Cutting Tool System to Minimize Soft Tissue Damage for Robot-Assisted Minimally Invasive Orthopedic Surgery

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Abstract. Minimally invasive surgery in orthopedic field is considered to be a challenging problem with a milling robot. One objective of this study is to minimize collision of the cutting tool with soft tissue. The authors have developed a robot with redundant axis to avoid the collision so far. Some important components are modeled based on physical requirements, and a geometric optimization approach based on the model has been also proposed to improve performance. In this paper, a protective mechanism to cover the non-working part of the cutting edge is proposed to avoid soft tissue damage. Hardware and software have been developed for this application and the effectiveness of this technique was evaluated with urethane bone.

1 Introduction

The number of surgical procedures with minimally invasive techniques has increased in orthopedics. Minimally invasive surgical approaches utilize small incisions and offer several advantages over traditional open surgery, such as reduced pain and trauma to the body, faster recovery and shorter hospital stays. New ways to open the knee are becoming important in reducing length of the incision. However, difficulty of the procedure increases with smaller incisions, and results of such operations depend on the skill of the surgeon. Mechanical or robot-assisted surgical systems are thus hoped to prove useful for this procedure, and many robots have been developed.

ROBODOC has been developed as a robotic orthopedic surgery system [1] and is the most famous in the orthopedic field. The system has 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 Davies

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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.

Many of the robots developed to date, including our multi-axis bone-cutting robot[6], use an end mill as the cutting tool, and some problems must be solved to allow application to minimally invasive orthopedic surgery. Minimally invasive surgery (MIS) makes incisions smaller, reduces pain and trauma to the body, and enables faster recovery. Smaller incisions mean small and narrow opening areas. This means that robot attitude for bone resection becomes restricted, and this can result in collision of the tool with surrounding soft tissue, the existence of untouched areas and the degradation of joint position accuracy. Any approach to minimize soft tissue damage in bone cutting is expected to resolve these issues.

Collision of the cutting edge with soft tissue should be taken into account as a problem of invasiveness. The end mill is a rotational tool, and all angles around the shaft function as a cutter. Therefore, damage to the surrounding soft tissues, vessels and nerves becomes more likely. A protection mechanism to cover the non-working part of the cutting edge is required to avoid this damage. Necrosis of bone cells caused by cutting heat or tool friction heat should also be prevented by cooling the cutting edge.

In this paper, a toolpath generation method and a tool mechanism for the protection of soft tissue are proposed to minimize damage to the surrounding tissues in robotic-assisted minimally invasive orthopedic surgery. With these methods, the cutting tool can approach the resection area through a narrow-opening area, proceed with machining of bone without any damage.

2 Milling System for Minimally Invasive Surgery

2.1 Milling Robot

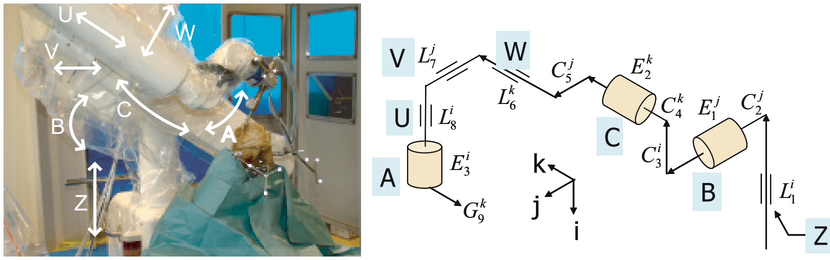
Fig.1 shows the developed milling robot with 7 degrees of freedom and the kinematics. The problems in the minimally invasive surgical procedure are to approach and resect the target bone through a narrow, visible area. To solve these problems, the machine tool is equipped with a redundant axis (A-axis in Fig. 1) so the cutting tool can avoid interference, such as with soft tissue, under a minimum change of robot attitude.

Figure 2 shows a redundant axis and spindle with the cutting tool. The tool tip does not move during the rotation, and the cutting tool approaches inside the joint and resects the target bone by suitably controlling tool attitude.

Serial kinematics is realized in the order of $Z \rightarrow B \rightarrow C \rightarrow U \rightarrow W \rightarrow V \rightarrow A \rightarrow$ from the base part. The attitude matrix and position of the cutting tool are expressed as follows.

