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Original Article

Safety control strategy for vertebral lamina milling task

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Abstract

Vertebral lamina milling task is one of the high-risk operations in spinal surgeries. The operation is to remove part of vertebral lamina and release the pressure on the spinal nerve. Because many important vessels and nerves are under the vertebral lamina, any incorrect operation may cause irreparable damage to patients. To improve the safety of lamina milling task, a fuzzy force control strategy is proposed in this paper. Primary experiments have been conducted on bone samples from different animals. The results show that, with the fuzzy force control strategy, the bone milling system can recognize all surgery states and halt the tool at the proper location, achieving satisfactory surgery performance.

Keywords: Safety control; Force feedback; Fuzzy logic control; Vertebral lamina milling; Spinal surgery

1. Introduction

Advances in science and technology have led to the use of various robots in the field of medical application. In recent years, surgical robots have been widely applied in different types of orthopedic surgery, such as laminectomy, total knee arthroplasty, artificial disc replacement [1–3], etc. Spinal surgery is believed to be high-risk since any damage to the spinal cord may cause paralysis or even death to the patients. Traditionally, the spinal surgery is performed manually, and the long duration time will cause surgeons' fatigue, reducing the surgery quality.

Laminectomy is to restore the function of the compressed spinal nerve by expanding the spinal canal space. The vertebral lamina milling operation is regarded as one of the most critical and risky operations. In the surgery, the surgeon needs to hold the high-speed-rotating bone drill to mill the vertebral lamina from the surface to the inner cortical bone, removing the spike process part and releasing the pressure on the spinal nerve [4,5] (Fig. 1).

Laminectomy has been widely used to treat patients with lumbar spinal stenosis [7,8], to release the oppressed spinal nerve and recover the function of spinal cord. The key to the success of Laminectomy is to ensure the proper amount of lamina remained. Too small amount of residual volume may cause harm to the spinal canal and spinal nerve, and too large amount cannot achieve the effect of spinal nerve decompression [9].

Researchers have tried using robots to assist surgeons to improve the surgery accuracy and efficiency. An Israel company has marketed a parallel robot to help surgeons to guide the tools and implants (Renaissance Guidance System, Mazor Robotics®, Caesarea, Israel) [10]; Ortmaier has designed a robot for accurate placement of pedicle screws with the help of an optical navigation system [11]; Chung has designed a robot to insert pedicle screws in the spinal fusion procedure [12]; Hu

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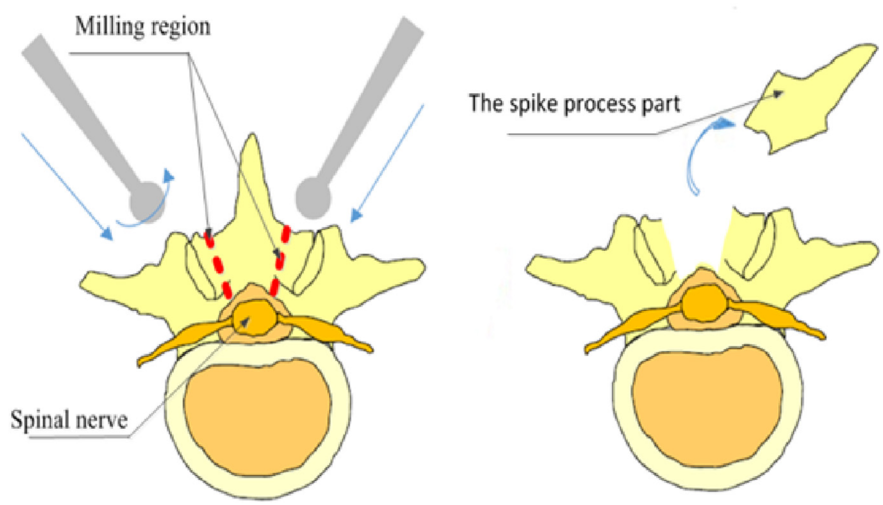


Fig. 1. The laminectomy operation [6].

has developed a spinal surgical robot and successfully recognized the different states during the pedicle screw insertion process with a real-time force sensing algorithm [13]. For the vertebral lamina milling task, some safety control strategies have been studied. Wang et al. [14,15] milled the vertebral layer by layer from the outer cortical bone to the inner cortical bone at a constant depth. Based on the analysis of typical characteristic parameters of the force profiles, the cross-correlation to the standard profiles are adopted to judge the milling status. Because this method was unable to adapt to the complex surfaces of the vertebrae, the profile pattern is in close relation to the three-layer structure, which is to the disadvantage of milling status distinguishment. Zhang et al. [16] proposed a fuzzy logic control method for bone drilling operation to treat laminectomy. Based on surgeons' experience , the database of fuzzy rules was established. The pressure on the drill and the thickness of the bone are set as input, the drilling depth and drilling velocity are set as output. The fuzzy logic control system was simulated with MATLAB and SIMULINK, and the result showed its feasibility. Deng et al. [17] designed a fuzzy force controller for vertebral lamina milling operation. The force control was implemented to adjust the milling parameters to adjust for the complex anatomical structure of the vertebral lamina. For safety purposes, a state detection method based on energy consumption was also proposed. The results of contrast experiments showed that the milling operation under fuzzy force control took shorter time and was with more stable longitudinal contact force. The state detection method could detect the three milling states successfully, resulting in an acceptable vertebral lamina residue.

