Mechatronics 35 (2016) 1–10

Contents lists available at ScienceDirect

Mechatronics

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

Fuzzy force control and state detection in vertebral lamina milling

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ARTICLE INFO

Article history:
Received 26 April 2015
Revised 16 September 2015
Accepted 12 February 2016

Keywords:
Surgical robot
Vertebral lamina milling
Fuzzy force control
State detection

ABSTRACT

Laminectomy is a typical high-risk surgical operation on the spine, during which milling is the key procedure to remove part of vertebral lamina and release the pressure on the spinal nerve. Because many important vessels and nerves surround the vertebral lamina, any incorrect maneuver can cause irreparable damage to patients. In this paper, a fuzzy force control is designed specifically for vertebral lamina milling. The force control is implemented to adjust the milling parameters to copy the complex anatomical structure of the vertebral lamina, and fuzzy combiner is integrated into the force controller to tune its control parameters on-line. For safety purposes, the state detection method based on energy consumption is proposed in the process of vertebral lamina milling. Three different milling states can be detected and the safety control point, which is the stop point of the milling, is found, effectively improving the quality of the vertebral lamina milling. The results of contrast experiments showed that the milling process under fuzzy force control has shorter time and more stable longitudinal contact force. The state detection method based on energy consumption can detect the three milling states, resulting in an acceptable thickness of the remaining vertebral lamina.

1. Introduction

Recently, surgical robots have been widely applied in many types of orthopedic surgery, such as laminectomy, total knee arthroplasty, artificial disc replacement [1–3], etc. In laminectomy, for example, the vertebral lamina needs to be reduced until an acceptable thickness is obtained to relieve the pressure on the spinal nerve [4]. Because many important vessels and nerves surround the lamina, any incorrect operation can cause irreparable damage to the patient. In the process of vertebral lamina milling, high levels of accuracy, efficiency and safety are the basic requirements. By using a robot, the surgical accuracy of the milling process can be enhanced, and the risk of surgery can be reduced. This paper focused on the operation of vertebral lamina milling, but the proposed methods could also be applied to some other types of orthopedic surgery.

To date, some milling control strategies for surgical operations have been studied, but less research has focused on vertebral lamina milling, and the requirements of milling operations vary with different processing environments. Wolf et al. [5] presented a mini bone-attached robotic system for joint arthroplasty, which, through patellar tracking, optimized the planned position of the implant and ensured that it was properly aligned and congruent with the surrounding healthy cartilage. Sugita et al. [6,7] sculpted the joint surface to fit the shape of the setting plane of the artificial joint. The milling path was planned pre-operatively by setting the tool path data to simulate the continuous path by scattering points, and the milling operation was then carried out following those data points. Wang et al. [8] milled the vertebral layer by layer from the outer cortical to the inner cortical bone at a constant longitudinal cutting depth. By controlling the position of the longitudinal cutting depth, the safety of the milling operation could be ensured. Because this method was unable to adapt to the complex surfaces of the vertebrae, satisfactory processing results could not be achieved. The same operation also was used for knee replacement surgery. Meister et al. [9] developed a trajectory generator for a robot control system to generating the milling path using given base-points. Because many data needed to be generated with this method, it is only suitable for bones with a regular structure.

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http://dx.doi.org/10.1016/j.mechatronics.2016.02.004
0957-4158/

In order to copy with the complex anatomical structure and irregular surface of the vertebral lamina, some researchers have attempted to apply force control to improve the milling outcome. Yen et al. [10, 11] introduced a cooperative impedance force control strategy between the robot and the surgeon for lateral milling of the bone. Sugita et al. [12] controlled the milling process dynamically. The feed rate of the milling tool was adjusted according to the difference between the actual and the desired cutting force to maintain a constant cutting force. For total knee arthroplasty, Inoue et al. [13] introduced an optimal control of the cutting feed rate, which was depending on the hardness of the bone tissue predicted on the basis of a medical image. Landers et al. [14] compared four model-based machining force controllers with regard to their performance and stability. Shirase et al. [15] developed an adaptive force control module, in which the feed rate was controlled to maintain a constant cutting force. In conclusion, the control strategy of milling process in existing studies includes two strategies: position control and force control. Position control is unable to adapt the complex surfaces of vertebral. So the satisfied processing results would not be achieved. Few force control strategy focus on transverse motion of milling tool. But the transverse motion is also play an important role in milling operation. An effective control of transverse motion can reduce milling time and avoid too high milling temperature. Hence, two different force control strategies are respectively presented in two different directions. Moreover, most of force control used the fixed control parameters that can reduce the adaptability of control strategy.

