones obtained after registration or machining. The values in the table are maximum/average distance and standard deviation from the planned planes. The error ratio of registration and machining is about 75% : 25%. The ratio of registration is large. The large error is caused by the point matching registration method with three characteristic points; the surface registration decreases the error. Fig.7 shows the roughness of each plane. The error in the posterior plane is large.

This paper focuses on the machining errors caused by robot deformation in order to increase the precision of implant position. However, the machining error also includes the influences of leg fixture and system rigidity. These factors should be also considered in the near future.

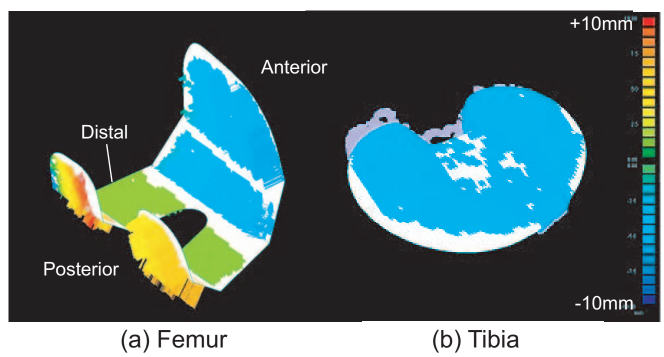


Fig. 7. Flatness of machined plane

Alignment of bone axis is important for the evaluation of a system because it affects the implant position directly. Therefore, it is calculated and estimated from the normal vector of plane after preplanning or registration. Table II and Table III show the results for femur and tibia. The alignment errors between registration and machining are 1.0 deg. at the epicondyle axis of the femur, 1.4 deg. at the load axis of the femur, and 1.8 deg. at the load axis of the tibia, respectively.

In the next two chapters, we attempt to improve the cutting precision by compensating for robot deformation due to gravity and cutting force.

III. DEFORMATION ANALYSIS OF A MILLING ROBOT

A. FEM Analysis of Robot Deformation

1) FEM model: Purposes of analysis are as follows:

TABLE II

AXIS ALIGNMENT ERROR OF FEMUR

Axis	Planned [deg.]	Registration [deg.]	Cut [deg.]
Epicondyle	90.0	83.5	84.5
Load	0.0	1.4	0.0

TABLE III

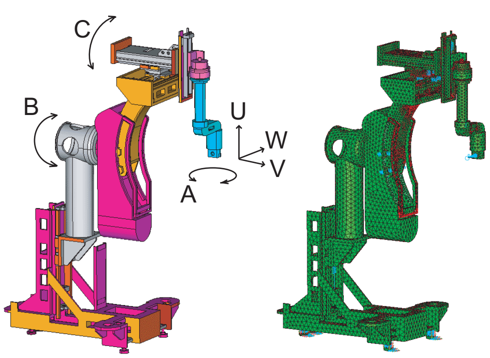
AXIS ALIGNMENT ERROR OF TIBIA

Axis	Planned [deg.]	Registration [deg.]	Cut [deg.]
Load	0.0	2.6	0.8

- Measure and calculate the static rigidity of the surgery robot;
- Measure the static deformation caused by gravity;
- Measure the tool-tip deformation caused by gravity and the cutting force;
- Measure and calculate the component contribution for the rigidity of the surgical robot.

The bone cutting robot performs according to the NC code output in the CAM. Each axis moves to the indicated point, and the cutting tool resects the bone. The precision of the motion affects the machining error. The robot posture during bone cutting depends on the rotational axes B and C (regarding the definition of axis, please refer to Fig.8). Three translational axes U, V, W, and 1 rotational axis A, are used to resect the bone. In this section, deformation of the robot by gravity and cutting force is analyzed.

3D tetrahedral elements are defined on each component with the given material type, and a rigid element is used to simulate the cutting tool. Cutting force is defined along the U V W directions (Fig.8). Linear guides and ball screw are defined as the spring elements with the calculated rigidity, and fixed translation and rotation boundary condition are defined at four jacks. C-axis driving unit is defined as the axial spring element with the rigidity of 1e10 N/mm.