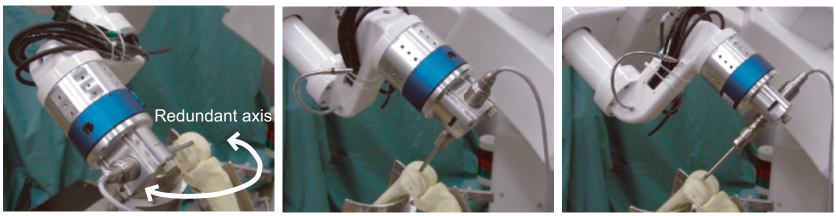
Attitude matrix

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



(a) 7-axis milling robot (b) Kinematics

Fig. 1. Overview and kinematics of milling robot



(a) Control of tool posture 1 (b) Control of tool posture 2 (c) Control of tool posture 3

Fig. 2. Redundant axis for minimally invasive surgery

Tool position

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

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

2.2 Toolpath Generator[7]

Concept. In minimally invasive orthopedic surgery, the cutting tool needs to approach the target through a small hole and resect the large area inside the joint. The opening area, positions and attitudes of the femur and tibia are measured by an infrared positioning sensor, and the workspace for the operation is precisely defined. A toolpath generator has been developed to avoid collisions with surrounding soft tissue (Fig.3).

Measurement of incision area. The opening area is measured using a 3-dimensional optical position sensor. The border of the area is measured as points for the opening plane. Based on the stored data, regression analysis is used.

Calculation of initial cutting tool posture. Utilizing cross detection of the cutting tool vector and target plane, machinable area is calculated at a given

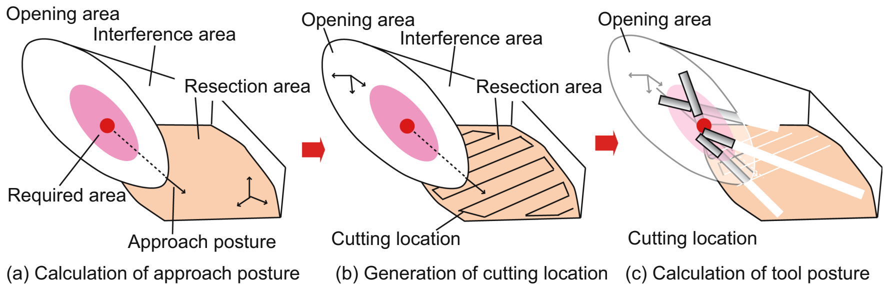


Fig. 3. Strategy for toolpath generation in MIS

cutting tool attitude, and a posture to maximize this area without collision is selected. A local coordinate system is set on the opening area measured with the 3-dimensional sensor. The normal direction is along the Z-axis and is defined. The resection plane is divided into triangular patches, 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 $\mathbf{p} + t\mathbf{l}$.

When it is machinable, collision with the interferences is checked next. 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. Likewise, the machinable area is computed on other triangle patches. Attitude $\mathbf{l}$ to maximize the evaluation function is selected as the initial tool posture.

3 Tool Mechanism to Protect Soft Tissue

3.1 Overview of Design

Damage to soft tissue should be avoided when the bone is machined. Damage will occur for the following reasons: (1) collision of cutting tool and soft tissue; (2) thermal damage caused by cutting temperature; and (3) long cutting time and mechanical stress to the patient. When the opening area is large relatively, the toolpath generator for MIS is sufficient for the operation. However, in the minimally invasive surgery this study targets, completing resection without any collision of 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 we developed a spindle equipped with a tool cover as shown in Fig.4.

The tool system comprises the cutting tool, tool attachment, tool cover, decelerator and motor, and 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, $\phi 8$; 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 a machine tool for medical use. A positive pressure structure is

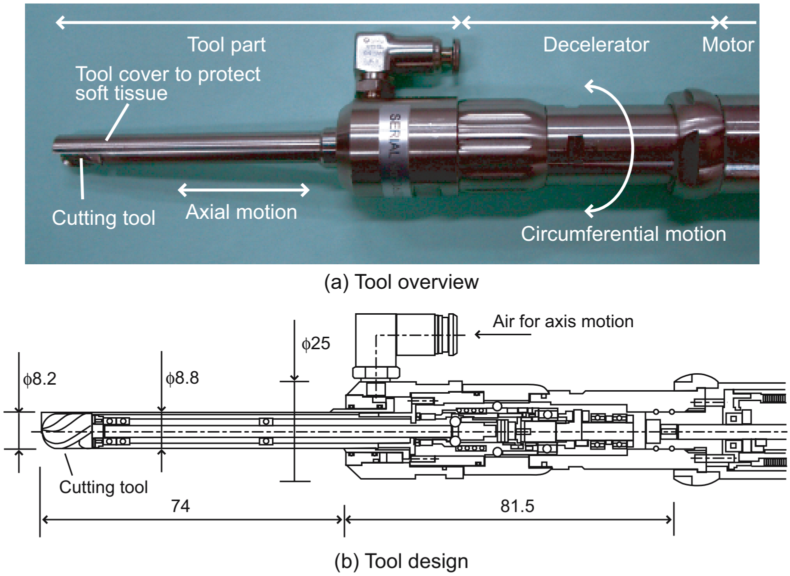


Fig. 4. Overview of tool part

adopted in the tool attachment to evacuate the comtaminant, and it is possible to sterilize.