The prevention of the vertebral lamina from being milled through is another crucial safety issue. State detection method has become a hotspot in safety control. Lee et al. [16, 17] established the breakthrough detection method by using information on the thrust force threshold, the trend in torque and the feed rate. Hu et al. [18] presented the state recognition of pedicle drilling using a force sensor in a robotic spinal surgical system. A state recognition model was established, which contained pre-treatment data, force feature extraction, and state recognition. Based on the state recognition model, five different states could be recognized. Kasahara et al. [19] proposed a linear master–slave manipulator to control the drilling process by estimating the cutting torque. Li et al. [20] presented a pedicle screw measurement device with an optical probe that could send out a warming signal before the pedicle screw tip broke the vertebral pedicle wall, and the detection depth was defined by the Monte Carlo simulation and phantom models. Compared with bone drilling, vertebral lamina milling is more difficult and time consuming due to more complex structure of lamina. Cao et al. [21, 22] presented a hybrid model to identify milling faults and improve the safety of operation. The model was established by extracting the features of the current and force signals. However, the performance of this state detection method largely depended on the accuracy of the pre-built recognition models, which was difficult to be established due to the influences from multiple factors.

Meantime, some researchers have attempted to use pattern recognition to detect the various surgical states. Kaburlasos et al. [23-25] designed a mechatronics drilling tool for stapedotomy, and used the force and torque data during drilling to estimate the thickness of the stapes and the d–σ Fuzzy Lattice Neuro-computing scheme as the classification method. Pohl et al. [26] controlled the micro-drill unit of a surgical robot to stop at the breakthrough using audio pattern recognition. Sound analysis based on the anatomical morphology of the rat skull was used to establish a support vector machine (SVM) classification of the time-frequency representations of the drill sounds. Osa et al. [27] also estimated the cutting state using SVM outputs, from which the penetration of the work material could be detected and the actuation of the cutting tool could subsequently be stopped autonomously. In a brief, the state detection methods in existing researches are mainly based on pre-built recognition model or pattern recognition. Due to differences between the vertebral, a prebuild recognition model is different to be accurately established. The performance of pattern recognition largely depends on the selection of feature vector signal, which is easily interfered [28]. And it is difficult to get real-time. Consider the accuracy and real-time, the state detection method based on energy consumption is presented.

In this paper, we firstly describe the anatomical structure of the vertebral lamina. The motion and force analysis of vertebral lamina milling indicated that the quality of the milling significantly depends on the control effect of the transverse and longitudinal motion. Therefore, two different force control approaches were applied in this study. In transverse motion, the milling time was the main consideration in the design of the force controller. Hence, the feed rate of the milling tool needed to be adjusted on-line and controlled precisely by a speed servo-based control. In contrast, in longitudinal motion, the accuracy of milling and the milling load were the main considerations in the design of the force controller. The longitudinal cutting depth of the milling tool was adjusted to control the contact force indirectly. Meanwhile, fuzzy combiner was presented for the two force controllers to adapt their control parameters to the variations in the processing environment. The force control and fuzzy combiner were used to design the fuzzy force control strategy. Finally, regarding to safety issues, a state detection method based on the energy consumption is presented to detect three milling states during the milling process.

The remainder of this paper is organized as follows. The analysis of vertebral lamina milling, fuzzy force control strategy and the state detection method are illustrated in Sections 2, 3 and 4, respectively; Section 5 presents the results and discussion; and the last section (Section 6) presents the conclusion.

2. Analysis of vertebral lamina milling

In laminectomy, vertebral lamina milling is the key and most difficult procedure. Orthopedists must handle the milling tool to mill vertebral lamina very carefully to ensure that the pressure on the spinal nerve is relieved but the spinal nerve and its surrounding vessels are not damaged. Fig. 1(a) shows the process of vertebral lamina milling. The vertebral lamina is located in a small space, and is surrounded by the spinal nerve, rendering the milling operation difficult for orthopedists. Fig. 1(b) shows the anatomical structure of the vertebral lamina and its irregular surface. It is mainly composed of two different bone tissues: cortical bone and cancellous bone. The cortical tissues, which have a dense microstructure, cover the surface of the vertebral lamina, and the cancellous bone, which is composed of trabecula structures, is located within the vertebral lamina and is surrounded by the cortical bone. The mechanical properties of the two different bone tissues differ remarkably, and the cortical bone has a higher density than the cancellous bone [29,30].

The analysis of the motion and force of the milling tool on different surfaces of the vertebral lamina is presented in Fig. 2. The motion of the milling tool is a composite of three different components: rotary motion, transverse motion (Y direction), and longitudinal motion (Z direction). The transverse and longitudinal are the main motions and play the core role in vertebral lamina milling. The transverse motion determines the feed rate of the milling in each milling layer, and the longitudinal motion controls the cutting depth. Correspondingly, the milling tool can experience a contact force with the bone. The force f_y hinders the transverse motion of the milling tip and f_z is produced from the longitudinal motion of the milling tool. To obtain a satisfactory milling outcome, the surgical operation should attempt to reduce the milling time, avoid