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Adaptive Controlled Milling Robot for Orthopedic Surgery

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Abstract— **Adaptive control of the machining process in orthopedic surgery will increase not only productivity but also the safety issues of tool usage. The authors have developed a technology for an adaptive control system. The system has two modes, the "predictive mode" and the "adaptive mode." The predictive mode is used to shorten the air cutting time. In the adaptive mode, the system monitors the cutting force and the cutting temperature, and controls the feed override according to the difference between the real and the desired cutting force. The software is implemented on the robot controller and its effectiveness is evaluated with a urethane bone.**

I. INTRODUCTION

A. Background

The joint replacement procedure restores the physical function that has failed due, for example, to rheumatoid arthritis or osteoarthritis. In this procedure, an artificial joint and machined bone are cemented together. It is required that the cement strength is high. Lundskog [1] explained that cellular necrosis of bone is initiated at 50 °C and the thermal effect on bone tissue can result in denatured enzymes and membrane proteins, causing the cellular death.

The level of invasiveness, accuracy of the cut surface, high efficiency and machining safety are the main requirements in minimally invasive orthopedic surgery. The knee replacement technique attempts to achieve minimal invasiveness by performing this procedure through a smaller incision and accessing the joint without cutting through the quadriceps tendon. This is said to be less invasive to soft tissue and bone. The shape accuracy of the setting plane is important to fit the artificial joint, and the absolute position of the artificial joint should be precise. The operation time for bone cutting is limited to about 15 minutes. Maintaining patient safety around the machine is required.

B. Purpose and Goals

By controlling the cutting conditions, the cutting tool can be used on all types of bone under an allowed maximum load, and the cutting temperature can be lowered to avoid necrosis. The objectives of this paper are summarized in the following four items.

1) Setting of cutting conditions to shorten the operation time
2) Detection of tool overload and protection from degrading precision and rising temperature
3) Improvement of machine safety by force control
4) Detection and protection of tool breakage

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C. Related Work

The recent trend in orthopedic robot development with machining reflects the focus on minimal invasiveness of the surgical procedure in addition to high accuracy [2]. A robot by Plaskos can be mounted on the bone directly [3], and the "ARTHROBOT" by Kwon et al. was aimed at minimally invasive joint replacement [4]. Dario et al. developed a drill for bone that optimally controlled the feed rate [5]. This study attempts to shorten the cutting time by controlling the mechanical load on the patient and lowering the influence of an overload. This results in minimal invasiveness.

Meanwhile, studies of adaptive control for a machine or robot have been reported for a long time. Recently, the cutting process was added as a control factor. A transfer function is obtained based on the relation between the cutting force and feed rate, and the optimal feed rate is calculated by predicting the system gain according to the material and the cutting condition [6][7].

The goal of this study is to adapt the cutting force and temperature by controlling the feed rate and the tool rotational speed for machining in orthopedic surgery. In this paper, we describe the adaptive and predictive modes of a milling robot, then present the results of experiments using a urethane bone model. We conclude this paper with a discussion of the results and future work.

II. DEVICES AND METHODS

A. Milling Robot for Orthopedic Surgery

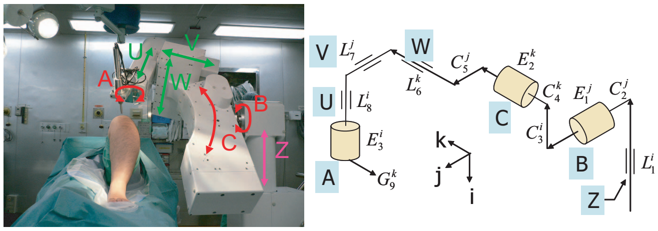
Figure 1 shows an overview of the robot and the kinematics. The robot applies serial kinematics with seven axes. The bone-cutting robot is located beside the operating table, as shown in Fig. 1. The rigidity is 271 N/mm, 72 N/mm, and 65 N/mm for the U-axis, V-axis and W-axis, respectively, at the home position.

The 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 function with high system rigidity compared with a conventional robot having rotary degrees of freedom. (2) The axes of all rotary degrees of freedom intersect at the same point. When the attitude of a cutting tool is changed, other axes do not have to move for safety reasons.