In this paper, we firstly describe the anatomical structure of the vertebral lamina and the milling procedure. Then, the fuzzy force control theory is introduced. The milling force in the horizontal direction is controlled constant, and the milling force in the vertical direction is used to distinguish the structure of the bone layer. The principle of milling state distinguishment is established through six groups of vertebral lamina milling experiments. Then, twelve groups of experiments are conducted to validate the robustness of the safety control strategy based on this principle.

The paper is organized as follows. The fuzzy force control strategy is proposed in Section 2 and 3. The principle of milling state distinguishment is established and validated in Section 4 and 5. The conclusions are presented in Section 6.

2. Safety control strategy

In laminectomy, vertebral lamina milling is the key and most difficult procedure. Orthopedists must handle the 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. During the vertebral lamina milling operation, the bone drill needs to drill through the outer cortical bone, cancellous bone, and the inner cortical bone (Fig. 2). During the actual operation, if not controlled well, the bone drill may drill through the inner cortical bone and seriously damage the spinal cord and nerves, this will cause paralysis or even death of the patients (Fig. 3). Therefore, it is very important to detect the milling state and ensure the safety in a robot-assisted surgery.

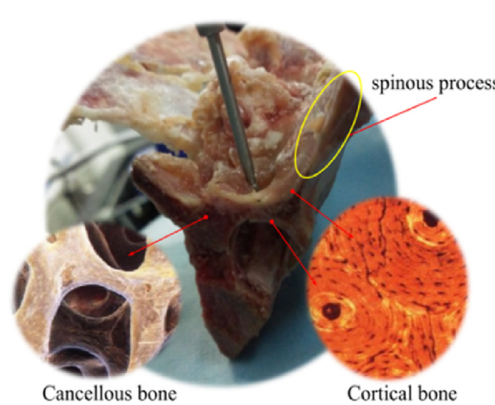


Fig. 2. Physiological structure of lamina.

The interacting force between the bone drill and vertebral lamina is affected by many factors during the milling operation. It mainly includes: bone density, rotating speed, milling speed and milling depth. In our case, the milling speed and the rotating speed of bone drill are both set to a constant value. With the bone drill mills different layers and the milling depth changes, the interacting force between the vertebrae lamina and bone drill will change. During the milling operation, the bone drill needs to work on three bone layers including outer cortical bone, cancellous bone and inner cortical bone. The bone density of the cortical bone is larger than that of the cancellous bone [18,19]. With the same milling depth, the interacting force between bone drill and cortical bone is larger than that of the cancellous bone. The interacting force between the bone drill and vertebral lamina is analyzed to recognize the milling state.

During the milling operation, the bone drill mills along the surface of the vertebral lamina, and the milling force can be decomposed into two components: axial force Fy and tangential force Fz (Fig. 4). To ensure the safety of the surgery, a safety control strategy based on fuzzy logic is proposed (Fig. 5). At the beginning of milling operation, an initial milling depth is given, and the tangential force with this milling depth is set to be the reference value. The real-time tangential force signal is introduced into the fuzzy logic controller. By adjusting the milling depth of the bone drill, the tangential force is kept in a constant range. At the same time, the axial force signal generated in milling operation is used to estimate the state of the vertebral lamina milling; if the bone drill is milling in the outer cortical bone layer and cancellous bone layer, the milling operation continues; if the bone drill is milling in the inner cortical bone layer, the milling operation stops.

3. Fuzzy force control

Fuzzy control system is a closed loop control system based on fuzzy language representation and logic inference. Its core component is fuzzy logic controller (FLC) [20]. It transforms the measured values by various sensors into the fuzzy quantities suitable for the fuzzy operation. Then fuzzy rules are constructed to infer the output result. In the end, the fuzzy quantity in the operation result is converted to the exact quantity, in order to carry out the specific operation of the actuator control (Fig. 6). Since the control output of the fuzzy logic control system is calculated from the fuzzy inference, it does not need the system mathematical model. The parameters of the membership functions and fuzzy rules need to be planned by the expert or based on experience [21].

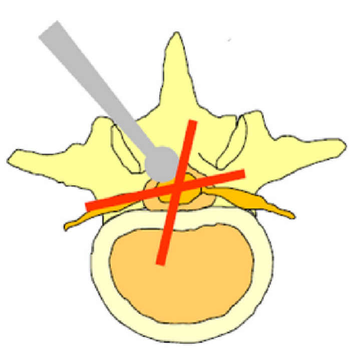


Fig. 3. Dangerous operation [4].

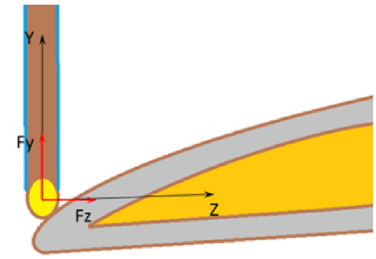


Fig. 4. Analysis of the milling force.

