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Advances in tissue state recognition in spinal surgery: a review

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Abstract Spinal disease is an important cause of cervical discomfort, low back pain, radiating pain in the limbs, and neurogenic intermittent claudication, and its incidence is increasing annually. From the etiological viewpoint, these symptoms are directly caused by the compression of the spinal cord, nerve roots, and blood vessels and are most effectively treated with surgery. Spinal surgeries are primarily performed using two different techniques: spinal canal decompression and internal fixation. In the past, tactile sensation was the primary method used by surgeons to understand the state of the tissue within the operating area. However, this method has several disadvantages because of its subjectivity. Therefore, it has become the focus of spinal surgery research so as to strengthen the objectivity of tissue state recognition, improve the accuracy of safe area location, and avoid surgical injury to tissues. Aside from traditional imaging methods, surgical sensing techniques based on force, bioelectrical impedance, and other methods have been gradually developed and tested in the clinical setting. This article reviews the progress of different tissue state recognition methods in spinal surgery and summarizes their advantages and disadvantages.

Keywords spinal surgery; tissue state recognition; image; force sensing; bioelectrical impedance

Introduction

Spinal disease is an important cause of cervical discomfort, low back pain, radiation of pain to the limbs, and neurogenic intermittent claudication [1,2]. At present, the incidences of common spinal diseases, such as spinal disc herniation (approximately 18.5%–22.4%), spinal stenosis (approximately 20%–25%), and spondylolisthesis (approximately 12.7%) are increasing annually [3–5]. These diseases can cause fecal incontinence and even paralysis when they are severe. From the etiological viewpoint, these symptoms are directly caused by the compression of the spinal cord, a nerve root, or a blood vessel and are most effectively treated with surgery [5–8].

Spinal surgery is divided into two main techniques: spinal canal decompression and internal fixation. Given the increased difficulty, high risk, numerous potential complications, and long learning curve of spinal surgery, the surgeon's ability to make accurate judgments during the course of the surgery should be determined. In the past, surgeons' perception and judgement of safety in the operating area mainly depended on their tactile sensations. However, this method of perception is too subjective and relies heavily on surgeons' experience [9,10]. Moreover, it suffers from other problems, such as poor accuracy; great risk of error; lack of standardization; and heavy mental, physical, and psychological burden on surgeons. Therefore, spinal surgery research has mainly focused on strengthening the objectivity of tissue state recognition; improving the accuracy of safe area location; and avoiding surgical injury to the spinal cord, nerves, blood vessels, and other important structures. Aside from traditional imaging methods, surgical sensing techniques based on force, bioelectrical impedance, and other methods have been gradually developed and tested in the clinical setting [11–13]. This article reviews the progress of different tissue state recognition methods in spinal surgery and summarizes their advantages and disadvantages.

Regional tissue state recognition in spinal surgery based on image technology

The intraoperative imaging system is the most common technique for tissue state recognition in spinal surgery. As bone structures have high density, a good imaging contrast

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is formed with nerves, muscles, blood vessels, and other soft tissues. Therefore, the C-arm machine and O-arm machine, which are based on the principle of X-rays, have been widely used in the clinical setting [14]. Intraoperative X-ray fluoroscopy is convenient, fast, and capable of providing clear findings, which can effectively enhance the accuracy of pedicle screw implantation, improve operation quality, and reduce operative time [15]. A research study showed that the accuracy of posterior pedicle screw placement assisted by the isocentric C-arm (ISO-C-arm) system can be increased to 97.6% [16] relative to the average accuracy (79%) of unarmed screw placement. With the development of computed tomography (CT)/magnetic resonance imaging fusion techniques, three-dimensional C-arm navigation, O-arm combined with real-time navigation, and other technologies [17,18], image-based intraoperative recognition methods can effectively improve the safety and accuracy of spinal surgery and reduce the intraoperative radiation exposure dose and injury to operators. By reviewing the imaging data and recovery of 732 patients with pedicle screw implantation, Tang *et al*. [19] confirmed that the accuracy of using three-dimensional fluoroscopy navigation for screw implantation is high and that the complication rate is low. Yang *et al*. [20] reported that the accuracy rate of pedicle screw implantation under three-dimensional ISO-C-arm navigation is 97.2%, whereas that under traditional radiography is only 91.7%. Bledsoe and Oertel [21,22] also reported that pedicle screw implantation under three-dimensional ISO-C-arm navigation can increase the accuracy rate of the procedure to about 95%. In terms of radiation dose, the exposure dose when the three-dimensional O-arm scan is used is only one-sixth to one-third of the dose when conventional intraoperative fluoroscopy is used (i.e., 5–7 mSv). In short-segment surgery, the required number of radiation sessions and the screw implantation time of CT navigation are significantly lower than those of conventional fluoroscopy [23].

