A Study on Improvement of Machining Precision in a Medical Milling Robot*

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Minimal invasiveness and increasing of precision have recently become important issues in orthopedic surgery. The femur and tibia must be cut precisely for successful knee arthroplasty. The recent trend towards Minimally Invasive Surgery (MIS) has increased surgical difficulty since the incision length and open access area are small. In this paper, the result of deformation analysis of the robot and an active compensation method of robot deformation, which is based on an error map, are proposed and evaluated.

1. Introduction

Knee joint replacement is a type of orthopedic surgery performed in order to reduce the pain caused by the destruction of a joint by osteoarthritis or rheumatoid arthritis and to thereby enhance the Quality Of Life (QOL) of patients. In the surgical operation, the damaged articular region is excised to fit the shape of the remaining region to the setting plane of an artificial joint, and the original joint is then replaced by the artificial joint. The number of patients who suffer from osteoarthritis ranges from 12 to 20 % of the total population. The number is expected to increase rapidly owing to the aging trends in developed countries.

In the replacement of a joint, 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, and 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 joint replacement and to increase the accuracy of bone cutting, as shown in Fig. 1.

ROBODOC has been developed as a robotic orthopedic surgery system [1] and is the most famous system of its kind in the orthopedic field. The system has already been used in numerous clinical operations. Recent orthopedic robots display unique features. Some work passively to support the surgeon, and others are downsized and mounted directly on bone. For example, “ACROBOT”, developed by

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Fig. 1 Knee joint surgery with milling robot
Davies et al. passively supports the surgeon, and is used clinically \[2\]. Maillet et al. developed “BRIGHT”, which has a guide jig for a bone saw implemented on the tip of a robot arm \[3\]. “ARTHROBOT” by Chun et al. is intended for minimally invasive joint replacement \[4\], and a robot by Plaskos can be set on bone directly \[5\]. The recent tendency has been to focus on high accuracy and minimal invasiveness of the surgical procedure. Burger et al. presented the design 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 have 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, the deformation of the milling robot by gravity and cutting force is analyzed using a finite elemental method, and the deformation is actually measured by a three-dimensional position sensor. This enables the creation of an error map at some robot postures. Likewise, a method of active compensation of the robot deformation is proposed and evaluated based on the error map.

2. Machine Tool System for Medical Use

Considering use in the operation room, the size of the machine is 910 mm in width and 2,080 mm in height. The weight is approximately 300 kg, and the developed machine tool has 7 degrees of freedom. Mechanical and structural features are as follows: (1) High rigidity is realized by adopting a linear guide and a circular guide. The mechanical elements which are used for the robot have a high system rigidity compared with a conventional robot having rotational degrees of freedom. (2) The axes of all rotational degrees of freedom intersect at the same point. When the attitude of a cutting tool is changed, the other axis does not have to move for safety reasons. The bone cutting robot is located beside the operating table. The rigidity is 271 N/mm, 72 N/mm, 65 N/mm for U-axis, V-axis and W-axis at the home position, respectively. Each axis is driven by servo motor (U, V and W axes) or rotary actuator (A, B and C), and a timing belt is used for C axis.

Fig. 2 shows the overview of the robot ((a)(b) in the figure) and the kinematics ((c) in the figure). A serial kinematics is realized in order of $E \rightarrow B \rightarrow C \rightarrow U \rightarrow W \rightarrow V \rightarrow A$ from the base part. The forward kinematics of the cutting tool are expressed as follows.

$$
\begin{bmatrix}
1 & 0 & 0 & E \\
0 & 1 & 0 & U \\
0 & 0 & 1 & V \\
0 & 0 & 0 & W
\end{bmatrix}
\begin{bmatrix}
CB \cdot SC & -SB \cdot SC \cdot CA + SB \cdot SA \\
SC & CC \cdot CA \\
-SC \cdot CC & SB \cdot SC \cdot CA + CB \cdot SA \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
CC & -SC & 0 & 0 \\
SC & CC & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & CA & -SA & 0 \\
0 & SA & CA & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

where the used symbols are

- $CA : \cos \theta_A$, $SA : \sin \theta_A$
- $CB : \cos \theta_B$, $SB : \sin \theta_B$
- $CC : \cos \theta_C$, $SC : \sin \theta_C$
- $\theta_A, \theta_B, \theta_C :$ angle of $A,B,C$ axes, respectively,

The robot has two redundant axes $E$ and $A$. $E$-axis is used for the initial setting of robot height. $C$-axis is used during the machining of bone. The problems in the minimally invasive surgical procedure are to approach and resect the target bone through the narrow visible area. To solve these problems, the machine tool is equipped with a redundant $A$-axis, and the cutting tool can avoid the interference like the soft tissues under the minimum change of the robot attitude. The tool tip does not move during the rotation of this redundant axis, and the cutting tool approaches inside the joint and resect the target bone.
by controlling the tool attitude suitably. Damage to soft tissue should be avoided when the bone is machined. Damage can occur for the following reasons: (1) collision of cutting tool and soft tissue; (2) thermal damage caused by cutting temperature and tool friction heat; and (3) long cutting time and mechanical stress to the patient. When the opening area is relatively large, the tool path generator for MIS is sufficient for the operation. However, in the minimally invasive surgery that this study targets, completing resection without any collision of the cutting tool and soft tissue is difficult as the opening area is small and interferences surround the target area. A protective mechanism to cover the non-working part of the cutting edge is thus required, and a spindle equipped with a tool cover is developed as shown in Fig. 3.