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

Attitude matrix:

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



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

Fig. 1. Overview and kinematics of the milling robot

Tool position:

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

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 indicate the operation in the U-axis, V-axis W-axis direction, respectively.

B. Real-time Force Monitoring

A 6-axis force sensor (Nitta, IFS-100M40A) was installed in the spindle to measure the cutting force, as shown in Fig. 2. The rated values are 400 N, 800 N and 40 Nm in the spindle axis direction, other directions perpendicular to the spindle axis, and the moment in all directions, respectively. The cutting force can be measured at 8 kHz. It is possible to realize adaptive control.

The spindle (Nakanishi, Primado) is composed of a fingertip cutting tool, attachment and motor to allow speeds from 0 rpm to 20,000 rpm. The mechanism can be sterilized. The rotation, rotational speed and emergency stop can be set to On/Off by an external command. A mechanism for positive airway pressure is also implemented so as not to pull in dirty dust. The cutting tool is 8 mm in diameter with a ball or square end mill, 2 or 4 flutes and high-speed steel or bio-metal.

III. CONTROL MODES AND MONITORING

A. Machine States

As stated previously, the purposes of this study are (1) shortening of the cutting time, (2) detection of tool overload and protection against precision degradation and a temperature rise and (3) improvement of machine safety by force control. The cutting conditions are controlled adaptively.

A sudden change of cutting environment is significant when the cutting condition is controlled adaptively. Fig. 3 shows the machine states in the joint replacement procedure. There are two states during machining. One is the change when the cutting process is started after cutting through air. Another is the transition from cancellous bone to cortical bone. Cancellous bone is porous and weak. In contrast, cortical bone is dense and stronger. A risk such as tool breakage is high when the cutting tool cuts the hard workpiece before slowing the speed. In the air-cutting state, by reconstructing the 3-dimensional shape from computed tomography (CT) data, the cutting area is predicted and the conditions can be controlled in advance. In the bone-cutting state, it is difficult to know the position and shape of the cancellous and cortical bone, and the cutting conditions are adjusted with a control algorithm.

In this paper, the ”Predictive mode” and ”Adaptive mode” are set, and the cutting mode is transferred between them. In the ”Predictive mode,” the shape of the cutting area is predicted from the reconstructed data, and the cutting conditions are modified before the sudden change of the cutting environment. During air cutting, the cutting speed should be the fastest to shorten the cutting time. However, when the actual cutting process begins at the fastest speed, the mechanical impact is large. To avoid this, the cutting speed (feed rate and rotational speed) is controlled based on the prediction of the distance between the air-cutting area and the cutting area and the toolpath.

In the ”Adaptive mode,” the control parameters are adjusted adaptively. The cancellous bone is porous and weak, and so the cutting force is small. A faster feed speed can be set. Therefore, when both cancellous bone and the cortical bone exist in the cutting area, the feed rate is computed so that the cutting force is constant. The cutting temperature should also be taken into account.

B. Predictive Mode

In this mode, the air cutting time should be as short as possible. As shown in Fig. 4(b), the 3-dimensional shape (or

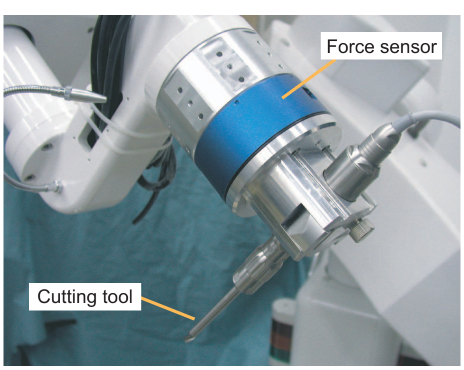


Fig. 2. Force monitoring

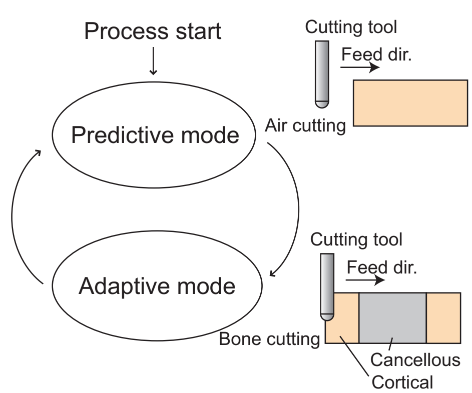


Fig. 3. Machine states

resect plane) is reconstructed from the CT data. Next, the air cutting area is predicted for the toolpath (Fig. 4(c)), and the feed speed is decreased before the start of the actual cutting process.