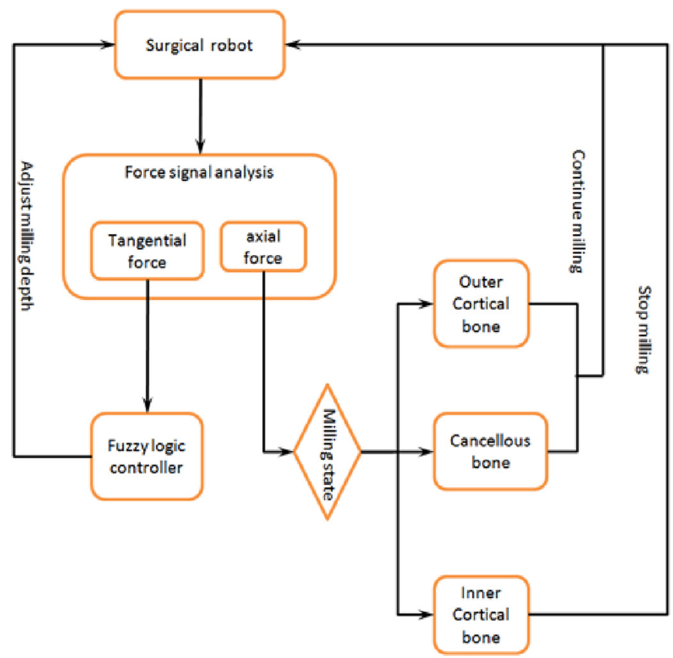


Fig. 5. Safety control strategy.

In order to test the safety control strategy presented in this paper, the milling experiments have been conducted with the three-axis robot system. The experiment setup is shown in Fig. 7. The bone mill is with diameter of ∅4 mm and its rotating speed can be regulated from 0 r/min to 80000 r/min. The interacting force between the bone dill and bone sample is measured by the force/torque sensor with sampling frequency of 1000 Hz. The milling speed is 1.5 mm/s, the initial milling depth is 0.5 mm.

The original force signal is noisy, caused by motor vibration, so the collected force signal needs to be filtered before subsequent processing. In this study, recursion average filtering is used to process the original force signal. Fig. 8 shows the filtering result of the original force signal.

The force controller is based on admittance control, constructed with milling depth ∇d, horizontal milling force F_Z and reference milling force F_{ref}, as shown in Eqs. (1) and (2).

$$\nabla d = G_e \left(F_Z - F_{ref} \right) \tag{1}$$

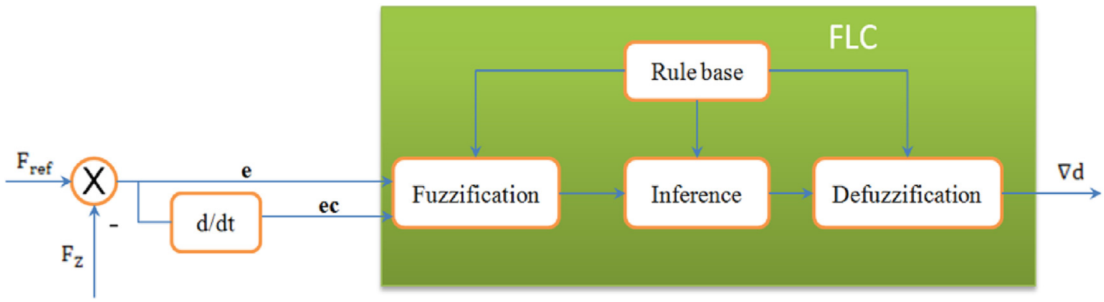


Fig. 6. The structure of fuzzy logic controller.

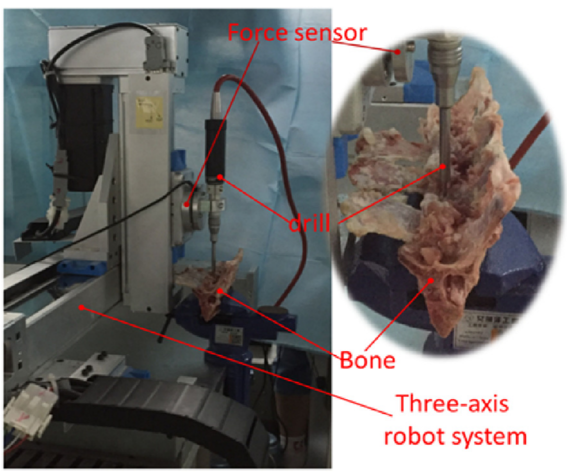


Fig. 7. Milling experiments.

$$\nabla d = y - y_{ref} \tag{2}$$

Where G_e is the contact admittance between the ends of the bone drill and the lamina, y and y_{ref} are the actual space co-ordinate and the reference space coordinate of the bone drill in the direction of milling depth for the bone drill.

We define linguistic variables “E” in the domain of system error e. We define the linguistic variable “Ec” in the domain of the error changing rate ec. We define the linguistic variable “U” in the domain of control u, as shown in Eqs. (3)–(5).

$$e = F_{ref} - F_Z \tag{3}$$

$$ec = e_i - e_{i-1} \tag{4}$$

$$u = \nabla d \tag{5}$$

Fuzzification is the first step of fuzzy combiner, which transforms the input and output variables into the fuzzy quantity. In the discrete domain, the input and output variables are denoted as {−6, −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5, 6}, respectively. Their corresponding fuzzy quantities are defined for the rule base as {NB (negative big), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), PB (positive big)} [19].

