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Experimental analysis of human bone grinding methods by a skilled surgeon in microsurgery

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Abstract
This paper describes the quantification and visualization of human bone processing techniques performed by skilled surgeons during endoscopic surgery. In the experiment, human and bovine cortical bones were manually ground by an experienced surgeon, for which the grinding force and grinding conditions were measured. Moreover, the grinding conditions' effects on the human bone grinding characteristics were investigated through experiments using machine tools under certain conditions. The results demonstrated that surgeons adjust the grinding conditions such that the grinding force is ≤10N during bone machining, for a cutting depth of approximately 2 mm, tool inclination angle of approximately 60°, and feed rate of 55 mm/min. Moreover, sudden peak values of the grinding force were observed when the tool inclination angle was less than the surgeon's machining condition, and the grinding force increased significantly when the feed rate exceeded this condition, based on the turning experiments using machine tools.

Microsurgery, human bone, grinding, quantification

1. Introduction

Percutaneous endoscopic surgery has been widely performed in recent years because it is a minimally invasive type of surgery that burdens patients less than conventional surgery does. In recent years, rapid advances have been made in robotic surgery. However, spinal surgery involving bone processing has not undergone robotization owing to the lack of progress regarding the elucidation and quantification of bone processing characteristics [1]. Moreover, endoscopic procedures in spinal surgery require a very high level of skill in bone processing and a large amount of time to acquire the necessary skills (learning curve (LC)). The quantification of bone processing techniques by skilled surgeons is an urgent aspect that needs to be explored for shortening the LC. Moreover, the differences in processing characteristics between porcine and bovine bones used for training and human bones need to be clarified to shorten the LC. In this study, an attempt was made to quantify and visualize human bone processing techniques performed by skilled surgeons. In the experiment, the surgeons ground human bone, and the grinding force and grinding conditions were verified. Moreover, machining experiments were conducted under various grinding conditions using machine tools, and the effects of the varied grinding conditions on the machining characteristics of the bones were investigated. A similar experiment was also performed using bovine bone to highlight any differences from the grinding characteristics of human bone.

2. Experimental methods

2.1. Experimental materials

In this study, two types of bovine and human bone (from males in their 90s) were used. The iliac bone was used because it has a relatively flat surface. The thick part of the cortical bone was shaped into a block using a chisel, a saw, and a milling machine, and the bone was fixed to a vice and used in the experiments. The surface of the vertebral body, which is excised during surgery, comprises an interior spongiosa consisting of trabeculae with stomata and meshwork, and the outside is surrounded by hard cortical bone. In this experiment, cortical bone, which has a higher hardness and grinding force than those of cancellous bone, was used as the grinding specimen.

2.2. Bone grinding experiment by surgeon's manual operation

In this experiment, the tool was attached to a handpiece (Nakanishi Inc. (NSK), Primado2 Control Unit), as shown in Figure 1 (left), and the surgeon performed bone groove grinding experiments using the handpiece. In the experiment, a quartz piezoelectric four-component force dynamometer (Kistler9272) was mounted onto a rotary multi-vice (DREMEL Model 2500-01) via a jig to fix the bone. The tool used in the experiment was an electrodeposited diamond tool (NSK, PDS-2CDL-40) used in general endoscopic surgery. The diameter of the tool was 4 mm, the grain size of the diamond was 181–271 μm, and the tool rotation speed was set to 64000 rpm. The grinding environment mimicked actual surgical environments, and water was supplied to the grinding points. The grinding was performed in the Y direction, and grooving, which is often employed during surgery, was performed.

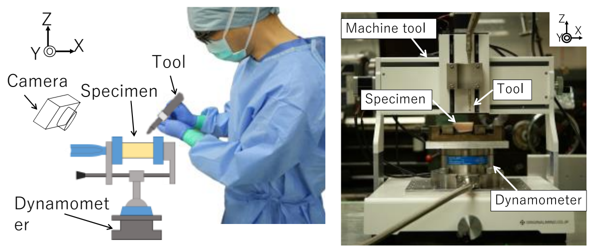

Figure 1. Experimental setup and method (left: manual operation by surgeon, right: grinding using machine tool).

2.3. Machining experiments under constant grinding conditions using machine tools

The same handpieces and tools used in the manual experiments were used for the bone machining experiments involving machine tools. The handpiece was attached to the main spindle of a small CNC milling machine (Original Mind Inc., KitMill CL100), and the grinding experiments were performed (Figure 1, right). During this process, the handpiece could be attached to the machine tool through the spindle at a given inclination angle. In addition, a quartz piezoelectric four-component force dynamometer was installed on the table of the small CNC milling machine, and the bones were fixed via a vice installed on the dynamometer. Tool feed, cutting depth, and tool inclination angle were selected as the standard grinding conditions based on the results of the manual experiments. As human bone could not be used in this experiment, bovine ilium was used as the work material. In the grinding experiments, the tool was placed vertically standing and grooved in the Y-direction, and water was supplied during the grinding.