Figure 4(a) shows the relation between the cutting force and the feed rate. As shown in the figure, the value of the cutting force is zero during the air cutting, when the feed rate is the fastest and also limited to a maximum speed in most cases. The feed rate is decreased to a set value before the actual bone cutting starts, and the cutting mode is transitioned to the "Adaptive mode." The cutting parameters are controlled based on the cutting force and temperature.

C. Adaptive Mode

1) Concept: In the "Adaptive mode," the cutting time for the cancellous bone is shortened, and the cutting load on the patient is reduced. Cutting parameters such as the feed rate and the rotational tool speed are controlled adaptively so that the cutting force is constant. The cutting force is kept constant, and the cutting time for the cancellous bone is shortened.

As shown in Figure 5(a), if cortical bone is also cut, the feed rate is adjusted so that the cutting force is constant. After the cutting area is moved from the cortical bone to the cancellous bone, the value of the cutting force falls suddenly. The feed rate is increased until the condition in which the cutting force is a set value or the feed rate reaches the maximum value. When the cutting area is moved from the cancellous bone to the cortical bone again, the feed rate should be decreased smoothly because of the sudden force fall. If the time constant is large, there is an extra time cost for the deceleration of the cutting speed, and it is possible that the cutting tool can collide with the cortical bone at the faster speed. This is not preferable in terms of the safety of the machining system. Therefore, the time constant should be different when the speed is accelerated and decelerated.

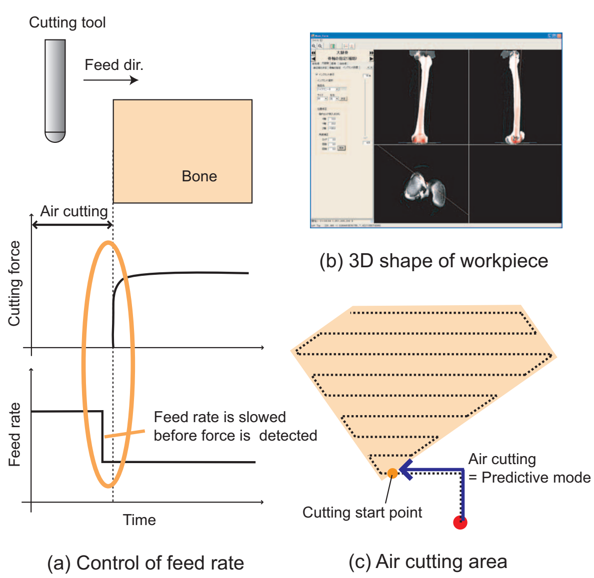


Fig. 4. Predictive mode

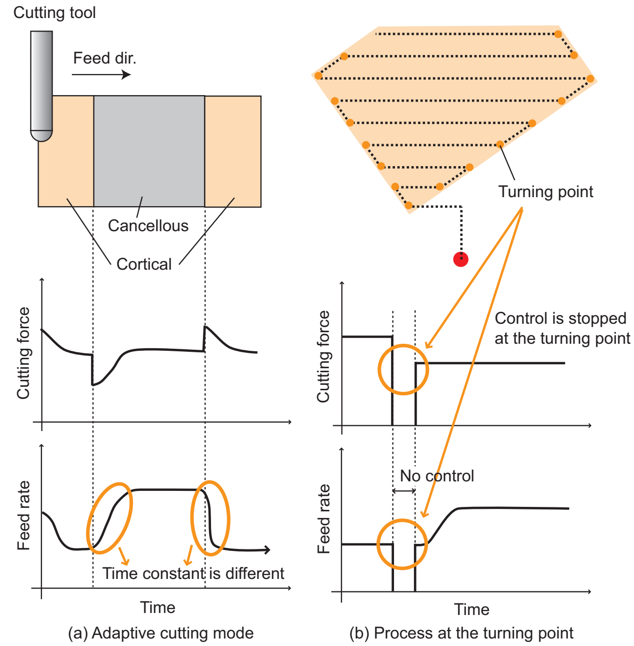


Fig. 5. Adaptive mode

This parameter is determined from some experiments.