The values of the e and u are scaled to the interval of [−0.5, 0.5] and the interval of [−0.09, 0.09] for the ec, as shown in Eqs. (6)–(11).

$$e = [e_L\ ,\ e_H] = [-0.5, 0.5] \tag{6}$$

$$ec = [ec_L\ , ec_H] = [-0.09, 0.09] \tag{7}$$

$$u = [u_L\ ,\ u_H] = [-0.5, 0.5] \tag{8}$$

$$k_e = \frac{12}{e_H - e_L} = \frac{12}{0.5 + 0.5} \tag{9}$$

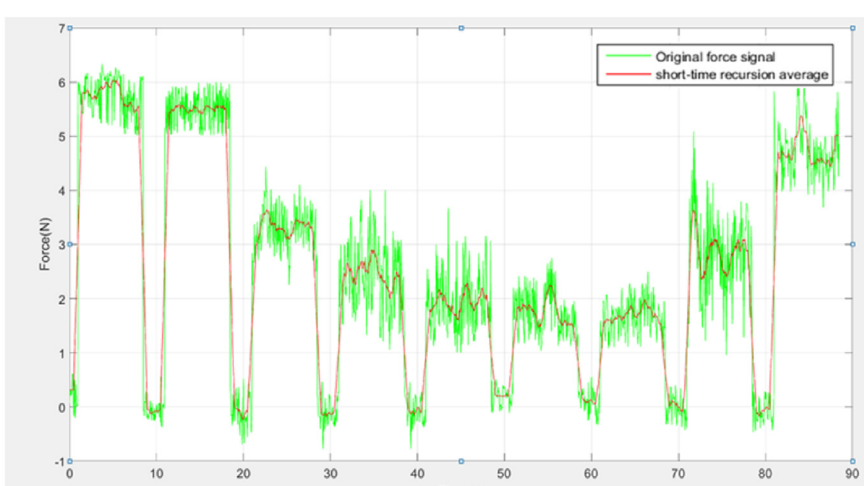


Fig. 8. Original force signal and its short-time recursion average.

$$k_{ec} = \frac{12}{ec_H - ec_L} = \frac{12}{0.09 + 0.09} = 66.67 \quad (10)$$

$$k_u = \frac{u_H - u_L}{12} = \frac{0.5 + 0.5}{12} = 0.08 \quad (11)$$

where k_e and k_{ec} denote the quantization factors of input, and k_u denote the scaling factor of output.

After fuzzification, fuzzy inference is used to establish the fuzzy rules. In this study, the triangular membership function is used for all variables, as shown in Fig. 9.

The fuzzy rules are constructed using if-then statements, and 49 rules are defined to form the fuzzy rule base for the fuzzy combiner, as shown in Table 1.

FLC is developed using the Fuzzy Logic Toolbox for MATLAB and Simulink. Surface viewer is utilized for the determination of the characteristics of the proposed fuzzy controller, as shown in Fig. 10.

In order to show the advantages of fuzzy force control strategy, two groups of experiments have been conducted on the same bone sample, which is a vertebra bone of pig with thickness of 57 mm. The rotating speed of the bone drill is set to be 15000 r/min. In the first experiment, the milling depth remains constant; the bone drill mills down 0.5 mm layer by layer, until the inner cortical bone. In the second experiment, the milling depth is adjusted with the tangential milling force based on fuzzy control strategy, keeping the tangential force a constant value.

The milling force signals of the two experiments are shown in Figs. 11 and 12. There are 10 layers in Figs. 11 and 7 layers in Fig. 12 in the milling process until milling to the inner cortical bone. Comparing the two figures, it is noticed that the experiment with fuzzy force control has less milling layers (meaning less time used) and obtains a more regulated drill-bone interacting force, which will benefit the milling operation [22].

4. State recognition of vertebral lamina milling

To ensure the safety of milling operation, the bone drill needs to stop when it gets to the inner cortical bone. To obtain the relationship between the axial force and the state recognition, the experiment below has been conducted. Three kinds of bone samples including vertebra of pig, vertebra of sheep and vertebra of cattle are used in the experiment, with bone drill rotating speed of 15000 r/min and 20000 r/min separately. The initial milling depth is set to be 0.5 mm, and the tangential force during the milling operation is controlled to be constant with the fuzzy logic. The mean value of the axial force is

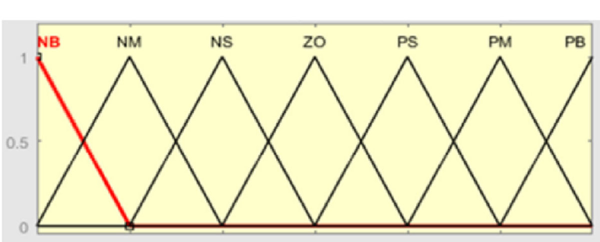


Fig. 9. Membership functions of the input and output variables.

Table 1
The rule base for FLC.

