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Toolpath Optimization for a Milling Robot of Minimally Invasive Orthopedic Surgery

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***Abstract*— Toolpath generation and optimization is considered as a challenging problem in the minimally invasive orthopedic surgery with a milling robot. The objective of this paper is to minimize the collision of the cutting tool with the soft tissues. A novel approach of toolpath generation and optimization is proposed. A redundant axis is implemented to avoid the collision in the robot. Some important components are modeled based on the physical requirements. A geometric optimization approach based on the model is proposed to improve the toolpath. Case studies show the validity of this approach. Software is developed for this application and the effectiveness is evaluated with a cadaveric bone.**

I. INTRODUCTION

A. Background

In the surgical procedure of joint replacement, the setting position of the artificial joint affects the inferior limb direction after the operation. Therefore, postoperative pain, reduction in the useful lifespan of the artificial joint, and organization necrosis due to abrasive wear particles shed by the bone-joint system will occur if the artificial joint is not properly fixed. The accuracy of the cut surface conventionally depends on the surgeon's skill, because the bone is shaped by hand. Therefore, the use of a bone-cutting robot is expected to increase the quality of the surgery, and many robots have been developed worldwide.

Meanwhile, the number of surgical procedures with minimally invasive technique has been increased also in orthopedic field. The minimally invasive surgical approach utilizes small incisions and offers several advantages over traditional open surgery as reduced pain and trauma to the body, faster recovery and shorter hospital stay. New ways to open the knee may be more important than the length of the incision. However, the difficulty of the procedure increases with the smaller incisions, and the result of the operation depends on the surgeon's skill. Therefore, it is hoped that a mechanical or robotic assisted surgery system is introduced in the procedure.

B. Purpose and Goals

Invasiveness, accuracy of cut surface, high efficiency and safety of machining are required in the minimally invasive orthopedic surgery mainly. The minimally invasive knee replacement technique attempts to accomplish the procedure through a smaller incision, and the knee joint is accessed through the quadricep tendon. This is said to be less invasive to soft tissues and or bone. The shape accuracy of the setting plane is important to fit the artificial joint, and the setting absolute position of the artificial joint should be precise. Operation time for bone cutting is limited to about 15 minutes in terms of nacrosis. The safety of machine and tools is also required.

Many of developed robots so far including our multi-axis bone cutting robot uses an end mill as a cutting tool, and the following problems should be solved to apply them to the minimally invasive orthopedic surgery.

The minimally invasive surgery makes the incisions smaller, reduces pain and trauma to the body and helps faster recovery. The smaller incision means the small and narrow opening area. This results that the robot attitude for the bone resection is restricted, and it can result in the collision of tool with the surrounding tissue, the existence of untouched area and the degradation of joint position accuracy. Toolpath generation technique specialized for the bone cutting is expected to resolve these issues.

Also the collision of the cutting edge with the soft tissue should be taken into account as a problem of invasiveness. The end mill is a rotational tool, and all the angles around the shaft function as a cutter. Therefore, it is likely to damage the surrounding soft tissues, vessels, nerves. The protection mechanism to cover the unworking part of the cutting edge will be required and avoid the damage. The necrosis of bone cell caused by the cutting heat or the tool friction heat should be prevented by cooling the cutting edge.

In this paper, a toolpath generation method is proposed to minimize the damage of the surrounding tissues in the robotic assisted minimally invasive orthopedic surgery. With the method, cutting tool can approach the resection area through a narrow opening area, proceed the machining of the bone without any damage and accomplish the procedure.

C. Related Works

ROBODOC has been developed as a robotic orthopedic surgery system [1] and is most famous in the orthopedic field. It has been used in many clinical operations. The recent orthopedic robots have unique features. A robot works passively supporting the surgeon, and another is downsized and mounted on the bone directly. For example, "ACROBOT" developed by Davies,B. et al. is former, and it is used clinically [2]. Dombre,E. et al. developed "BRIGHT", and a guide jig for the bone saw is implemented on the tip of robot arm [3]. "ARTHROBOT" by Kwon,D.S. et al. aimed at the minimally invasive joint replacement [4], and a robot by Plaskos,Ch. can be set on the bone directly [5]. The recent

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tendency is focused on the minimal invasiveness of surgical procedure in addition to the high accuracy.