Augmented reality (AR) and virtual reality (VR) are emerging computer imaging technologies. They have been gradually applied to clinical examination, surgery, and operative teaching. AR technology acquires image data (including object position, angle, etc.) in real time and then presents real-world and virtual-world information after calculating and editing the data. Bernhardt *et al*. [24] used virtual cameras to improve the imaging effect of endoscopy. Their quantitative and qualitative experiments proved that the accuracy of anatomical tissue recognition by AR could reach the submillimeter level. VR technology collects data from the real world, generates electronic signals through computers, and presents them to users through different output devices in the form of three-dimensional models, thus creating a sense of immersion in the environment. In the prospective study of Zheng *et al*. [25], VR technology was applied to the preoperative planning of minimally invasive discectomy. The results indicated that VR technology could effectively improve the identification accuracy of relevant surgery-related angles and distances (except for depths), improve the puncture accuracy of percutaneous endoscopic lumbar discectomy, and reduce the duration of fluoroscopy and localization.

Mixed reality (MR) technology is a combination of VR and AR. This technology combines digital image information with surgeons' perception of the real surgical environment and provides them with realistic feedback through different modalities, such as vision and tactile senses. It is currently being applied to many clinical skills training and surgical research studies [26,27]. Coelho and Defino [28] constructed a surgical simulation platform by using MR to recognize spinal anatomy, show pathological diagnosis, and identify surgical instruments and other related knowledge to be taught to residents. The effectiveness of this simulation platform was verified by evaluation, and the learning curve of junior residents could be significantly reduced in a safe environment. Yu *et al*. [29] trained doctors to complete percutaneous transforaminal endoscopic discectomy (PTED) by using MR (Fig. 1); they confirmed that this technology is helpful in the preoperative planning of PTED and can significantly reduce the duration of puncture and intraoperative fluoroscopy and shorten the operative time.

Although these imaging techniques can derive tissue state information on the operative area and provide a basis for surgeons to make judgments during spinal surgery, a number of problems remain (Table 1). First, existing imaging techniques can provide accurate tissue location information, but they offer hazy tissue type information, and they are particularly ineffective in distinguishing between different tissues. The final judgment still depends on the surgeon's clinical level and experience because the recognition result is highly uncertain. Second, these methods for tissue state recognition have a certain delay, which means that image data could only be acquired at the end of the operation; that is, the tissue state during operation cannot be acquired in real time. Although this recognition method can be used to judge the accuracy of an operation, it cannot directly warn of operational errors. Finally, these technologies cannot directly obtain physiologic information on tissues. Although they can improve the accuracy of operations, they cannot significantly reduce or avoid intraoperative complications. Additionally, the inevitable radiation exposure and complexity of operating the equipment restrict the development of intraoperative imaging technologies for tissue state recognition.