![Fig. 3 Overview of tool part](image)

The tool system comprises the cutting tool, tool attachment, tool cover, and decelerator and motor. The tool cover can be controlled in shaft and circumferential directions. From the perspective of requirements for the tool system, the main specifications are as follows: tool diameter: Φ8, rotational speed: 5000 rpm, and shaft length: 70 mm. In addition, the safety of the patient and the surgeon must be ensured and adequate irrigation and sterilization capabilities are provided in the machine tool for medical use. A positive pressure structure is adopted in the tool attachment to evacuate the contaminant, and it is possible to sterilize this.

### 3. Deformation Analysis of the Milling Robot

#### 3.1 FEM Analysis of Robot Deformation

In this section, the robot deformation is simulated, and the purposes of analysis are as follows:

1. Measure the static deformation caused by gravity.
2. Measure the tool-tip deformation caused by gravity and cutting force.
3. Measure and calculate the rigidity by cutting force.
The bone cutting robot is performed along the NC code output from the CAM. Each axis moves to the indicated points and the cutting tool resects the bone. The precision of motion affects the machining error. The robot posture during the bone cutting depends on the rotational axes B and C (regarding the definition of axis, please refer to Fig. 2). Three translational axes U, V, W and one rotational axis A are used to resect the bone. In this section, the deformation of the robot by gravity and cutting force is analyzed. A commercial software (I-deas, Siemens) is used for the calculation of the deformation. 3D tetrahedral elements are defined on each component with the given material type, and a rigid element is used to simulate the cutting tool. Depending on the geometry features in the model, the different element size are used. For the main structure, 30mm parabolic tetrahedral elements are used.

Each joint is modeled using connection spring, and bearing (A, B axes), linear guides (U, V, W, E axes), ball screw (U, V, W, E axes) and sliding surface (C-axis) are defined as spring elements with calculated rigidity. In the analysis, the displacement of the tool tip position in the global coordinates X-Y-Z is evaluated for the deformation of the robot. The strain energy is also evaluated, and the potential energy, i.e. strain energy, is mainly focused corresponding to the cutting load. The high strain energy areas are pointed out considering both stress and strain.

### 3.1.1 Deformation analysis by gravity

Fig. 5 shows the deformation estimation and strain energy distribution by gravity. The surgical robot inclines forward, and the position of the tool tip is shifted more than 1 mm, especially in the X minus direction as described in Table 1. From the table and figure, the cutting tool tip of the robot moves in the X minus direction in a bowing motion. Regarding the strain energy, it is recognized that the distributions in the E-axis and base station are very high.

### 3.1.2 Deformation analysis by gravity and cutting force

Table 2 shows the displacement of the robot owing to gravity and cutting force, and the strain energy distribution in the case of the 30 N cutting force is shown in Fig. 6. The authors measured the cutting force so far during the bone cutting, and it is around 30 N at maximum. Therefore, we applied a cutting force of 30 N in the simulation.

### 3.1.3 Deformation analysis by cutting force

The strain energy distribution for the case of 30 N force is shown in Fig. 7. In the case, the influence of the gravity is not considered. The displacement is largest in the Z direction, and this means the rigidity in the Z direction is smallest. The rigidity is much smaller than at the machining center, and it should be improved by any method. Compared Fig. 6 with

#### Table 1 Displacement of tool tip position by gravity

<table>
<thead>
<tr>
<th>Axis</th>
<th>Displacement [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>−1600</td>
</tr>
<tr>
<td>Y</td>
<td>315</td>
</tr>
<tr>
<td>Z</td>
<td>−64.7</td>
</tr>
</tbody>
</table>

#### Table 2 Displacement of tool tip position by gravity and force 30N

<table>
<thead>
<tr>
<th>Axis</th>
<th>Displacement [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>−1490</td>
</tr>
<tr>
<td>Y</td>
<td>733</td>
</tr>
<tr>
<td>Z</td>
<td>392</td>
</tr>
</tbody>
</table>
Fig. 6 Deformation and strain energy distribution by gravity and cutting force 30N

Fig. 7, although both results of simulation are under the same conditions with gravity and cutting force of 30 N, the strain shown around the spindle-head occurred to only the robot in Fig. 7. That’s because the strain energy caused by gravity is extremely larger than the strain energy caused by cutting force.