3.2 Mechanism

Axial motion. Motion of the tool cover in shaft direction is realized by air pressure. As shown in Fig.5, when air fills the chamber and pushes a spring to sustain the cover, the tool cover moves to the right side in the figure ((b) in Fig.5). This mode is adopted when the end of the cutting edge needs to be used. The upper side of the cutting tool is covered, and the safety is kept on even when soft tissue comes into contact with the cutting tool. When air is removed from the chamber, the tool cover returns the start position, and the end part is also covered ((c) in Fig.5). This mode is used for cutting with the side edge. All of the upper half is covered, and soft tissue can be further protected.

Circumferential motion. Motion in a circumferential direction is realized by the stepping motor, and the spindle itself rotates(Fig.6). The motion enables control of the position between resection area and the tool cover. The parts of the decelerator and motor are unclean, while the cutting tool and tool attachment are clean. The clean part adopts a pressing system and avoids suction of contaminated objects.

3.3 Control Mode

The tool cover needs to be controlled, as the part of the cutting edge used in machining depends on tool posture. The "End/Side mode" in Fig.7 is general

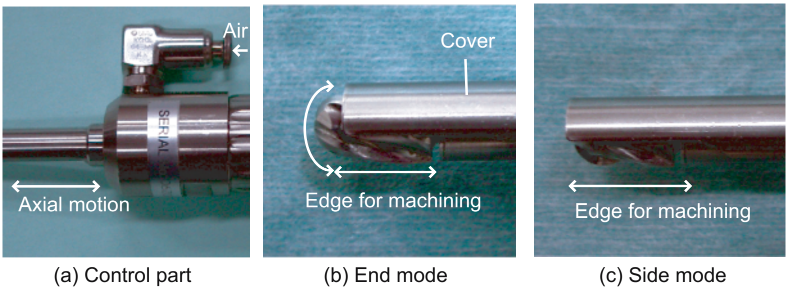


Fig. 5. Axial motion

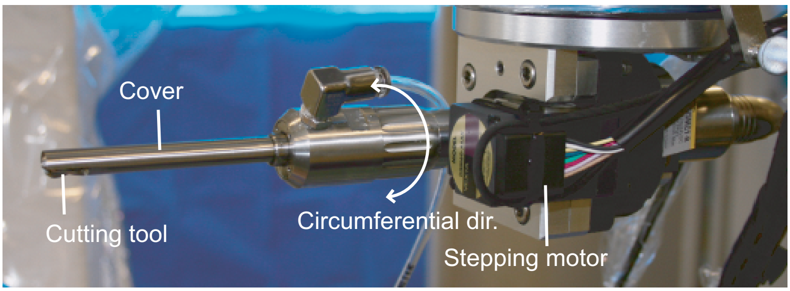


Fig. 6. Circumferential motion

and uses the whole of the cutting edge for the process. "End mode" and "Side mode" represent special cases. To control the area for covering the tool, the mechanism for motion of the tool covering a shaft direction is used. In "Side mode", half of the cutting tool is non-working, and the tool cover is controlled as in Fig.5(c). In "End mode" and "End/Side mode", the ball part of the tool is also used for machining, and half of the side edge is covered to protect soft tissue as in Fig.5(b).

Circumferential motion controls the relationship between the tool cover and resection area. The basic concept is to minimize the non-working area and uncovered cutting edge. To meet the condition, vector in the j-direction of cover coordinates and the normal vector at the cutting location are orthogonal in (a) of Fig.8, and the vector in i-direction of cover coordinates and the normal vector at the cutting location are in reverse. A matrix to express the attitude of the cutting tool **A** is represented in the robot coordinates as Eq.3. In the equation, θ_1 to θ_3 means the rotational angles to determine robot posture, and the attitude of the tool cover is finalized by θ_4.

$$\mathbf{A} = \mathbf{E}^{j\theta_1} \cdot \mathbf{E}^{k\theta_2} \cdot \mathbf{E}^{i\theta_3} \cdot \mathbf{E}^{k\theta_4} \tag{3}$$