The control system to realize this mode is depicted by the block diagram shown in Fig. 6. The system is composed of the adaptive control part and the processing part, and the cutting speed is adjusted by the difference between the planned cutting force and the actual force.

2) Adaptive Part: The adaptive part is composed of the loop filter and the accumulator, and a phase synchronous circuit is formed with the difference calculation of the cutting force. The difference of the force is input into the loop filter, and the control feed rate is calculated according to output from the loop filter in the accumulator. When the desired value of force F_{ref}, the actual force F, the output from the loop filter L and the control feed rate v_{ref} are defined, the relation between them is expressed in the following equation. The response of the system depends on the loop gain G_l in the loop filter, and the value is different at the time of acceleration and deceleration.

Loop filter:

$$L(i) = G_l \sum_{k=i-n}^{i} (F_{ref}(k) - F(k)) \qquad (3)$$

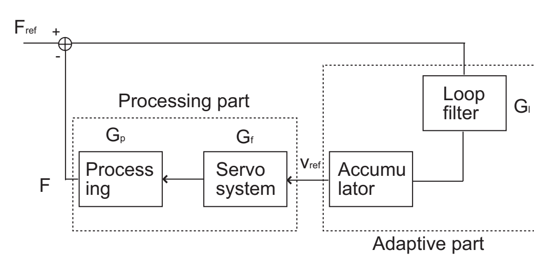


Fig. 6. Block diagram of the adaptive control system

Accumulator:

$$v_{ref}(i) = v_{ref}(i-1) + L(i) \tag{4}$$

3) Processing Part: Control of the processing part is accomplished by hardware, and the actual cutting force is influenced by this part. The positioning control system is equal to the servo system, and it is approximated to a secondary delayed system [6]. When the control feed rate v_{ref} and the actual feed rate v are defined, the transfer function is as follows.

$$G_p(s) = \frac{v(s)}{v_{ref}(s)} = \frac{K_p}{s^2 + 2\eta\varpi_n s + \varpi_n^2} \tag{5}$$

where K_p, η, ϖ are the gain, damping and natural frequency of the system, respectively.

Also, the cutting force and the transfer function in the end milling is described as follows.

$$F = Ch^{-\epsilon} = C(S_z sin\phi)^{-\epsilon} = C(\frac{v}{Nn}sin\phi)^{-\epsilon} \tag{6}$$

$$G_f(s) = \frac{F(s)}{v(s)} = K_f \tag{7}$$

where C, ϵ are the constant values dependent on the material, and $h, S_z, v, N, n, \phi, K_f$ are the depth of cut, feed per tooth, feed rate, rotational speed, number of flutes, rotational angle and gain, respectively.

IV. DETERMINATION OF TARGET PARAMETERS

As already stated, the control cutting force should be determined from the viewpoint of precision and cutting temperature. The determined target values of surface roughness and cutting temperature are used in the experiment, which is discussed below.

A. Surface Roughness

In joint replacements, the cement strength between the artificial joint and the bone is important for good postoperative results. The reason for this operation is generally to lessen the roughness of the finished plane. Therefore, roughness by the end milling of bone is discussed in this section from the data obtained by the authors [8]. The workpieces were a wet and a dry bone from the same pig femur diaphysis.

Figure 7 shows the relation between the depth of cut and the surface roughness (Rmax, Ra) in the end milling of the wet and dry bones. The cutting conditions were as follows. Cutting direction: down cutting, Axial depth of cut: 5 mm, Radial depth of cut: 1 mm. Fig. 7(a) shows the surface roughness result for the dry bone and Fig. 7(b) is the result for the wet bone with cutting speed as the parameter.

In both graphs, it is recognized that the value of roughness rises when the feed per tooth increases. When the feed per tooth is more than 0.3 mm/tooth, it is supposed that the roughness is due to brittle destruction by the large depth of cut. The required accuracy depends on the surgeons, and it has not been fully analyzed which roughness is most effective in joint replacement. However, when it is assumed that less roughness corresponds to large cement strength, as shown in this figure, the feed per tooth should be less than 0.3 mm.