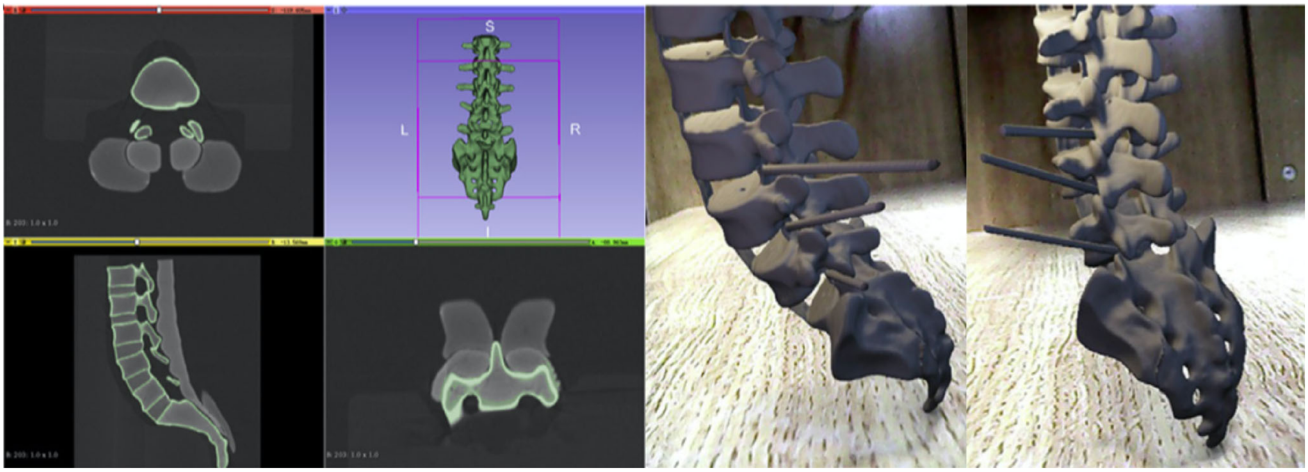

Fig. 1 Application of mixed reality technology to PTED training. Reprinted from Ref. [29] with permission.

Table 1 Different methods for tissue state recognition

Technology	Application	Advantages	Disadvantages
Imaging	C-arm, O-arm, AR, VR, MR, …	Provides accurate tissue location Improves the accuracy of operation	Fuzzy tissue type information Delays Cannot directly obtain physiologic information
Force sensing	Surgical instruments with force sensors	Has strong specificity Has been applied to clinical practice	Different operative methods, speed, etc. affect the force signal Lack of research on force feedback to the operator
Bioelectrical impedance	Health risk assessment system, pedicle probe and navigation system based on bioelectrical impedance technology	Reliable principle Simple operation Strong feasibility	Many factors can affect the accuracy of the numerical value Lacks a standard bioelectrical impedance database as a reference Suffers form deviations in data collection
Physical feature perception	–	Shows specific changes according to different contact tissues	Limited relevant research

AR, augmented reality; VR, virtual reality; MR, mixed reality.

Regional tissue state recognition in spinal surgery based on force sensing technology

Regardless of whether decompression or internal fixation is performed in spinal surgery, surgeons need to rely on tactile sensations to perceive the surgical area mainly through mechanical feedback from surgical instruments to help judge the nature and structure of the bones. However, controversy remains in the quantification of mechanical feedback and improvement of the accuracy of recognizing tissue state during spinal surgery. Lee and Shih [30] achieved numerical changes in force during surgery by using force sensors, which allowed the recognition of different bone layers according to changes in the contact force measured by the instrument. The research by Aziz *et al*. [31] and Hu *et al*. [32] was based on signal data obtained by force sensors. They designed real-time force sensing algorithms suitable for spinal operation to identify different bone properties. Marco *et al*. [33] summarized the established force model of bone drilling for recognizing bone structures. They concluded that bone mineral density is positively correlated with milling force, and such correlation provides a theoretical basis for force sensing research.

Compared with traditional manual surgery, robot-assisted surgery has the advantages of higher degrees of freedom, more accurate operation, and less risk of complications. In recent years, a large amount of scientific research has focused on studying the tissue state recognition technology of spine surgical robots, especially in terms of force sensing. The combination of robotic and force sensing technology reduces not only the loss of force feedback between the operator's hands, surgical instruments, and bone tissue but also manual errors intraoperatively. Ortmaier *et al.* [34] studied the positioning accuracies and machining forces during robot-assisted navigated drilling and milling for pedicle screw placement to improve the reliability of spinal surgery. Kim *et al.* [35] proposed a force-sensing scheme on the basis of previous research. The scheme can record the force exerted by the robot on the sensor and provide relevant force feedback to the surgeon through the double force/torque sensors. Deng *et al.* [36] proposed a method based on the principle of energy consumption to identify and control the milling state by collecting the force signals during milling. The end position of milling was found successfully. The stability and validity of the method were verified by comparative experiments. Fan *et al.* [37] also studied the use of the principle of fuzzy force control to achieve tissue state recognition by using vertical force signals in the milling operation (Fig. 2). They then used pig, sheep, cattle, and other animal spinal bone samples to verify the model. Jiang *et al.* [38] monitored the cutting depth in robotic laminectomy surgery by modeling the milling status using a particle swarm optimization algorithm. The model was validated on a fresh bovine bone with an accuracy of up to 0.2 mm in the target regions.