Table 3 Rigidity at reference position when 30N force applied

<table>
<thead>
<tr>
<th>Axis</th>
<th>Displacement [μm]</th>
<th>Rigidity [N/μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>110.6</td>
<td>0.271</td>
</tr>
<tr>
<td>Y</td>
<td>417.7</td>
<td>0.072</td>
</tr>
<tr>
<td>Z</td>
<td>459.8</td>
<td>0.065</td>
</tr>
</tbody>
</table>

3.2 Measurement of Robot Deformation

The deformation of the robot is measured by moving the rotational axes B and C as shown in Fig. 8 (regarding the definition of axis, please refer to Fig. 4). In the measurement, the translational axes U, V and W are fixed at the original position. Fig. 9 shows the displacement of the tool tip with the B-axis from 80 deg to −80 deg, and the C-axis from 18 deg to −18 deg. The position of the cutting tool is measured by a three-dimensional infrared sensor.

When it is assumed that X, Y and Z are defined as global coordinates, they correspond with the U, V and W axes respectively at the reference position. From the measured data, it is recognized that the displacement of the cutting tool tip position depends on the angles of the B-axis and C-axis. The values range between −1.5 mm and 2.0 mm. The weight of the translational axis will affect the phenomenon of deformation.

4. Active Compensation of Tool Tip Position Error

As described in the previous section, the position of the robot tool tip experiences some errors according to the change of robot posture, and this is one
of the causes of machining errors. The displacement of the cutting tool tip is influenced by the robot posture more than by the cutting force. Therefore, an active compensation of the tool position owing to the robot posture is conducted based on the error map measured in the previous section.

4.1 Evaluation Method of Active Compensation

The deformation map obtained in the previous section is interpolated using bicubic interpolation [8], and the displacement of the robot can be estimated at arbitrary posture. In the study, the cutting tool tip is adjusted to cancel the displacement and to modify the robot posture.

\[
\begin{bmatrix}
    CC & SC & 0 & 0 \\
    -SC & CC & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    CB & 0 & -SB & 0 \\
    0 & 1 & 0 & 0 \\
    SB & 0 & CB & 0
\end{bmatrix}
\begin{bmatrix}
    x & y & z & 1
\end{bmatrix}
\]

The robot is controlled along the numerical code output from CAM software. The measured deformation map is obtained in the global coordinates X-Y-Z, and the error is compensated using the translational axes U, V, W in this paper. Therefore, the error must be converted to the robot coordinates U-V-W from the global coordinates. When the current angles of the B and C axes are \( \theta_B \) deg and \( \theta_C \) deg respectively and the displacement error of the tool tip is \( x, y \) and \( z \) in the global coordinates X, Y and Z direction, the motion for the compensation is calculated from the following equation as \( u, v \) and \( w \) in the robot coordinates. The numerical code is modified along the values.

\[
\begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix} = \begin{bmatrix}
    CC & SC & 0 & 0 \\
    -SC & CC & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    CB & 0 & -SB & 0 \\
    0 & 1 & 0 & 0 \\
    SB & 0 & CB & 0
\end{bmatrix} \begin{bmatrix}
    x \\
    y \\
    z \\
    1
\end{bmatrix}
\]

\( CB : \cos \theta_B \), \( SB : \sin \theta_B \)

\( CC : \cos \theta_C \), \( SC : \sin \theta_C \)

\( \theta_B, \theta_C \) : angle of B, C axes, respectively

\( u, v, w \) : compensation value for U, V and W axes

\( x, y, z \) : displacement error of tool tip

in the global coordinates

4.2 Experimental Results

With the compensation method, the position of the tool tip is modified according to the robot posture, and the effectiveness of this method is evaluated by measuring the tool tip position using a three-dimensional position sensor. Fig. 10 shows the definition of the cutting planes. Fig. 11 shows the difference of the actual tool tip position from the ideal position when the actual tool path for the bone machining is applied.

Fig. 11 shows that the position error can be decreased after the compensation. In the case of the anterior slope and the posterior slope planes, the error before compensation is also small relatively. That’s because the change of the robot posture itself is small. In the case of the distal, it seems that the compensation is effective. The acceptable machining error is generally 1 mm for the position and 1 deg for the an-
Fig. 10 Definition of cutting planes

Fig. 11 Difference of the tool tip position from the ideal position

gle in the knee joint replacement. The results after compensation meet the requirement for the position. However, the influences of the cutting force and the measurement error should be investigated in the future.

5. Conclusions

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

(1) With the FEM model of the milling robot, evaluation is conducted of the static rigidity of the surgery robot, the static deformation caused by gravity, and the tool tip deformation caused by gravity and cutting force. The results show that the deformation is influenced by robot posture, and its length is more than 3 mm from the reference position to the travel end position.

(2) It was confirmed that the cutting precision can be improved with compensation of the robot position. The displacement of the tool tip is compensated according to the robot posture, and the error is decreased especially in the distal plane of the femur.

参 考 文 献

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