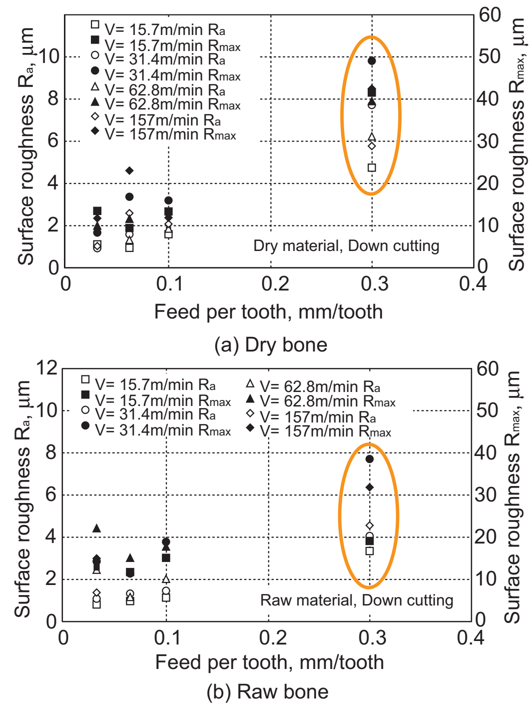


Fig. 7. Surface roughness

With regard to the influence of cutting speed to roughness, it seems that there is no significant difference in either wet and dry bone. When the feed per tooth is more than 0.3 mm/tooth, the variance is large, and Rmax ranges from 20 μm to 50 μm. To obtain a stable cutting precision, the feed per tooth should be less than 0.3 mm/tooth.

B. Cutting Temperature

In this section, the relation between the cutting speed and the cutting temperature is discussed from the data which the authors have measured so far [9].

Figure 8(a) shows the relationship between cutting speed and cutting temperature estimated from the measurement by a thermocouple. The cutting conditions are Cutting speed: 31.4 m/min, Radial depth of cut: 1 mm, Axial depth of cut: 5 mm, Cutting tool: 2-flute square end mill ϕ10. The conditions are the same as the previous experiment. The cutting temperature elevation remained at 10 °C for the range of cutting speed from 7.85 m/min to 62.8 m/min. This result shows that there is little influence of cutting speed on the cutting temperature.

On the other hand, Fig. 8(b) shows the influence of the tool feed on the cutting temperature, as measured by the thermocouple. Although there is little difference of the cutting force in up-cutting and down-cutting, the temperature for up-cutting is higher than that for down-cutting. In the down-cutting, the cutting edge collides with the workpiece mechanically at the cutting point. The bone is destructed in a brittle manner, and that results in the smaller cutting force and the lower cutting temperature.

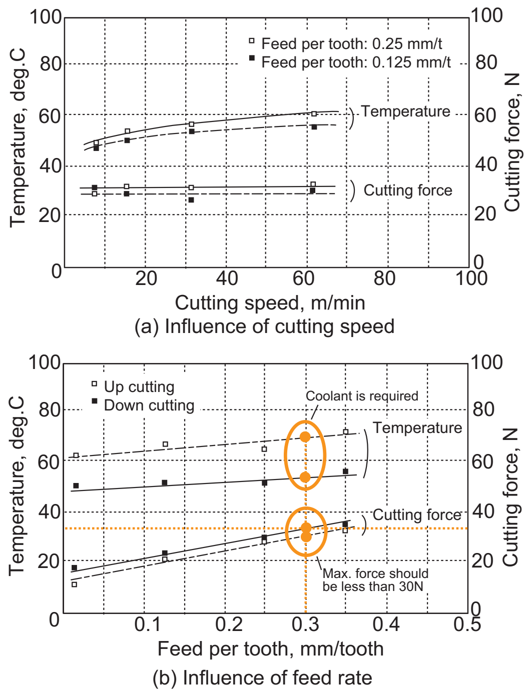


Fig. 8. Cutting temperature

The previous section showed that the feed per tooth should be less than 0.3 mm/tooth to obtain stable cutting precision. As depicted in Fig. 8(b), the cutting force should be less than 30 N for the desired result. However, it is predicted that the cutting temperature would be about 55 °C in the down-cutting, and 70 °C in the up-cutting. It is possible that these temperatures could cause necrosis, and a cooling method is required.

Even when the feed per tooth is at a minimum, the cutting temperature is over 40 °C. Therefore, the maximum cutting force is set to 30 N with any coolant.