The force signal itself suffers from a number of defects, such as large noise and filtering delay, which make it difficult to acquire and analyze. Furthermore, existing

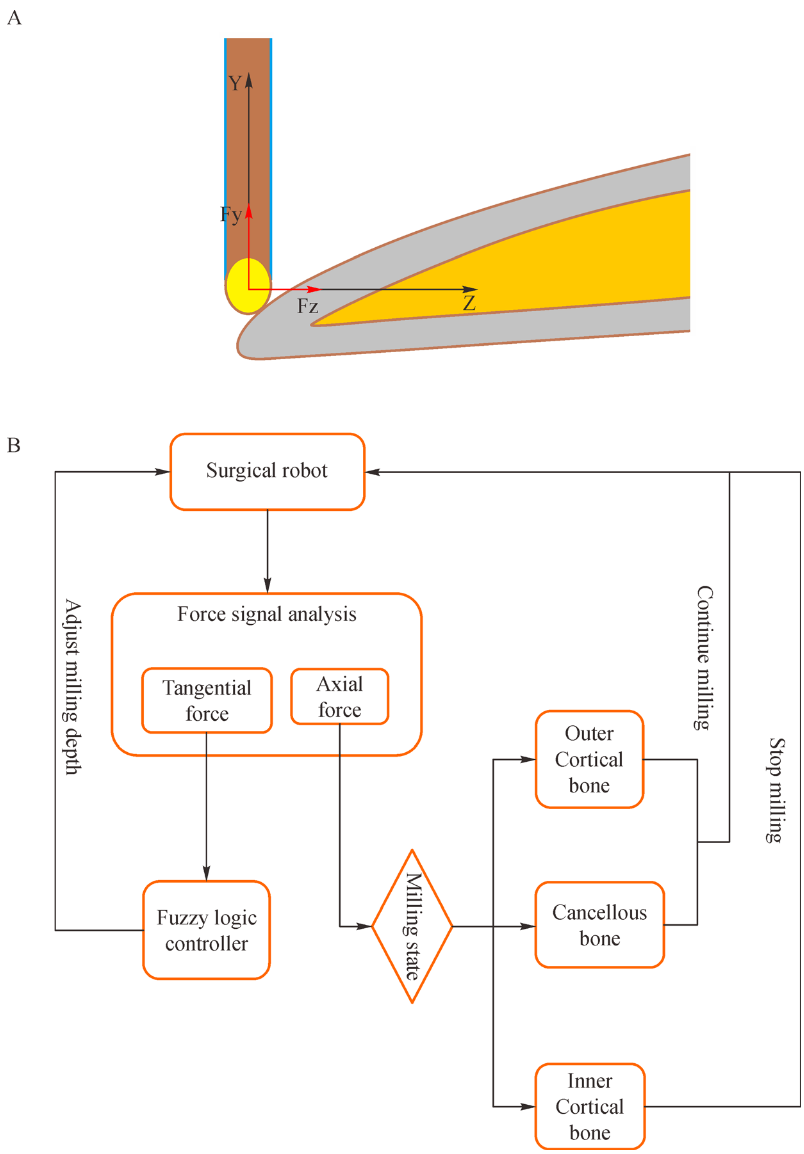

Fig. 2 Schematic of the analysis of milling force (A) and the safety control strategy (B). Reprinted from Ref. [37] with permission.

studies have shown that the recognition of bone layers on the basis of force signals is affected by the calibration threshold. If the threshold is too high, then it will cause recognition delay; if the threshold is too low, then it will cause recognition error. Therefore, some studies have also focused on obtaining other data to indirectly reflect force information so as to achieve tissue state recognition. Kasahara *et al*. [39] used the magnitude of the milling current intraoperatively to calculate the resistance of the milling bit and determine the bone tissue state. Osa *et al*. [40] developed a system to determine tissue state by using a handheld bone cutting tool according to changes in cutting resistance. This system learned the motion and cutting states from demonstrations using support vector machines on the basis of the motor current and rotational speed of the cutting tool and the outputs of the acceleration sensor. The approach subsequently contributes to the improvement of the safety of spine surgery. Dai *et al*. [41] performed research on spine tissue state recognition based on robot-assisted vibration sensing technology. They proposed an analytical method for modeling varying bone dynamics and proved that the vibration amplitude of the bone indicates its status change. On the basis of a previous study, a laser displacement sensor was used to collect the amplitudes of different bone tissues during vibration, and the vibration amplitudes were analyzed to distinguish the types of bone tissues [42]. Finally, a noncontact system was proposed to achieve the real-time detection of the bone milling state and thereby address the shortcomings of contact sensors to a certain extent.