U	E						
	NB	NM	NS	ZO	PS	PM	PB
Ec							
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
MS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PB	PM
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZE	PM	PM	PB	PB	PB
PB	ZO	PS	PB	PB	PB	PB	PB

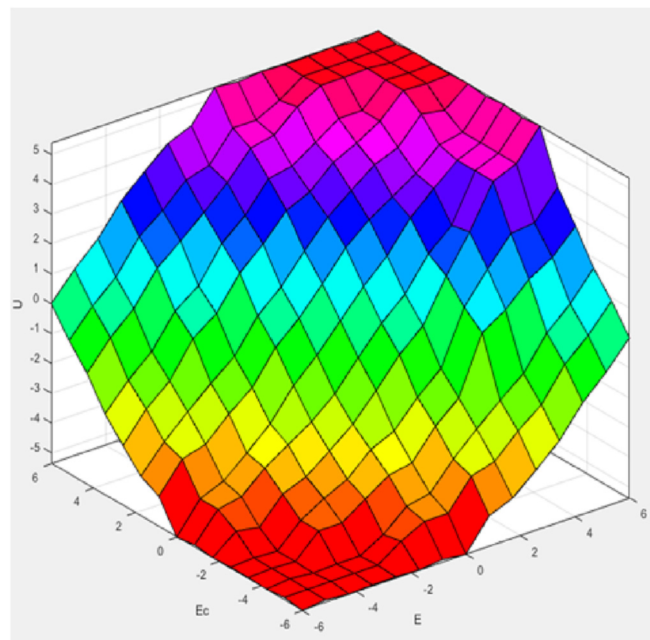


Fig. 10. Surface viewer.

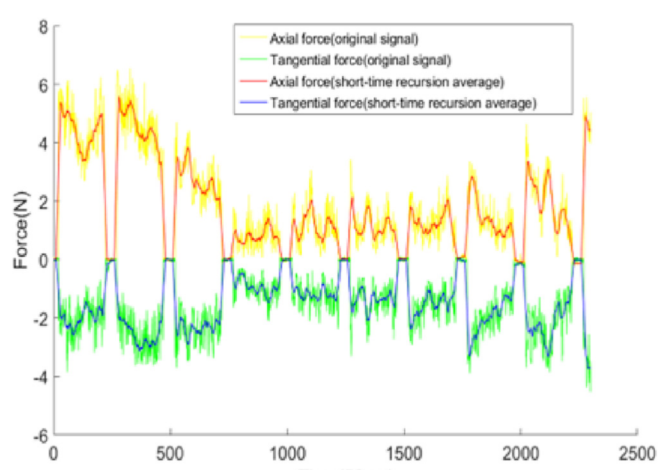


Fig. 11. Result of the first experiment.

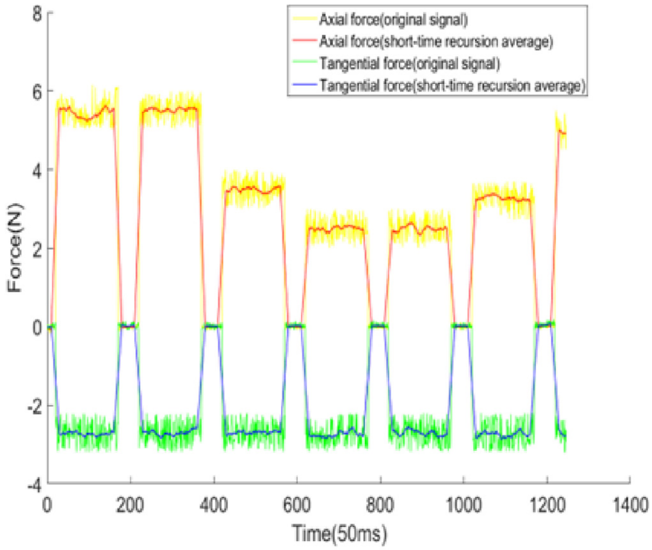


Fig. 12. Result of the second experiment.

recorded for each layer, until the bone drill gets to the inner cortical bone. Table 2 shows that the axial milling forces are different on different bone samples and the force value is also affected by drilling speed.

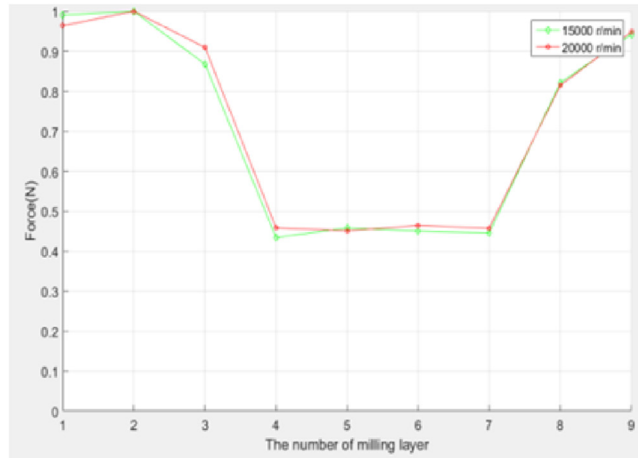
To prove that the surgical system can detect the milling states for all the cases, the data is normalized. By using the normalized mean feature, the characteristic parameter range of the axial force is mapped to the [0, 1], as shown in Fig. 13.