V. EXPERIMENT AND RESULTS

A. Method

To evaluate the effectiveness of the force controlled machining system, a cutting experiment is conducted with a urethane (plastic) model of bone (SawBone, 1179-1) using a multi-axis bone cutting robot. The overview is shown in Fig. 9(a). The result is compared with the case of the constant feed rate. As shown in Fig. 9(b), the cutting part is the tibia, which has both cortical bone and cancellous bone. The influence of heat is also observed with an infrared heat image instrument (NEC-sanei, TH5104R) in Fig. 9(c). The cutting tool is a $\phi 8$, high-speed steel and ball end mill. The conditions are as follows: Cutting speed 150 m/min (6000 rpm), Radial depth of cut 1 mm, Axial depth of cut 5 mm and Feed rate 3 mm/s constant (normal), maximum 12 mm/s (adaptive).

The control algorithm proposed in Section III is implemented on the robot controller (Linux, RTAI), and the loop gain and the filter coefficient are determined by a preliminary experiment in advance. Based on the force data sampled at 8 kHz, the feed rate is calculated with the control system

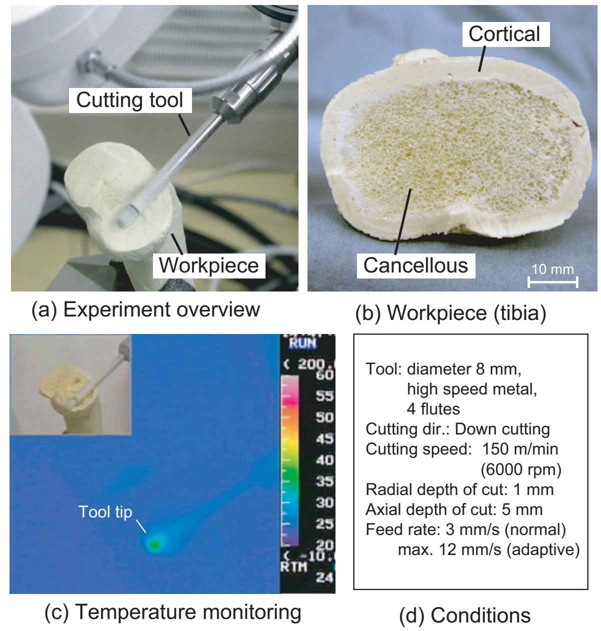


Fig. 9. Experiment with plastic bone

shown in Fig. 6. The feed rate is updated at 100 Hz in the software. In the future, the data of the cutting temperature will also be input into the control system, and it is desirable that the cutting conditions are determined from both the force and temperature. In the experiment, only the cutting force is input, and the temperature data is used as a reference.

Section IV showed that the maximum cutting force should be less than 30 N. In this experiment, the average control force is set to 12 N. The feed rate is limited to 12 mm/s as the maximum because of the performance of the servo system.

The loop filter is a low pass with 5 taps, and the loop gain depends on the work material. The gain for the urethane model of bone is set to $G = 0.05$ at acceleration and $G = 0.1$ at deceleration. Because the characteristics of the plastic model of bone and real bone are different, the parameters for real bone should be used in an actual surgical procedure.

B. Evaluation of adaptive machining

Figure 10 shows the results of the cutting force, control feed rate and cutting temperature when the feed rate is constant (Case1, left in Fig. 10) and is controlled adaptively (Case2, right in Fig. 10).

As shown in Fig. 9(b), the workpiece has both cortical and cancellous parts. The cutting range is width 66 mm x height 40 mm, and the cortical area exists with a width of 5 mm along the contour. The other area is cancellous bone. The toolpath is a zigzag in Fig. 10(a-1), and the cutting direction is down-cutting only. The figure shows the result of the first three paths. The first path is occupied by the cortical bone, and the second and third paths have both cortical and cancellous parts. Each path is named as Line1, Line2 and Line3, respectively.

1) Cutting time: In a comparison of Case1 with Case2 in Fig. 10, the cutting time is about 80 s in Case1, but it is about

42 s in Case2, and so it is clear that the time is shortened. The degree will depend on the value of the control force and the setting of the maximum feed rate. In the Line1 cut to the cortical bone, the cutting time is almost the same as in Case1 and Case2, and the decrease of the cutting time is notable in Line2 and Line3, which have more than 80% cancellous bone. From these results, the effectiveness of the control algorithm is expected to shorten the cutting time inside the joint, where both cortical and cancellous bone exists.