Force is the most direct signal between surgeons, surgical instruments, and the surgical area during spinal operation, and it has high specificity. Therefore, it has long been the main direction of the research in tissue state recognition in the surgical area, and over time, a number of advanced force sensing algorithms have been applied to clinical practice. However, the current research on this technology still has some deficiencies (Table 1). First, spinal surgery includes milling, drilling, screw placement, and other operations using an osteotome, grinding drill, ultrasonic bone scalpel, pedicle probe, and other instruments. Moreover, different operative methods, speed, and power of the equipment affect the magnitude of the force signal, thus making tissue state organization difficult. Second, the surgeon's tactile sensations not only represent the force value of the device in contact with the tissue but also include the force value of the feedback from the device to the surgeon's hand. However, the existing force sensing technology focuses less attention on the feedback to the operator's hand. If the perceived force signal can be analyzed, processed, judged, and fed back to the operator to assist the surgeon in making decisions, then tissue state recognition technology in the surgical area will reach a new level of evolvement.

Regional tissue state recognition in spinal surgery based on bioelectrical impedance technology

Bioelectrical impedance is an intrinsic physical property of human tissue. Its numerical value is closely related to the size, nature, water content, cell arrangement, cell connection mode, and intracellular and extracellular environment of tissue cells. The electrical impedance of biological tissues has been proved to have a linear relationship with the water content of their cells [43]. Moreover, the value of bioelectrical impedance is affected by voltage frequency, that is, it decreases gradually with an increase in frequency because the imaginary part of impedance and dielectric loss are closely related to frequency [44,45]. Bioelectrical impedance technology is the measurement of tissue electrical impedance values that reflect tissue characteristics and physiologic or pathological changes indirectly and then enable tissue state recognition [46]. This method entails a simple operation and low cost, and it has no radiation; it has also been applied in the clinical setting. Antakia *et al*. [47] used this technique to collect the electrical impedance spectra of cervical tissues and distinguish between thyroid and parathyroid tissues. Through *in vivo* animal experiments, Dai *et al*. [48] demonstrated that the bioelectrical impedance values of the liver, gastrointestinal tract, kidney, bladder, muscle, and fat in rabbits were significantly different.

Regarding orthopedics, obvious differences exist in the structure, density, strength, and tissue fluid content of different types of bone. Hence, adequate bioelectrical impedance research and prospective applications are available. Studies have confirmed that bioelectrical impedance between the cortical bone and cancellous bone in long bones greatly varies. Dai *et al*. [48] studied the electrical impedance data of long bones in a pig, along with the path of the long bone drilling process (i.e., cortical bone, cortical bone–cancellous bone junction, cancellous bone, cancellous bone–cortical bone junction, and cortical bone perforation). The position recognition of the drill bit in bone was achieved. Relevant electrical impedance studies have also been conducted in the field of spinal surgery. On the basis of previous studies, Shao *et al*. [49] focused on spinal tissue (including cortical bone, cancellous bone, fibrous ring, and nucleus pulposus) and nonspinal tissue (esophagus, tracheal cartilage, tracheal annular ligament, anterior longitudinal ligament, long carotid muscle, and carotid artery) in the anterior cervical surgery area. The results of the Kruskal–Wallis test and pairwise comparison test showed that the logarithmic difference in electrical impedance between different tissues is most significant at a frequency of 200–600 kHz. The study concluded that this frequency is the best range of electrical impedance identification for anterior cervical surgery. Wyss Balmer *et al*. [50] established a mathematical model to predict the thickness of bone between electrodes and achieved an error of 0.7 mm.

Given the reliable principle, simple operation, and strong feasibility of electrical impedance technology, some medical equipment and instruments based on this technology have been gradually developed and popularized. For example, the health risk assessment system can use bioelectric sensing technology to assess human health and provide guidance on diagnosis and treatment according to the electrophysiological activity of organ cells. For the spine, many products, such as the pedicle probe and navigation system for internal fixation, are based on bioelectrical impedance technology. Turan *et al.* [51] confirmed that bioelectrical impedance measurement can effectively identify different tissues in the pedicle fixation pathway through the study of sheep spine and human cadaveric bones. It is an economical, simple, and safe method to prevent screw dislocation. Halonen *et al.* [52] designed a puncture needle with bioelectrical impedance technology and early warning function. It can measure the bioimpedance spectrum of cerebrospinal fluid, fat, and muscle intraoperatively (Fig. 3) and provide audiovisual feedback to the operator. The device has a sensitivity of 100% for cerebrospinal fluid recognition. Li *et al.* [53] invented a bioelectrical impedance pedicle probe to assist surgeons in completing pedicle screw implantation, and its effectiveness was verified through live animal experiments.