This study focuses on the issues of the tool attitude control and the toolpath generation due to the narrow opening area, and these problems are resolved in a robotic assisted minimally invasive surgery. Toolpath optimization problems themselves have been discussed in manufacturing systems and robot manipulators for a long term. The toolpath generation in the multi-axis machining tool and the path planning to avoid the interference in the robot manipulator have been studied.

For example, Morishige,K. et al. applied the concept of the configuration space to the collision avoidance for 5-axis control machining. The concept was studied in the robot field originally [6]. Pritschow,G., et al. presented the design and test of a fail-safe numerical control (NC) for robotic surgery, which has assisted in a wide range of surgical treatments [7].

The minimal invasiveness in the robotic assisted orthopedic surgery comes to the toolpath generation study. A cutting tool approaches the target through the small hole and resects the large area inside the joint. This paper proposes a toolpath generation method to cut the bone without damaging the surrounding tissues.

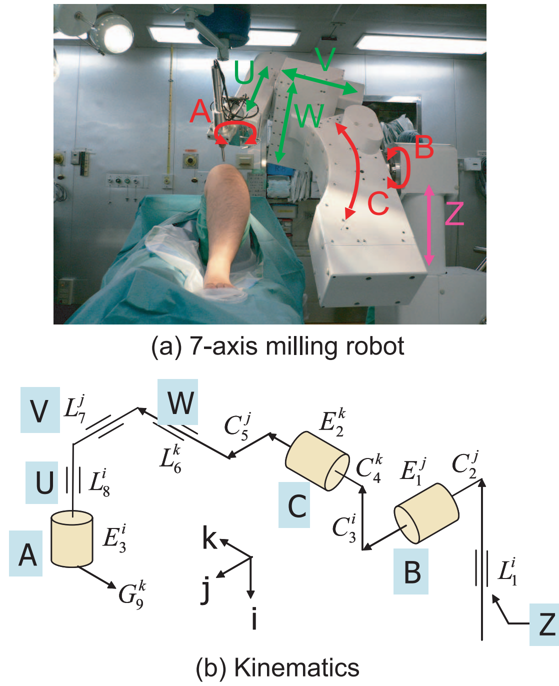

Fig. 1. Overview and kinematics of milling robot

II. MILLING ROBOT DESIGNED FOR MIOS

A. Concept

Considering the use in the operation room, the size of the machine is designed to 900mm, 1,800mm for width and height, respectively. The weight is approximately 300kg, and the developed machine tool has 7 d.o.f. 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 realize 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 as shown in Fig.1. 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.

B. Kinematics

Figure 1 shows the overview of the robot ((a) in the figure) and the kinematics ((b) in the figure). A serial kinematics is realized in order of $Z \rightarrow B \rightarrow A \rightarrow U \rightarrow W \rightarrow V \rightarrow C \rightarrow$ from the base part. The attitude matrix and the position of the cutting tool are expressed as follows.

Attitude matrix:

$$\mathbf{E} = \mathbf{E}^{j\theta_1} \cdot \mathbf{E}^{k\theta_2} \cdot \mathbf{E}^{i\theta_3} \tag{1}$$

Tool position:

$$\begin{aligned}\mathbf{P} =& \mathbf{L}_1^i + \mathbf{C}_2^j + \mathbf{E}^{j\theta_1} \cdot (\mathbf{C}_3^i + \mathbf{C}_4^k + \mathbf{E}^{k\theta_2} \cdot \\ & (\mathbf{C}_5^j + \mathbf{L}_6^k + \mathbf{L}_7^j + \mathbf{L}_8^i + \mathbf{E}^{i\theta_3} \cdot \mathbf{G}_9))\end{aligned} \tag{2}$$

where the position of the cutting tool $\mathbf{P}$ is composed of rotational matrix $\mathbf{E}$, variable matrix $\mathbf{L}$, fixed vector $\mathbf{C}$ and $\mathbf{G}$. The subscripts i, j, k mean the operation to U-axis, V-axis W-axis, respectively.

C. Redundant Axis for Minimally Invasion

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 axis (C-axis in Fig.1), and the cutting tool can avoid the interference like the soft tissues under the minimum change of the robot attitude.

Figure 2 shows the redundant axis and spindle with the cutting tool. 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.

III. STRATEGIES FOR TOOLPATH OPTIMIZATION

A. Toolpath in MIS

In the minimal invasiveness of the procedure, the control of the tool attitude and the toolpath generation are problems caused by the restricted opening area. As shown in Fig.3, the cutting tool approaches through the opening area (the range where the tool can enter) and resect the large part. In the total knee arthroplasty (TKA), there are 5 planes (anterior, anterior slope, distal, posterior slope, posterior) for femur, and the cutting tool needs to work deep inside the joint.