3. Experiment results

3.1. Measurement of bone resection conditions based on the surgeon's technical skill

The measurement results of the grinding force based on the surgeon's manual technical skills are shown in Figure 2. The grinding force used for the cortical bone specimens was approximately 5–10N and was similar for both the human and bovine bones. This suggests that surgeons adjust the grinding conditions to always produce a force of ≤10N during the manipulation of the bone, regardless of differences in the bone type. On the basis of this result, the status of bone grinding based on the surgeon's technical skill was evaluated using photos and videos. A photograph captured during the bone processing is shown in Figure 3, indicating that the conditions during bone machining were a cutting depth of 2 mm (tool radius), inclination angle of 60°, and feed rate of 55 m/min.

3.2. Verification of bone resection conditions using machine tools

After clarification of the conditions for bone resection by the surgeons, the reason for the surgeons performing bone processing under these conditions was investigated. In the experiment, the effects of cutting conditions on bone machining characteristics were investigated by changing the feed rate (from 30 mm/min to 70 mm/min in 10-mm/min increments) and tool inclination angle (from 0° to 60° in 15° increments) for the bovine bones using a bench top machine tool. Examples of the measurement results of the grinding force, for when the tool inclination angle was changed, are shown in Figure 4. The figure shows that sudden peak values occurred at an inclination angle of 30°. At these peak points, the noise from the tool became louder momentarily as the tool was deflected from the bone because of uneven contact with the hard part of the bone. However, when the inclination angle was 60°, no sudden peaks occurred, and the processing force was the lowest. This is considered to be owing to the increase in removal efficiency as a result of the increase in actual cutting speed due to increase in the inclination angle; the measurement results of the grinding force, for when the feed was changed, are shown in Figure 5. As shown in the figure, while there were no significant differences in the machining force between 30 and 50 m/min when the feed was changed to process cortices, there was a sharp increase at 70 m/min. These results indicate that surgeons perform bone grinding at a tilt angle of 60° and a feed rate of 55 mm/min, which results in a low and stable machining force.

4. Conclusions

In this study, an attempted was made to quantify the technique used by skilled surgeons in processing human bones during endoscopic procedures in spinal surgery. The results clarified that the feed and tool inclination angles were set so that the processing force was ≤10N for both cortical and cancellous bone. Our investigation of the effects of machining conditions on the machining characteristics of bone using machine tools showed that the machining conditions employed by the surgeons were those resulting in a low and stable machining force. In spinal surgery, if the grinding temperature during bone processing exceeds the damage temperature of nerves near the bone, sequelae may be caused owing to the surgery. Therefore, it is necessary to measure the grinding temperature when the grinding conditions are changed. In addition, although this experiment was performed using microscopic surgical instruments, it is necessary to perform grinding experiments using endoscopic instruments used in actual surgery. We therefore aim to develop a spinal surgery robot based on the results obtained from these experiments in the future.

References

[1] Bürger T, et al., Design and Test of a Safe Numerical Control for Robotic Surgery. CIRP Ann. 2001, 50, 295–298

Declaration

This study was approved by the Institutional Review Board for human studies at Shizuoka University (Registration number 19-36, approved on October 18, 2019) and at Hamamatsu University School of Medicine (Registration number 19-193, approved on September 5, 2019). This study was conducted in accordance with the Declaration of Helsinki and the Guidelines for Proper Conduct of Animal Experiments (Science Council of Japan, 2006).

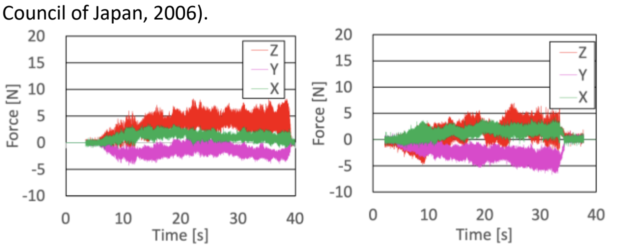

Figure 2. Grinding force measurement results from surgeon's manual operation (left: Bovine, right: Human).

Figure 3. Observation of manual operation by surgeon.

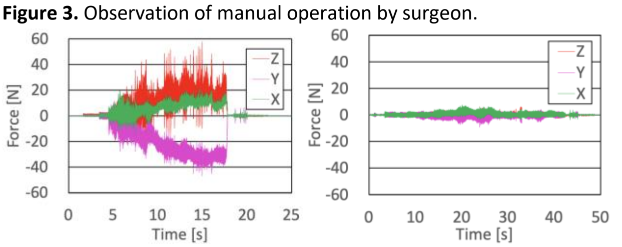

Figure 4. Relationship between tool tilting angle and grinding force (left: 30º, right: 60º).

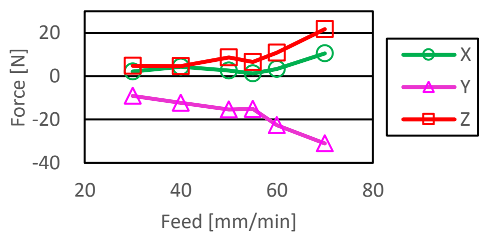

Figure 5. Relationship between feed rate and average grinding force.