(a) Surgical robot (b) FE-model

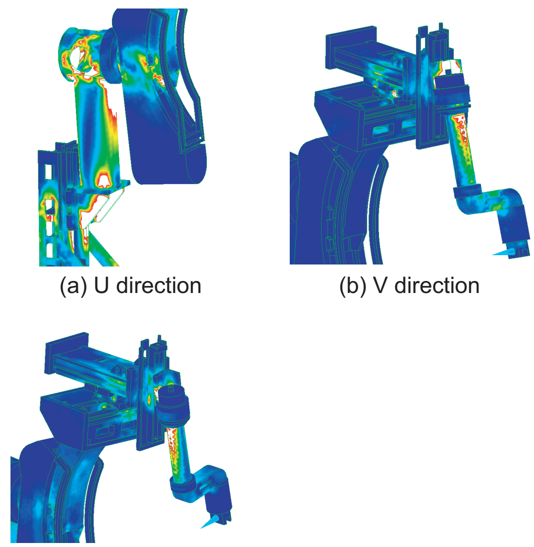
Fig. 8. Modelization for FEM analysis

2) Static rigidity: Table IV shows the static rigidity when the robot is at the reference position (posture in Fig.8). The values in the table mean displacement in the case of cutting force 30 N. The linear static solver was used to perform this analysis, so the relationship between the force and displacement is linear. The strain energy distribution for the cased of 30-N force is shown in Fig.9.

TABLE IV

STATIC RIGIDITY AT REFERENCE POSITION WHEN 30 N FORCE APPLIED

Axis	Displacement (micrometer)	Rigidity (N/micrometer)
U	110.6	0.271
V	417.7	0.072
W	459.8	0.065



(a) U direction (b) V direction

(c) V direction

Fig. 9. Strain energy distribution in analysis of static rigidity

3) Deformation analysis: Table III-A.3 shows the displacement of the robot due to gravity and cutting force. The strain energy distribution for the case of gravity and 30-N force is shown in Fig.10. Fig.10(a) is the estimation of deformation by gravity. From the table and figure, the tool tip of the robot moves in the U minus direction like bowing.

Concerning the strain distribution, the U direction is unique, and the strain is concentrated at the joint part of the elevation axis. The analysis of this feedback will contribute to the design of the robot.

B. Measurement of Robot Deformation

Contribution of B and C axis to the robot deformation is large, and the deformation of the robot is measured by moving the rotational axes B and C within the limit (regarding the definition of axis, please refer to Fig.8). In the

TABLE V

DEFORMATION ESTIMATION

Axis	Gravity Displacement [um]	Gravity and force (30N) Displacement [um]
U	-1600	-1490
V	315	733
W	-64.7	392

