Journal of Materials Processing Technology 209 (2009) 5777–5784

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Dynamic controlled milling process for bone machining

Naohiko Sugita[a,*], Taiga Nakano[a], Yoshikazu Nakajima[a], Kazuo Fujiwara[b], Nobuhiro Abe[b], Toshifumi Ozaki[b], Masahiko Suzuki[c], Mamoru Mitsuishi[a]

[a] Department of Engineering Synthesis, School of Engineering, The University of Tokyo, Tokyo, Japan
[b] Graduate School of Medicine, Density and Pharmaceutical Sciences, Okayama University, Okayama, Japan
[c] Graduate School of Medicine, Chiba University, Chiba, Japan

ARTICLE INFO

Article history:
Received 22 April 2009
Received in revised form 14 June 2009
Accepted 15 June 2009

Keywords:
Bone-cutting
Milling process
Force control

ABSTRACT

Optimal control of the machining process in orthopedic surgery can not only increase productivity but also ensure safety during tool usage. The authors have developed a technology for a force control system. The system has two modes of operation: the "air-cutting mode" and the "force control mode." In the air-cutting mode, tool feed is scheduled by predicting the air and bone-cutting zones from the CAD/CAM system. In the force control mode, the software monitors the cutting force and the cutting temperature, and it controls the feed override according to the difference between the real and the desired cutting force. The software is installed on a robot controller, and its effectiveness is evaluated with a urethane bone.

1. Introduction

Joint replacement restores physical function that has failed because of rheumatoid arthritis or osteoarthritis. In a joint replacement procedure, an artificial joint and a machined bone are cemented together using high-strength cement. Lundskog (1972) explained that cellular necrosis of bone is initiated at 50 °C, and the thermal effect on bone tissue can denature enzymes and membrane proteins, thereby causing cellular death.

Fig. 1 shows the structure of the bone. Its main components are cortical and cancellous bone and cartilage. Cortical bone is also called "compact bone." Cortical bone exists mainly at the diaphysis, and cancellous bone is typically surrounded by cortical bone, as shown in Fig. 1a. Histologically, the haversian canal exists at the center of the cortical bone, and the lamellar bone surrounds it concentrically. Blood vessels that run inside the haversian canal are connected with blood vessels that run inside the volksmann's canal. The structural unit of the cortical bone that encircles the haversian canal is called the "osteon." The osteon stretches along the cortical bone in the long bones. Therefore, the cortical bone can be considered to be a one-directional, continuous fiber, reinforced-type of compound material.

Recent trends in orthopedic robot development via machining reflect increased focus on minimal invasiveness of the surgical procedure and high accuracy (DiGioia and Hafez, 2005). A robot can be mounted directly on the bone (Plaskos et al., 2005), and the "ARTHROBOT" was aimed specifically at minimal invasive joint replacement (Chung et al., 2003).

Level of invasiveness, accuracy of cut surface, high efficiency, and machining safety are principal requirements in minimal invasive orthopedic surgery. Knee replacement techniques attempt to achieve minimal invasiveness by performing the procedure through a smaller incision and accessing the joint without cutting through the quadriceps tendon. This approach is said to be less invasive to soft tissue and bone than prior traditional methods. It is important to avoid tissue damage by imposing too much mechanical or thermal load during the machining process. Optimum safety of the machine and surgical tools is also required. While machining, minimal invasive and safe practices are required so as not to damage the surrounding tissues such as ligaments and muscles. Shape accuracy of the setting plane is important to fit the artificial joint, and absolute position of the artificial joint should be precise. Operation time for bone-cutting is limited to about 15 min because of the threat of necrosis.

Some researchers have proposed to solve these problems by controlling processing conditions. For example, Allotta et al. (1996) developed a drill for bone that optimally controlled the feed rate. Furthermore, with regard to metal cutting, studies of force control for a machine or robot have been reported for a long time. Recently, the cutting process itself was added as a control factor. A transfer function is obtained based on the relationship between the cutting force and the feed rate, and the optimal feed rate is calculated by predicting the system gain according to the specific material and the cutting conditions (Altintas, 1994; Shirase et al.,

* Corresponding author.
E-mail address: sugi@nml.t.u-tokyo.ac.jp (N. Sugita).

0924-0136/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2009.06.008

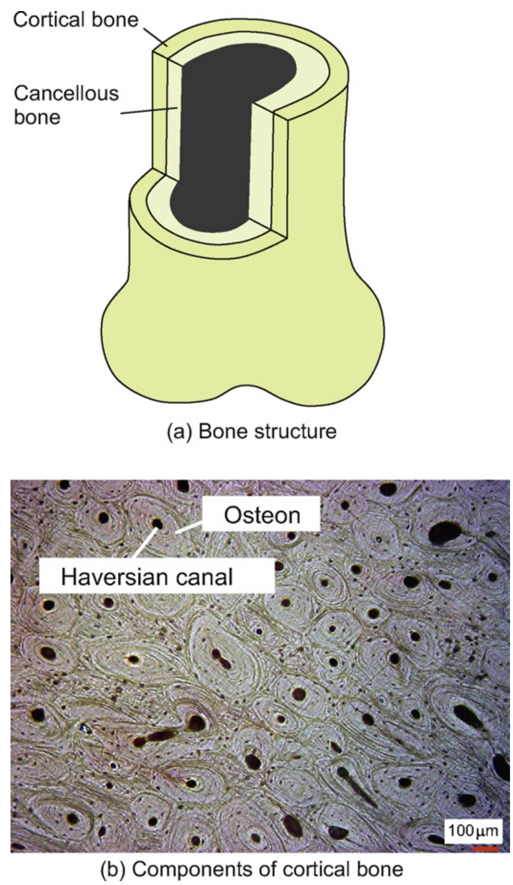

Fig. 1. Bone structure.