It is important not to collide with or damage the soft tissues during the bone resection, and it is necessary to calculate the optimum attitude of tool for that. Although the attitude of the cutting tool is restricted due to the small opening area, the degradation of the cutting accuracy is not allowed.

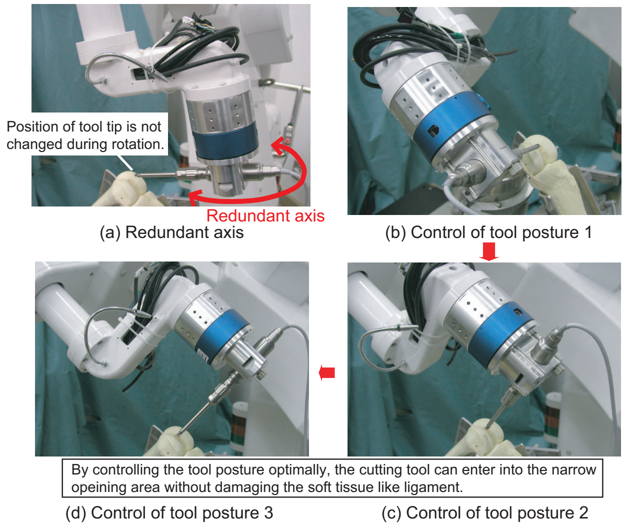

Fig. 2. Redundant Axis for Minimally Invasion

The preoperative CT images don't make clear the contour of the cartilage generally, and the posture of patient changes at pre- and intra-operation. Therefore, the precise shape and position of workpiece is determined at intra-operation, and the toolpath planning should be completed then. These environments are different from the industrial case.

These problems are unique in the surgical procedure, and this paper focuses on the toolpath generation in multi-axis bone machine tool. Specifically, as shown in Fig.4, the opening area, the interference plane, the resection part and the cutting tool are modeled geometrically. The task is to finish the target plane without any collision or damage, and the theme is how to solve this issue.

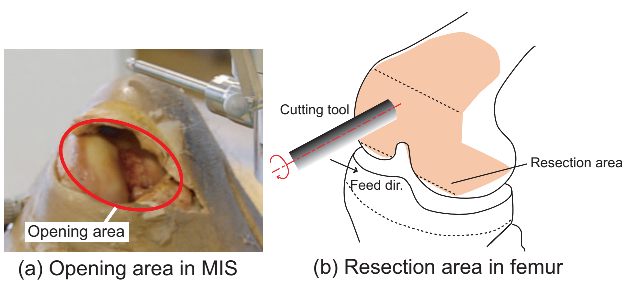

Fig. 3. Toolpath in Minimally Invasive Surgery

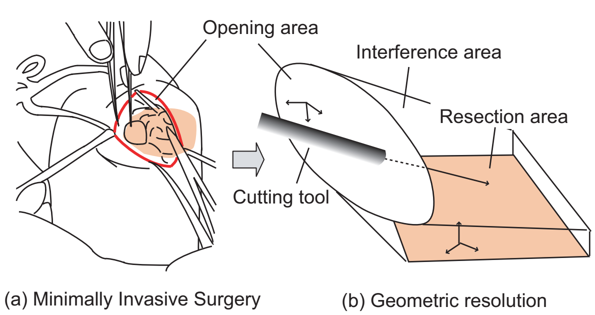

Fig. 4. Geometric model

B. Concept of Toolpath Generation

It is desirable to generate the tool to shorten the incision length in terms of the minimal invasion. However, considering the safety of machining, the frequent attitude change of the cutting tool makes difficult the prediction of the mechanical collision, and it is possible to prevent the emergency button from working. A collision risk with the soft tissues increases in the cutting part surrounded by the interferences. The following efficient machining concepts can be proposed from these things.

1) Incision Length Minimization Strategy: In the concept shown in Fig.5(a), the attitude of the cutting tool is changed actively, and the length of the incision is minimized. The tool can approach through the small and narrow opening area.

2) Safety First Strategy: In the concept shown in Fig.5(b), the safety is weighted, and the machining is proceeded with less attitude change. It is easy to predict the attitude and position of the tool, but it requires more length of the incision compared with the former Incision Length Minimization Strategy.