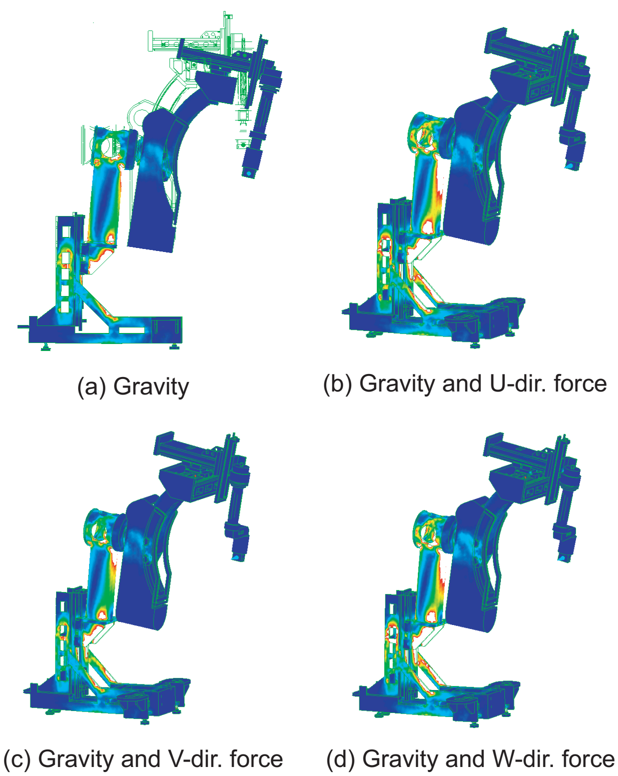


Fig. 10. Deformation estimation and strain energy distribution

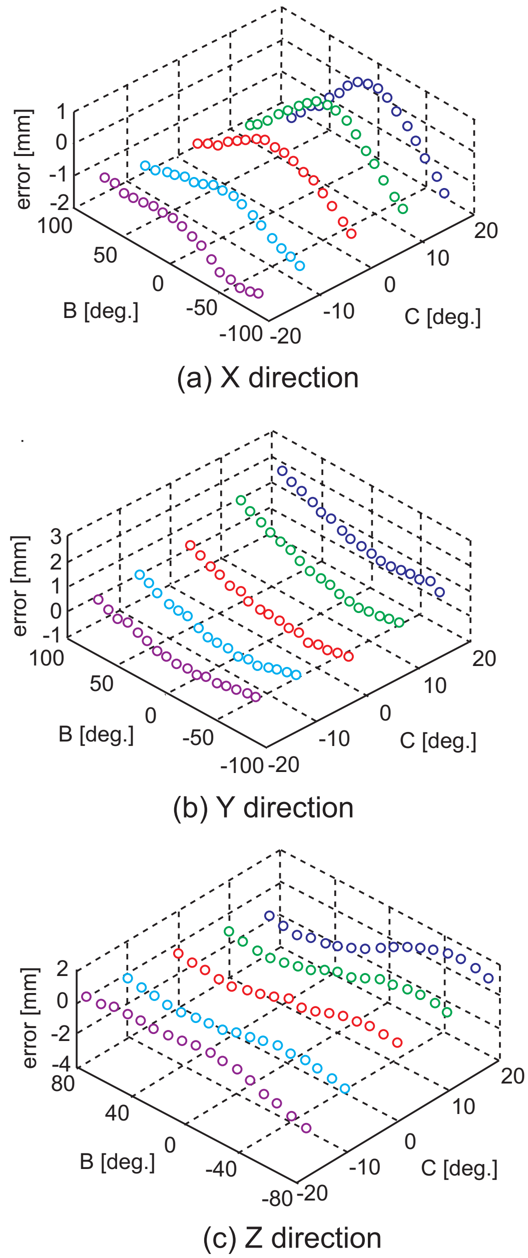


Fig. 11. Measurement result of deformation

measurement, translational axes U V W are fixed at origin position. Fig.11 shows the displacement of the tool tip with B axis from 80 deg. to -80 deg., and C axis from 18 deg. to -18 deg.

When X, Y, and Z are defined as global coordinates, they correspond with U, V, and W axes at the reference position, respectively. From the measured data, as the B axis is inclined, the position error of the tool tip increases in the direction of X minus and Y. The error in the Z direction increases according to the inclination of the B axis. The weight of translational axis affects the phenomenon of deformation.

IV. ACTIVE COMPENSATION OF ROBOT DEFORMATION

As described in the previous section, the position of the robot tool tip has some error due to the change of robot posture; this is one of the causes of machining error. In this section, the active compensation of tool position is conducted based on the error map measured in the previous section, and the position of the tool tip is adjusted according to the robot posture.

A. Active Compensation Method of Robot Deformation

The deformation map obtained in the previous section is interpolated by the spline function, and the displacement of the robot can be estimated at an arbitrary posture. In this study, the cutting tool tip is adjusted to cancel the displacement and to modify the robot posture.