It is possible that the cutting time can be shortened more by optimizing the control force and the loop parameters.

2) Cutting force: Figure 10(b-1)(b-2) shows the cutting force during the processing. From the comparison, it is recognized that Case2 can resect the bone without an overload by force control. For example, the cutting force is about 50 N at about 18 s in Case1, and also about 50 to 60 N at about 47 and 76 s in Line2 and Line3. On the other hand, the maximum force is under 30 N in Case2, and minimal invasiveness in terms of the load is expected. The cancellous area is very weak, and so the feed rate is limited to the maximum value before the cutting force reaches the control value. In this area, the difference of the cutting force between Case1 and Case2 is not very much.

3) Feed rate: Figure 10(c-1)(c-2) shows the control feed rate. In Case2 (c-2 in the figure), it is recognized that the feed rate is limited to the maximum value in the cancellous part (24 to 29 s, 34 to 40 s). If the performance of the servo system is improved and it is proved that the high-speed cutting is safe, the feed rate can be set faster.

4) Cutting temperature: It is difficult to evaluate the cutting temperature because the workpiece is a urethane model of bone. The cutting temperature is higher in the cortical area for both Case1 and Case2, and it is 37 °C in Case1 and 36 °C in Case2. The elevation of the cutting temperature reaches the range of necrosis, and so a cooling method needs to be investigated.

VI. CONCLUSIONS

In this study of robotic end milling during orthopedic surgery, the objectives were (1) shortening of the cutting time, (2) detection of tool overload and protection from precision degradation and temperature elevation and (3) improvement of machine safety by force control. The feed rate is controlled based on the cutting force monitored in real time, and the following conclusions are obtained.

1) A control system composed of a "Predictive mode" to shorten the cutting time in air and an "Adaptive mode" to control the conditions was realized, and the feed rate was adjusted adaptively by controlling the cutting force in the adaptive mode.
2) From the results of the end milling experiment with animal bone, the control value of the cutting force was discussed in terms of surface roughness and cutting temperature.
3) A proposed control algorithm was implemented on the robot controller, and a cutting experiment with a urethane model of bone was conducted. The experiment proved that force controlled machining is available, and the effectiveness was confirmed.

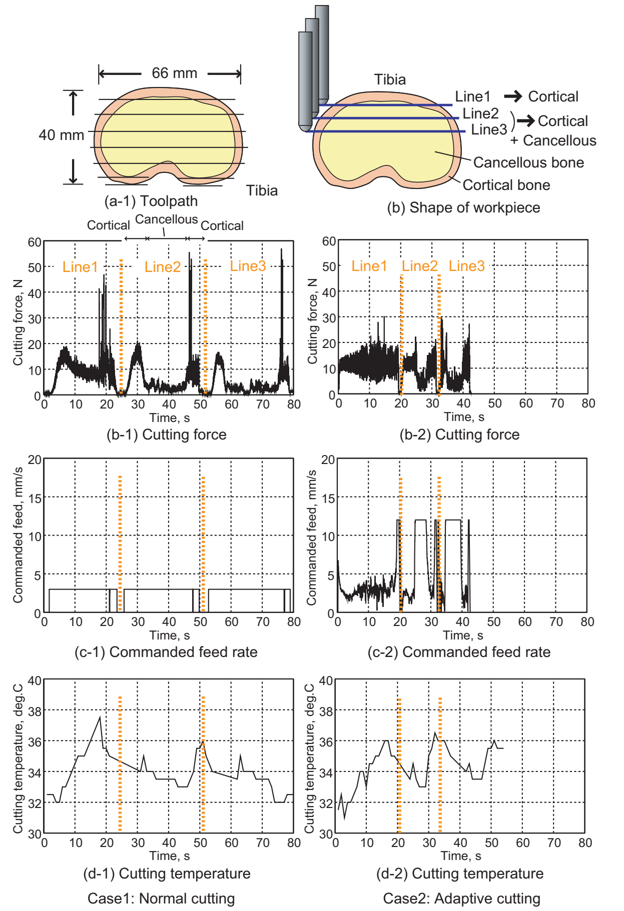


Fig. 10. Experimental results (Case1: normal mode, Case2: adaptive mode)

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