Each concept cannot accomplish the minimally invasive surgical procedure by itself, and a method to mix their advantages is proposed in this paper.

C. Proposed Toolpath Generation Strategy

Step1: As described in former sections, the machining process of orthopedic surgery is different from the industrial one. The shape of workpiece is complicated, and the surrounding interferences also have complexity in their shape. This collision avoidance problem comes to a geometric issue. First, the opening area, the interference planes and the resection part are measured and calculated with a 3-dimensional optical position instrument (Northern Digital Inc., Polaris). Based on the data of measured points, a plane is generated statically, and a geometric model is constructed(refer to SectionIV-A).

Step2:(Fig.6(a)) Next, it is determined which direction the cutting tool should approach from, and it is calculated how the attitude should be to cut the bone. Considering the collision with the interference, a tool attitude is obtained to cut all the target area. If there is no attitude to meet the condition, an attitude to maximize the possible area is selected. On the other hand, when some attitudes can attain

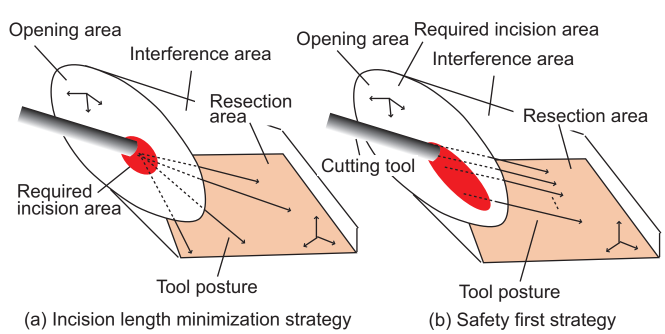

Fig. 5. Concepts of tool path generation for MIS

the purpose, an attitude to minimize the required opening area is selected. The selected one is set to the attitude for the approach and the toolpath generation.

Step3:(Fig.6(b)) With the attitude calculated in Step2, cutting location (CL) is computed. Zigzag path is used for it, and other parameters like cutting direction (down cutting, up cutting) can be set by the software. By those steps so far, initial tool attitude and cutting location are determined.

Step4:(Fig.6(c)) Tool attitude is computed for each CL point. Rotational B-axis and C-axis in Fig.1 are used for the initial tool attitude, and the angle of more one rotational and redundant axis fixes the tool posture during the bone cutting. There are two ways to move the redundant axis. One is what the attitude of the tool is modified continuously as shown in Fig.7(a). In Fig.7(b), the redundant axis is not changed as long as the tool collision with the soft tissue is not occurred. It should be discussed which is better way. In either way, the tool tip is controlled so that it moves along the cutting location. Finally, collision with the interferences is checked, and if the collision is detected, tool attitude is modified to avoid it with other rotational axis (θ in Fig.7(c)). Please refer to Section IV-C in detail.

Figure 8 shows the case which this method above is applied to the multi-axis bone cutting robot. Rotational angles θ, ϕ in the figure are used to avoid the collision during the machining of bone. It depends on the situation which axis is the redundant angle, and Posture1 and Posture2 in the figure remain the vagueness.

IV. TECHNICAL ISSUES FOR TOOLPATH GENERATION

A. Measurement of Opening Area and Interference Planes

To model the knee joint, the required planes, the opening plane, the interference planes and the resection plane,