When the current angles of B and C axes are b deg. and c deg., respectively, and the displacement in the X, Y, Z direction is x, y, z, the robot is compensated for according to the following equation.

$$\mathbf{A} = \begin{pmatrix} cos(b) & 0 & sin(b) & 0 \\ 0 & 1 & 0 & 0 \\ -sin(b) & 0 & cos(b) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}$$

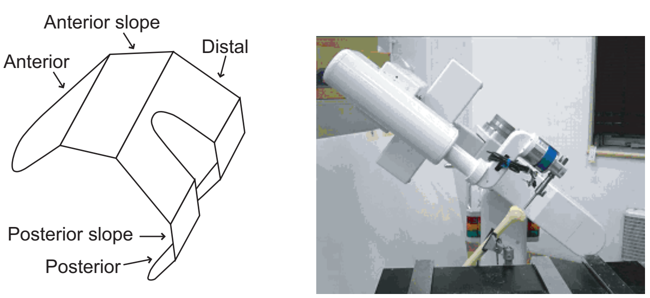
$$\mathbf{B} = \begin{pmatrix} cos(c) & -sin(c) & 0 & 0 \\ sin(c) & cos(c) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$$
\mathbf{A} \cdot \mathbf{B} \begin{pmatrix} u \\ v \\ w \\ 1 \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \tag{3}
$$

B. Experimental Results

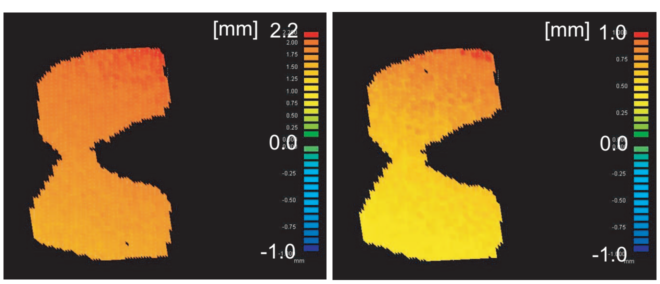
With the compensation method, the position of the tool tip is modified according to robot posture, and the effectiveness of the method is evaluated by measuring the tool tip position. Fig.12 shows the definition of the cutting planes and the robot posture during distal plane cutting. Fig.13 and Table VI show the result of compensation.

The position error decreases after compensation (Fig.13). In the case of anterior slope and posterior slope planes, the effectiveness of compensation looks small because the change of the robot posture itself is small. In the case of distal, anterior, and posterior planes, the compensation is effective, especially for the distal plane.



(a) Definition of planes (b) Robot posture for distal plane

Fig. 12. Cutting tool posture while machining the distal plane



(a) with compensation (b) without compensation

Fig. 13. Position error of tool tip in the distal plane

TABLE VI
EFFECT OF ERROR COMPENSATION

	before(mm)			after(mm)		
	Max.	Ave.	SD	Max.	Ave.	SD
Distal	2.48	1.77	0.50	1.40	0.68	0.46
Anterior	0.96	0.56	0.14	0.47	0.18	0.12
Posterior	0.83	0.48	0.16	0.68	0.24	0.17
Anterior slope	0.80	0.39	0.18	0.68	0.25	0.18
Posterior slope	0.49	0.28	0.08	0.23	0.06	0.04

V. CONCLUSIONS

In this paper, using our surgical system and milling robot as an example, the precision of registration and machining was analyzed. Deformation of milling robot was analyzed by the finite elemental method and measured by the 3-dimensional position sensor at some postures. Likewise, a method of active deformation compensation was proposed and tried based on the error map.

1) System errors were evaluated by the averaged distance between planned planes and ones after registration or machining.
2) With the FEM model of the milling robot, the static rigidity of the surgery robot, the static deformation caused by the gravity, the tool tip deformation caused by the gravity, and the cutting force were evaluated.
3) Cutting precision can be improved by compensating for the robot position. The displacement of the tool tip was compensated for according to the robot posture, and the error decreased from 1.77 mm to 0.68 mm in the distal plane of femur by evaluating the cutting tool position.

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