After normalizing the data of these 6 groups, we found that the axial force of the cancellous layer are always in the range of (0.4, 0.5) and the axial force of the cortical layer are always greater than 0.9.

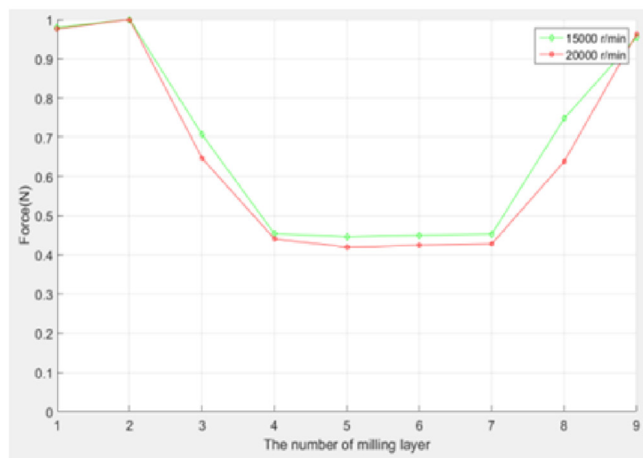
With the above experimental results, we has obtained the relationship between the axial force and milling state, and the control program is written , as shown in Fig. 14. Firstly parameters are initialized, then the system starts milling operation. In the initial milling stage, S = 1, the bone drill is located in the outer cortical bone. The average milling force of the first two layers is used to determine the maximum milling force Fo.

Table 2
Axial milling force (unit: Newton).

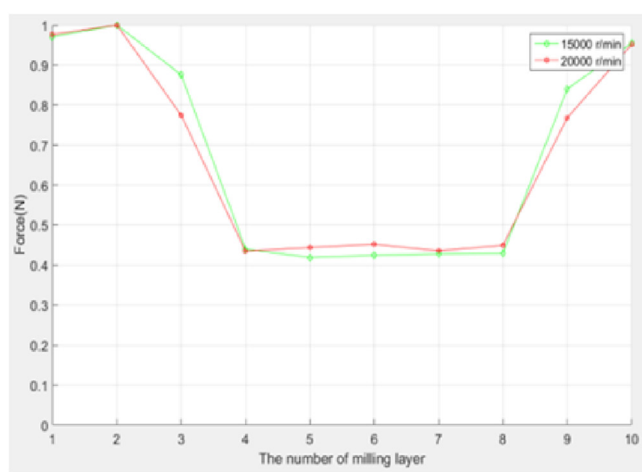
Sample		Vertebra of pig (depth 6.5–8.5 mm)		Vertebra of sheep (depth 6.6–9.0 mm)		Vertebra of cattle (depth 8.7–10 mm)	
Rotating speed		15 krpm	20 krpm	15 krpm	20 krpm	15 krpm	20 krpm
The number of layer	1	4.5874	4.0532	5.0268	4.5732	4.2532	3.7864
	2	4.6315	4.2026	5.1326	4.6823	4.3828	3.8786
	3	4.0230	3.8252	3.6258	3.0252	3.8368	3.0044
	4	2.0125	1.9283	2.3264	2.0628	1.9282	1.6856
	5	2.1232	1.8968	2.2882	1.9636	1.8348	1.7227
	6	2.0863	1.9528	2.3065	1.9858	1.8578	1.7536
	7	2.0646	1.9250	2.3224	2.0022	1.8734	1.6900
	8	3.8062	3.4252	3.8365	2.9858	1.8811	1.7434
	9	4.3644	3.9886	4.8990	4.5060	3.6823	2.9787
	10					4.1838	3.6882



a. Vertebra of pig



b. Vertebra of sheep



c. Vertebra of cattle

Fig. 13. Normalized axial force.