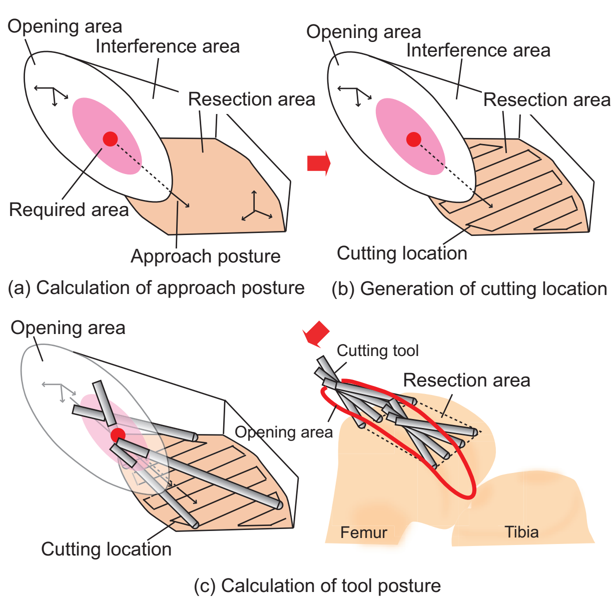

Fig. 6. Proposed strategy

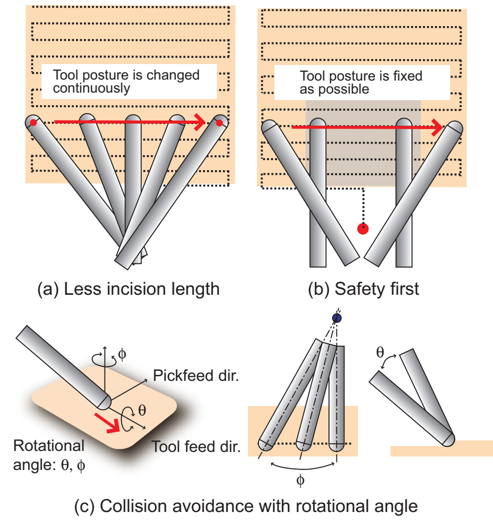

Fig. 7. Interference avoidance with rotational angle

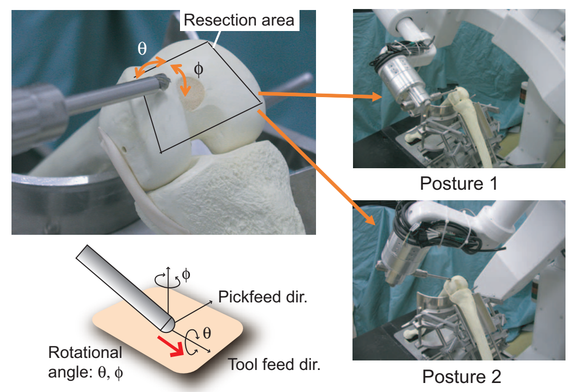

Fig. 8. Cutting tool Posture

are measured with a 3-dimensional optical position sensor (Northern Digital Inc., Polaris).

First, a probe is used to measure the points on the planes as depicted in Fig.9 left. For example, the border of the area is measured for the opening plane, and the points on other planes are probed for the interferences and the resection part.

Based on the stored data, a regression analysis is used, and the following equation is computed.

$$J(a, b, c) = \sum (z_i - ax_i - by_i - c)^2 \quad (3)$$
$$\frac{\partial J}{\partial a} = 0, \frac{\partial J}{\partial b} = 0, \frac{\partial J}{\partial c} = 0$$

A plane $z = ax + by + c$ is obtained from this equation. The opening area is defined as an inner part of the points.

B. Calculation of Initial Tool Posture

Utilizing the cross detection of the tool vector and the target plane, machinable area is calculated at a tool attitude, and a posture to maximize it without any collision is selected.

A local coordinate system is set on the opening area measured with the 3-dimensional sensor. The normal direction is z-axis and defined as $\mathbf{n}$. The resection plane is divided into

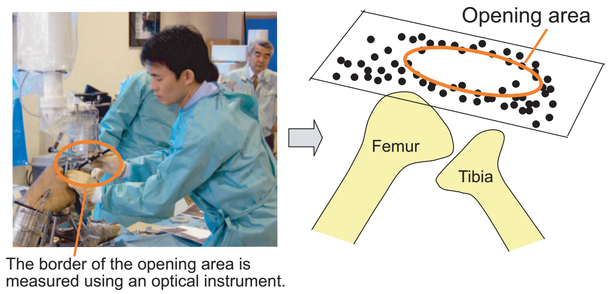

Fig. 9. Measurement of opening area

the triangle patches (K_i) in Fig.10(a), and vertex vectors are set($\mathbf{q_i}$). Tool vector with a attitude vector $\mathbf{l}$ and an offset vector from the origin $\mathbf{p}$ comes to $\mathbf{p}+t\mathbf{l}$, and Eq. 4 shows one of the triangle patches $K_i(i = 1...)$.

$$(1-u-v)\mathbf{q_0} + u\mathbf{q_1} + v\mathbf{q_2} \qquad (4)$$
$$0 < u, v < 1$$

The following equation detects whether this patch is machinable [8].

$$\begin{pmatrix} -\mathbf{l} & (\mathbf{q_1}-\mathbf{q_0}) & (\mathbf{q_2}-\mathbf{q_0}) \end{pmatrix} \begin{pmatrix} t \\ u \\ v \end{pmatrix} = (\mathbf{p}-\mathbf{q_0}) \qquad (5)$$