With the tool cover matrix **A**, the vector in j-direction **p** and the vector in i-direction **q** are translated to the robot coordinates in Eq.4.

$$\mathbf{p} = \mathbf{A}(0\,1\,0)^T, \quad \mathbf{q} = \mathbf{A}(1\,0\,0)^T \tag{4}$$

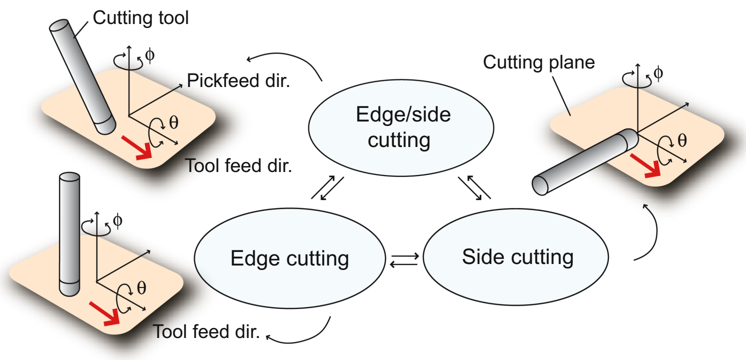


Fig. 7. Machine state

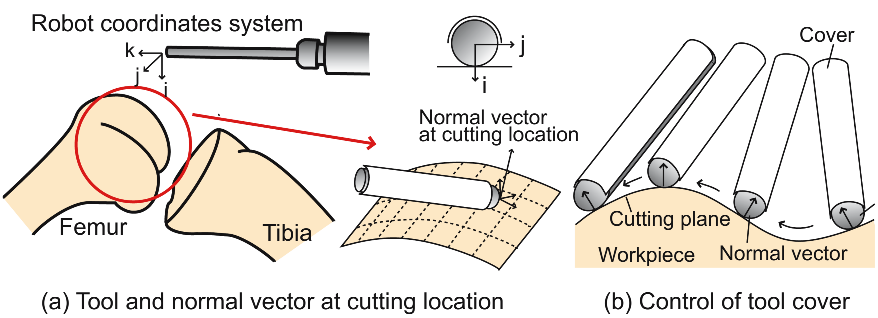


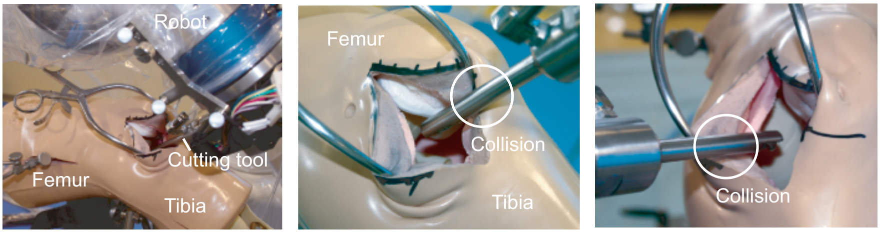
Fig. 8. Control of tool cover

Tool cover angle θ_4 is determined to meet the following equation with the inner products of the normal vector $\mathbf{n}$ and the vectors $\mathbf{p}$ and $\mathbf{q}$.

$$\mathbf{p} \cdot \mathbf{n} = 0, \qquad \mathbf{q} \cdot \mathbf{n} < 0 \tag{5}$$

4 Experimental Results

As shown in Fig.9, an evaluation is conducted with the plastic bone to confirm the effect of toolpath for MIS and the tool cover. Length of the incision is about 80 mm, and the toolpath generated by the proposed method is applied to avoid mechanical conflict. As a result, most of the area can be cut without collision, but the cutting tool touched the soft tissue at the end of stroke in (b) and (c) of Fig.9. However, with adequate control of the tool cover, damage to soft tissues did not occur, showing that the tool cover could protect soft tissue even when contact with the cutting tool was encountered.



(a) Overview of MIS (b) Collision at lateral side (c) Collision at medial side

Fig. 9. Collision check with urethane bone

5 Conclusions

In this paper, a redundant axis is used to avoid interferences by way of a minimal attitude change in a multi-axis bone-cutting robot for a minimally invasive joint replacement. A strategy of toolpath generation and a tool cover were proposed to accomplish the procedure; with this strategy based on an approach through a narrow opening area and machining without damage to soft tissue. Some techniques were described for realizing this strategy. Finally, an experiment was conducted using am incision length of 80 mm, and the toolpath and tool cover were evaluated in minimally invasive procedures.

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