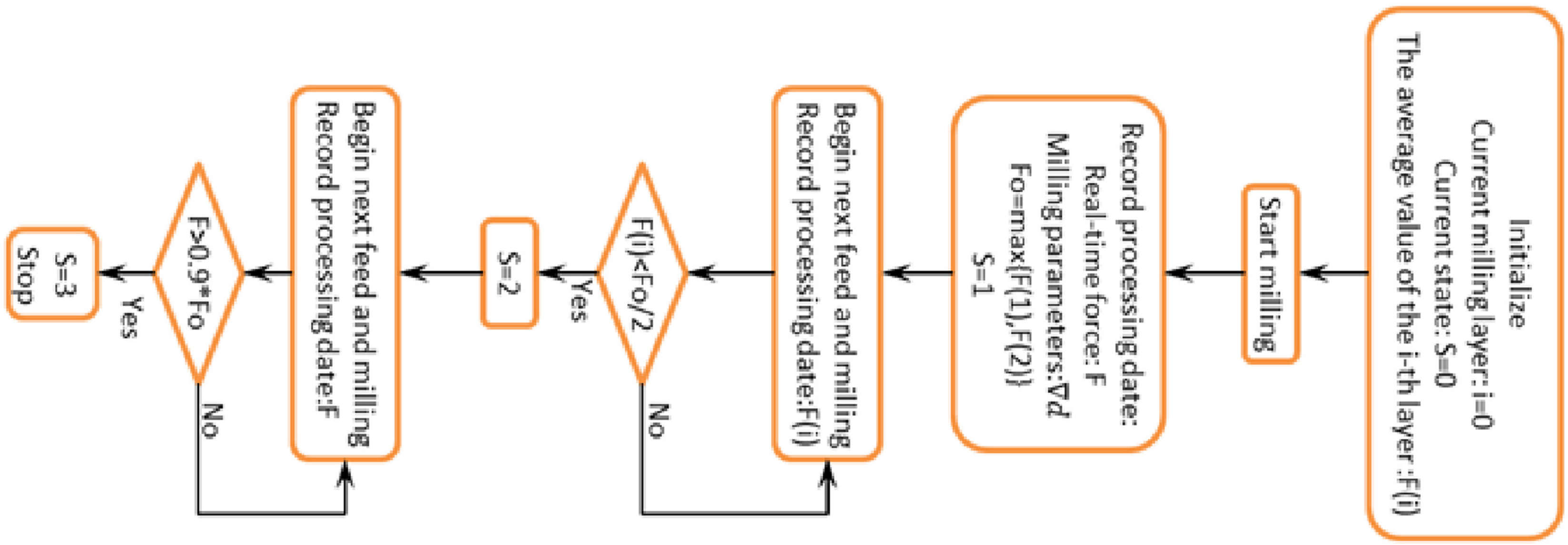


Fig. 14. Program control flow chart.

Table 3
Experimental date of axial milling force (unit: Newton).

Sample		Vertebra of pig		Vertebra of sheep		Vertebra of cattle		Vertebra of pig		Vertebra of sheep		Vertebra of cattle	
No.		1-a	1-b	2-a	2-b	3-a	3-b	4-a	4-b	5-a	5-b	6-a	6-b
The number of layer	1	4.6025	4.5963	5.0896	5.1002	4.2865	4.2632	4.0368	4.0350	4.5029	4.4602	3.6022	3.6332
	2	4.6872	4.6557	5.1025	5.1762	4.4024	4.3529	4.2316	4.1966	4.6859	4.5708	3.9004	3.8620
	3	4.0264	4.0355	4.2526	3.9685	4.0236	4.0192	3.8423	3.7023	3.5246	3.8654	3.7842	3.7264
	4	2.1036	2.1564	2.4167	2.3147	2.5394	3.1654	1.9874	1.9653	2.0314	2.0460	2.8526	2.5926
	5	2.0596	2.0895	2.3951	2.2659	2.0567	1.9623	1.8996	1.9387	1.9856	2.0983	1.6973	1.7122
	6	2.1325	2.1039	2.3562	2.2964	1.9835	1.9822	1.9255	1.9265	1.9689	1.9843	1.6958	1.7198
	7	2.0695	2.0698	2.3386	2.3312	1.9864	1.9687	1.9835	1.8689	2.0139	1.9346	1.7206	1.6840
	8	3.9744	4.0206	3.5278	3.8072	1.9956	1.9925	1.9623	1.9008	2.0354	2.0028	1.7064	1.6903
	9	4.5258	4.4983	4.9744	4.8098	1.9942	1.9723	2.5368	3.5564	3.6215	3.5776	1.6895	1.7011
	10					1.9863	1.9962	4.0282	4.0012	4.4659	4.3641	1.7142	1.7284
	11					3.7072	3.6824					2.5961	2.0980
	12					4.2530	4.1328					3.7098	3.5049

Table 4
Experimental result.

No.	Sample	Rotating speed (r/min)	Lamina thickness (mm)	milling speed (mm/s)	Milling length (mm)	number of layer	Residual lamina thickness (mm)
1-a	Vertebra of pig	15000	6.5	1	15	9	1.2
1-b		15000	6.7	1	18	9	1.3
2-a	Vertebra of sheep	15000	6.8	1	13	9	1.4
2-b		15000	6.7	1	14	9	1.4
3-a	Vertebra of cattle	15000	9.2	1	18	12	1.4
3-b		15000	9.3	1	16	12	1.3
4-a	Vertebra of pig	20000	7.5	1	14	10	1.4
4-b		20000	7.2	1	17	10	1.1
5-a	Vertebra of sheep	20000	7.3	1	18	10	1.1
5-b		20000	7.2	1	16	10	1.0
6-a	Vertebra of cattle	20000	9.5	1	17	12	1.6
6-b		20000	9.8	1	15	12	1.9