Despite these advances, tissue state recognition by bioelectrical impedance technology also has many limitations (Table 1). First, many factors can affect the accuracy of the numerical value in the process of bioelectrical impedance data acquisition. These factors include the nature of the tissue, environmental temperature and humidity, data collection technique, and so on. At present, no standard bioelectrical impedance database for biological tissues is available as a reference, and achieving unified norms in methodology is impossible. Second, because of the complexity of the anatomical structure and individual differences of tissues in the spinal system, deviations are common in bioelectrical impedance data collection, which is limited by experimental conditions. As the data acquisition of the existing bioelectrical impedance technology development process is mainly based on animal experiments, a bioelectrical impedance database of the human spine and surrounding tissues is lacking. Therefore, extensive research is needed in the future.

Regional tissue state recognition in spinal surgery based on physical feature perception technology

In addition to force and bioelectrical impedance, other physical signals generated during surgery have the potential for tissue state recognition. Especially for orthopedic surgery, surgical instruments often make contact with the bone structure to produce corresponding sound, heat, and other signals in the operation process. These physical signals also show specific changes according to different contact tissues (Table 1).

Tissue recognition by acoustic signals is still in the research stage, and no related instruments or products can be directly applied to the clinical setting. Boesnach *et al.* [54] recorded the acoustic signals emitted during the drilling of the pedicle during spinal surgery, and they

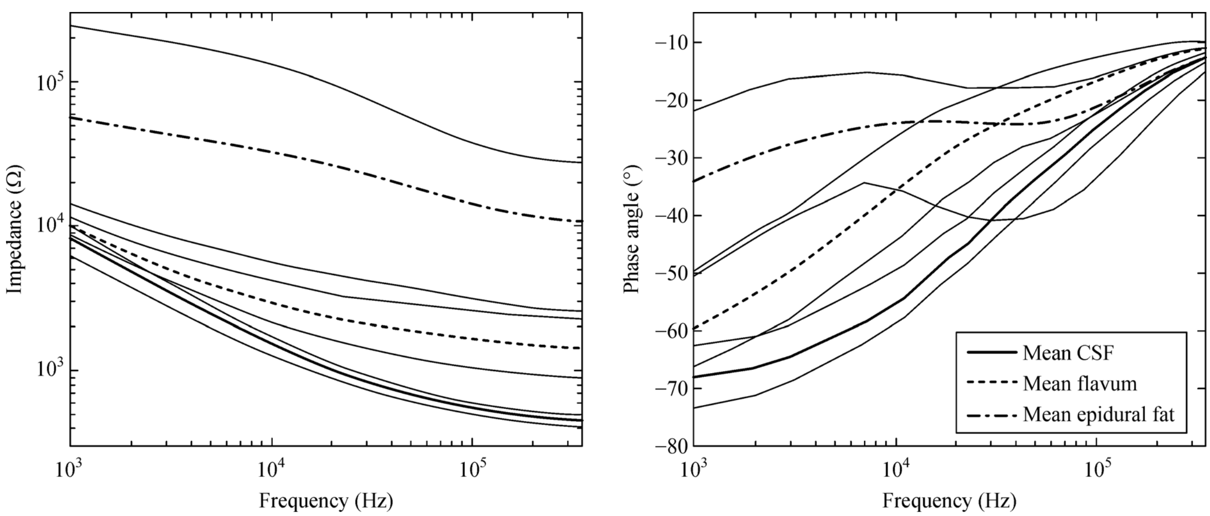

Fig. 3 Mean impedance magnitude and phase angle spectra of cerebrospinal fluid (CSF), ligamentum flavum, and epidural space. Reprinted from Ref. [52] with permission.