When it is machinable, the collision with the interferences $T_i(i = 1...)$ is checked next. As expressed in Eq.6, the offset vector $\mathbf{p}$ is varied on the opening plane with the parameter of the tool attitude $\mathbf{l}$, and the machinable area is calculated on the triangle patch K_i. Likewise, the machinable area is computed on other triangle patches. An attitude l to maximize the evaluation function Eq.6 is selected as the initial tool posture.

$$J(\mathbf{l}) = \sum_{K_1}^{K_n} \int E(\mathbf{l}, \mathbf{p}) dx dy \quad x, y, \mathbf{p} \in S \qquad (6)$$
$$E(\mathbf{l}, \mathbf{p}) = \begin{cases} 1 & (without collision) \\ 0 & (with collision) \end{cases}$$

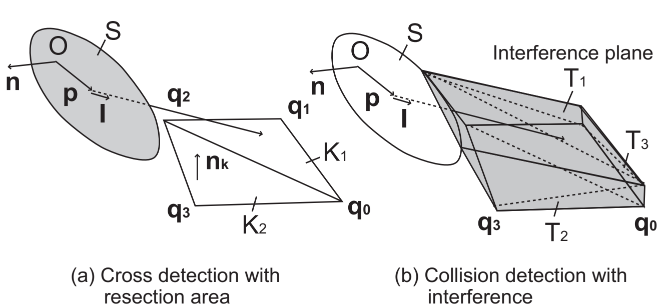

Fig. 10. Cross detection strategy

C. Calculation of Collision Avoidance

When the collision with the interference is detected, it is avoided with a minimal change of the tool attitude. In this case, the avoidance direction is equal to a vector which the normal vector of interference plane is projected on the tool axis coordinate system in Fig.11(a). α, β are the minimal angle of rotational axis to avoid the collision, and the new attitude of tool is expressed in the local coordinate system. The angle to control is calculated from the kinematics of the robot.

V. EXPERIMENTAL RESULTS

When the proposed toolpath generation method above is applied to the robotic assisted surgical procedure, the effectiveness is evaluated by the motion of the cutting tool during the process. The shape of workpiece is unique in the minimally invasive joint replace, and there are many interferences and a small opening area. The toolpath generation algorithm is implemented in the processor for the multi-axis bone cutting robot, and the cutting location data without any collision is generated automatically.

In the experiment, unicondylar knee arthroplasty (UKA) and total knee arthroplasty (TKA) are targeted, and a cadaveric bone was cut. In UKA case, 3 surfaces for femur (distal, posterior slope and posterior) and 1 surface for tibia are cut using the developed system. As shown in Fig.3, most of the resected part is surrounded by the soft tissues, and the collision avoidance is required by controlling the tool attitude optimally.

Figure 12 shows the cutting location (CL) data generated for femur automatically. Fig.12(a) is for UKA, and Fig.12(b) is for TKA. After resection plane, interference planes and opening plane are measured and computed, the data of the