2000). Xu and Shin (2008) developed an adaptive fuzzy control system to implement for online force control of end milling processes. Zhang and Chen (2007) discussed an in-process surface roughness adaptive control system in end milling operations using neural-network. Landers et al. (2004) compared four model-based machining force controllers in terms of performance and stability.

On the other hand, there are two areas where this previous research differs from force control performed in metal processing. First, in surgical applications, there is continuous cutting of the workpiece, which is composed of different materials instead of just metal. In surgical cutting, the material changes from cortical bone to cancellous bone continuously according to the tool path traversed during machining. These two types of bone tissues differ in mechanical properties. When force control applied to continuous cutting, the boundaries of these bone tissues become a problem because their mechanical properties such as strength differ. However, the borders are vague and required positioning cannot be determined precisely in advance. Therefore, during surgery when the cutting area is traversed from cortical bone to cancellous bone, detection and control to a high tool feed rate are required during transition points. When the cutting area is traversed from cancellous bone to cortical bone, detection and control during transition points are needed to slow down the tool feed. Thus, the important objectives of our current study are to shorten cutting time and to prevent potential damage to tissue that can be caused by collision of the cutting tool and the bone by controlling the feed rate for machining in orthopedic surgery.

A second critical point is that when the cutting tool approaches a cortical bone along the planned tool path, it initially tends to collide with the bone suddenly at high feed rate. This risk of collision must be avoided by predicting the precise starting point during air-cutting.

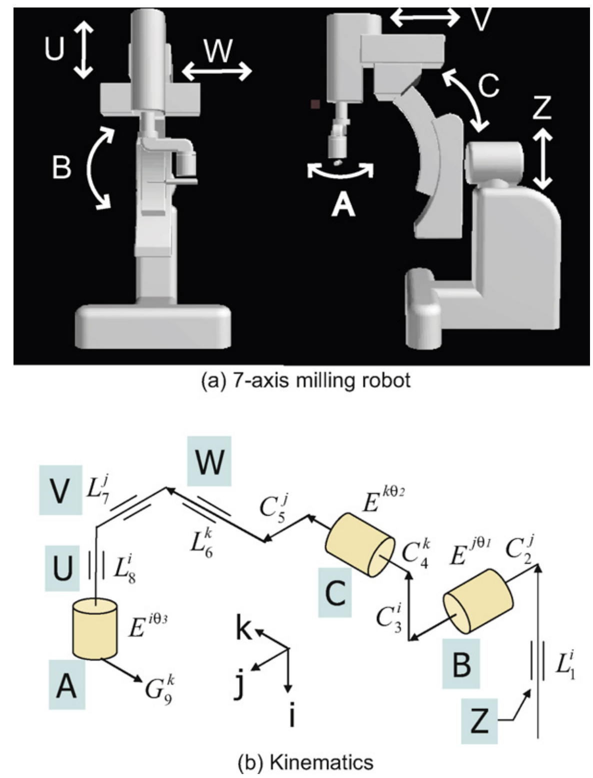

Fig. 2. Overview and kinematics of the milling robot.

Our study procedure attempts to reduce cutting time and avoid processing damage by controlling the mechanical load on the patient and reducing the influence of an overload based on in-depth consideration of and the mechanical properties of the bone tissues. Thus, our technique results in minimal invasiveness.

2. Method

2.1. Bone milling machine

Fig. 2 shows an overview of the bone milling machine and the kinematics of the milling robot. The machine applies serial kinematics with seven axes. Its stiffness 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.

Serial kinematics are realized in the order *Z*, *B*, *C*, *U*, *W*, *V*, and *A* from the base. In forward kinematics, $\mathbf{T}_Z$ and $\mathbf{T}_{UVW}$ show the translational matrix of the *Z* and *UVW* axes; and $\mathbf{R}_A$, $\mathbf{R}_B$, and $\mathbf{R}_C$ show the rotational matrix of the *A*, *B*, and *C* axes, as depicted in the matrix in Eq. (1). Cutting tool tip positioning is calculated along the matrix:

$$(\text{forward kinematics}) = \mathbf{T}_Z\mathbf{R}_B\mathbf{R}_C\mathbf{T}_{UVW}\mathbf{R}_A \quad (1)$$

A 6-axis force sensor (Nitta, IFS-100M40A) is installed in the spindle to measure the cutting force, as shown in Fig. 3. 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. Thus, it is possible to realize force control.

The spindle (Nakanishi, Primado) is composed of a fingertip cutting tool, an attachment, and a motor to allow rotational speeds from 0 rpm to 20,000 rpm. The rotation, rotational speed, and emergency stop can be set to On/Off by an external command. A