preliminarily noted a strong correlation between acoustic signals and bone mineral density by using statistical analysis. Liao *et al*. [55] further analyzed the structural characteristics and mechanical properties of the bone layer and found that the acoustic emission signals generated during drilling are related to the penetration depth and cutting bone layer and thus have good research and application potential. Sun *et al*. [56] used the fast Fourier transform algorithm to analyze the acoustic signals collected during bone drilling and verified the energy characteristics and stability of the signals by using the exponential average amplitude and the Hurst exponent. A real-time algorithm was developed to identify changes in the acoustic emission signal, which in turn reflects the nature of the grinding contact with the bone layer. Guan *et al*. [57] conducted further investigation on the basis of previous research; they determined that the frequency range of acoustic signals during pedicle drilling is 10–15 kHz and obtained the signal variation characteristics through the frequency distribution-based algorithm, which can distinguish between the two layers of interosseous transition between the cortical bone and the cancellous bone (Fig. 4). They also used neural network training to identify acoustic signals, thereby confirming that the recognition accuracy can reach 84.2%. Overall, the acoustic signal and force signal have characteristics that are consistent with those of the bone layer. Moreover, the acoustic signal has the advantages of being highly intuitive and easy to obtain, and it has the potential to identify the transition zone of the cortical bone–cancellous bone. It should be one of the future directions of the research into tissue recognition in spinal surgery.

In spinal surgery, particularly during milling, heat energy is inevitably generated. Heat energy may even cause damage to the bone and surrounding tissues. Studies have shown that bone tissue necrosis occurs with the exposure of tissues to a temperature of 47 °C for 1 min and that nerve tissue becomes irreversibly damaged with exposure to temperatures above 43 °C [58]. Therefore, identifying and monitoring thermal signals intraoperatively is potentially a way to recognize the tissue state in the operation area and improve the safety and accuracy of the operation. In the work of Shin and Yoon [59], the surface temperature of the bone during the milling process was first measured with an infrared thermometer; the maximum temperature of the milling bit varied from 49 °C to 115 °C under different cutting conditions, and the depth of bone tissue damage caused by heat energy was up to 1.9 mm. Additionally, Wen *et al*. [60] collected and calculated thermal signals during the process of cortical bone milling and found that the milling temperature exerted a significant effect on the moving speed of the

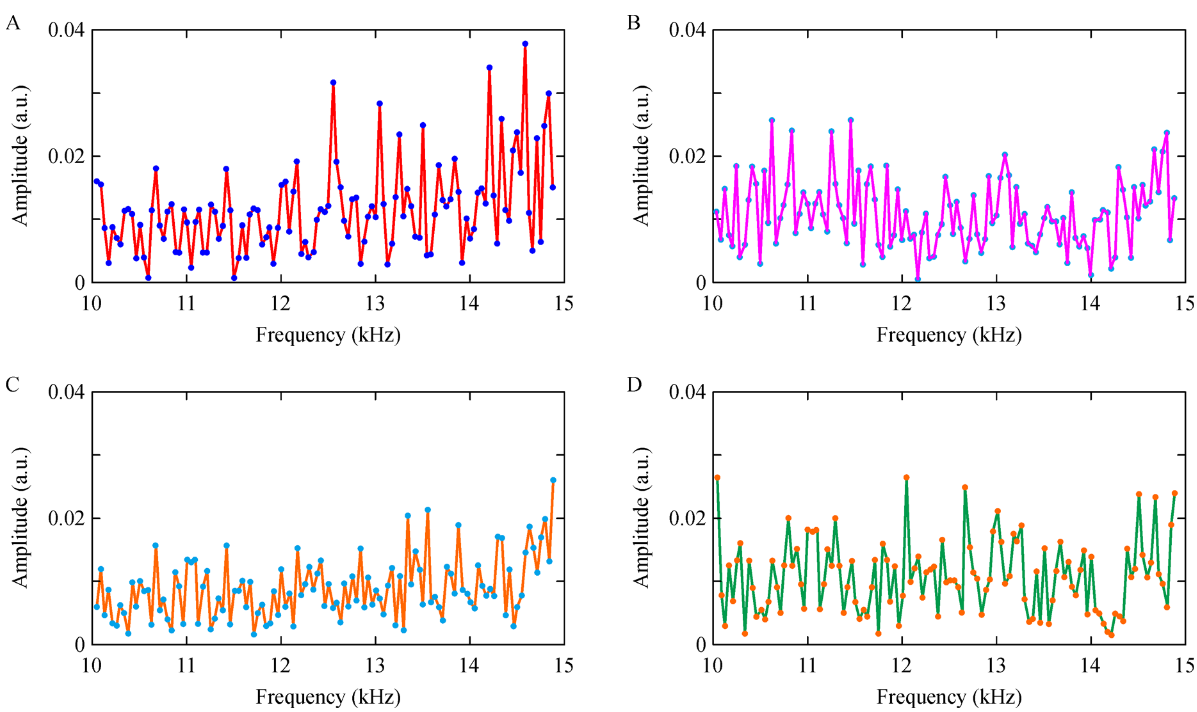

Fig. 4 Distribution of frequency between 10 and 15 kHz after using the recursive FFT for different moments: (A) drilling the cortical born; (B) cancellous bone; (C) transition region from cortical born to cancellous bone; (D) transition region from cancellous bone to inner cortical born. Reprinted from Ref. [57] with permission.