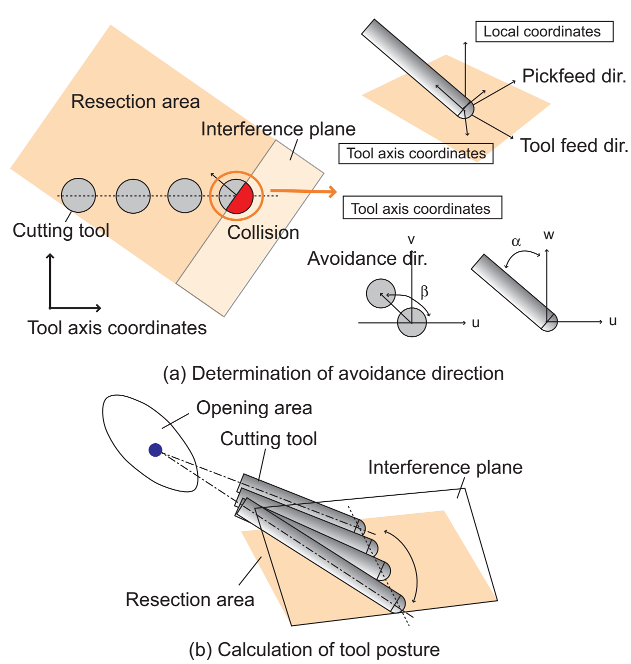

Fig. 11. Example of collision avoidance

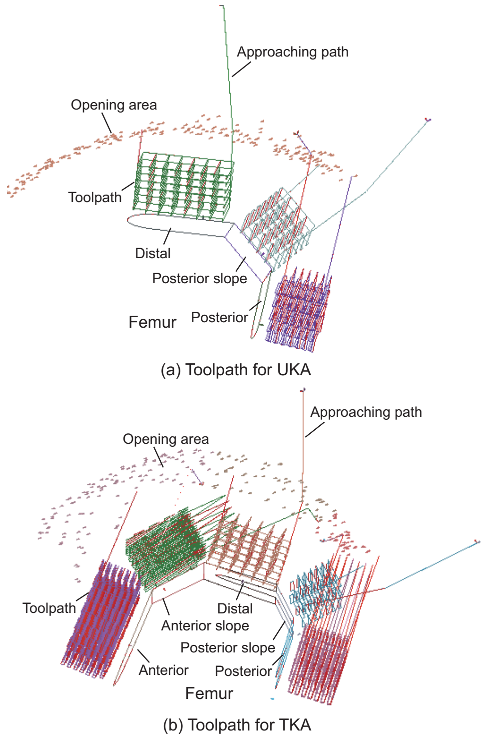

Fig. 12. Calculated toolpath

cutting location and the tool attitude is generated along the algorithm. In the CL data generation, some conditions are constrained. The tool attitude is normal to the distal and posterior slope planes, and is parallel to the anterior, anterior slope and distal planes. The calculation of initial approach attitude is simplified.

The cutting conditions are set to Tool rotational: speed 12000 rpm, Feed rate: 400 mm/min from the experiment so far, and a conventional end milling is conducted.

Figure 13 shows the overview of experiment and the tool motion behavior for UKA. The length of incision is about 100 mm, though many of the bone cutting robots required the length from 150 mm to 200 mm. This experiment proved the possibility to cut the bone without any damage of the surrounding tissues and that the motion in the collision avoidance is smooth.

VI. CONCLUSIONS

In this paper, a redundant axis to avoid the interferences with the minimal attitude change was implemented in the multi-axis bone cutting robot for the minimally invasive joint replacement surgical procedure. A strategy of toolpath generation was proposed to accomplish the procedure, and it aimed at the approach through the narrow opening area and the machining without the damage of soft tissues. To realize this method, some techniques were described. This method proposed in this paper is applicable to the universal milling robots. Finally, a cadaveric experiment was conducted with the incision length 100 mm, and the toolpath and the tool attitude were evaluated in the minimally invasive procedure. Conclusions are as follows.

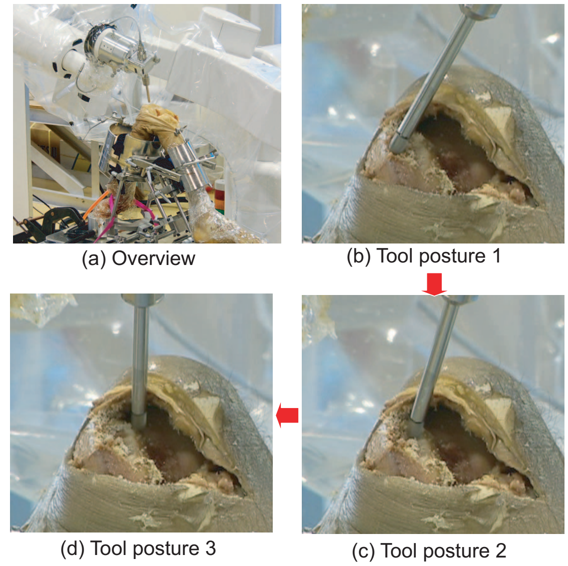

Fig. 13. Evaluation experiment with cadaver

1) A problem of tool collision came to the geometric one in the minimally invasive joint replacement, and it was defined as a problem to cut the large area of femur and tibia through the small and narrow opening area.
2) With geometric models, an algorithm to determine the tool attitude was proposed, and it enabled to generate the toolpath without the collision and to finish the surfaces.
3) The generated CL data was converted to the NC data in the post processor, and a cutting experiment was conducted. In the experiment, the cutting tool did not collide with the soft tissues, and accomplished the surgical procedure, and the effectiveness of the proposed method was confirmed.

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