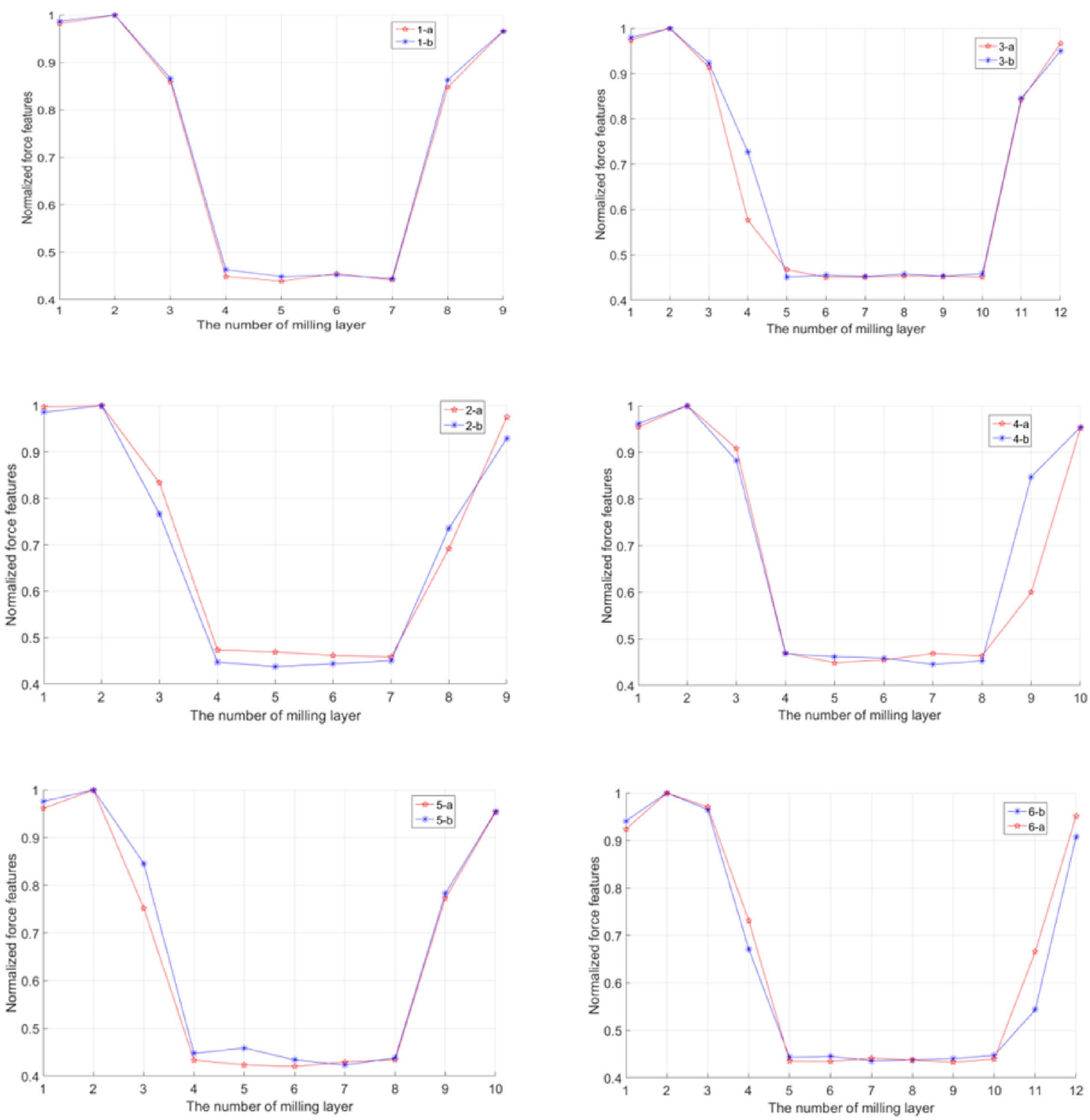


Fig. 15. Normalized force features in different milling situations.

When the average milling force of the i-th layer is less than Fo/2, S = 2. Bone drill is located in the cancellous bone, the milling operation continues. When the milling force is larger than 0.9*Fo, S = 3. The bone drill is located in the inner cortical bone, the milling operation stops immediately.

5. Experiment validation

According to the surgeons' experience, the vertebra lamina residue with thickness of 1–2 mm can meet the safety requirement of the operation, and the surgeons can easily open the spinal canal wall.

In order to verify the effectiveness of the safety control strategy in the lamina milling operation, we conducted 6 groups of experiments, 2 times in each group, with parameters shown in Table 4.

The experimental method is based on the three-axis robot system, using the vertebra of pig, vertebra of sheep, and vertebra of cattle for the milling experiment. We check the state of the milling process and measure the residual lamina thickness.

Table 3 shown the data collected with the 6 groups of experiments. In Fig. 15, the test data are normalized, and it is clearly shown that the normalized force feature of 0.4–0.5 for the milling in cancellous bone, and the normalized force feature higher than 0.9 for the milling in cortical bone. The data trend in Fig. 15 is similar to that in Fig. 13.

The experimental result is shown in Table 4. By measuring the thickness of the residual lamina, we found that the experimental results of the 6 groups are all located between 1 and 2 mm, which guarantees the safety of the vertebral lamina milling operation.

6. Conclusions

In this study, a safety control strategy based on fuzzy force control is proposed for vertebral lamina milling task. The anatomical structure of the vertebral lamina is described and the interacting force between the bone drill and the lamina is analyzed. The milling force in the horizontal direction is controlled constant with fuzzy force control logic, and the milling force in the vertical direction is used to distinguish the structure of the bone layer. Through several experiments on different bone samples, the milling state distinguishment principle is recognized, and by data normalization, a safety control strategy is designed and validated. The experiment results shows that, with the control strategy proposed in this paper, the system can obtain a regulated bone-tool interacting force and take less milling time. The state detection method can protect the vertebral lamina from being milled through and ensure an acceptable thickness of vertebral lamina residue.

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