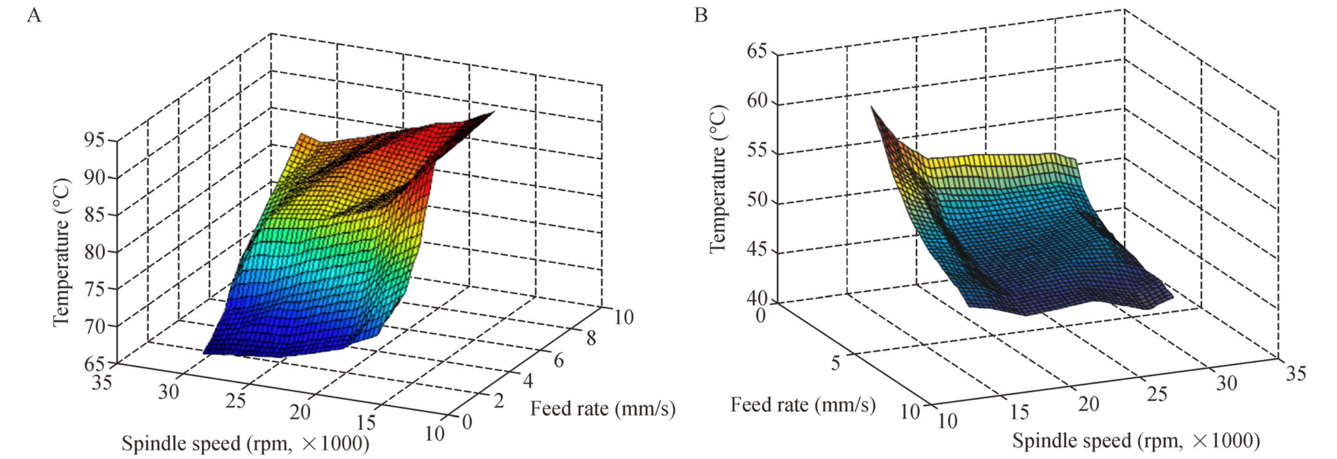

Fig. 5 Bur temperature (A) and fresh-milled bone temperature (B) as a function of feed rate and spindle speed. Reprinted from Ref. [61] with permission.

milling bit and the rotational speed. Kais *et al*. [61] established temperature models of the cancellous bone milling process. By measuring the parameters and temperature signal during the milling process, they found that the average temperature of milling increased with the increase in speed and that the maximum temperature was 76 °C. However, the average temperature of milling will decrease with the increase in the milling bit speed (Fig. 5). The aforementioned research results show that the thermal signal generated during the milling operation is related to the degree of milling of different bones. However, the related studies are still limited, and the specific change model needs further study (Table 1).

Conclusions

In summary, the research of tissue state recognition in the spinal surgery area is gradually developing in many directions, including image signal, force signal, bioelectrical impedance signal, acoustic signal, thermal signal, and so on. However, existing techniques still have some disadvantages. First, the anatomical structure of the spinal system is complex and has significant individualized characteristics. Second, different surgical instruments, surgical paths, operating methods, operating speeds, and other factors ultimately affect the tissue recognition signals during operation. Hence, *in vivo*, real-time, and accurate tissue recognition in the spinal surgery area is difficult. Finally, the related perception technology, which can be applied to clinical operation, is not available at present. The future direction of spine research on tissue state recognition should focus on improving the comprehension and accuracy of methods such that useful and reliable information can be obtained intraoperatively. The improvement will allow information to be integrated into multisensor technology to ensure the effectiveness and safety of spinal surgery.

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Compliance with ethics guidelines

Hao Qu and Yu Zhao declared no conflict of interest. This manuscript is a review article and does not involve a research protocol requiring approval by the relevant institutional review board or ethics committee.

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