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Safety analysis and control of a robotic spinal surgical system

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ABSTRACT

Screw path drilling is one of the most common and high-risk operations in many kinds of orthopedic surgery, especially in spinal surgeries. During spinal surgery, the bone screws are inserted into the vertebral body from the narrow vertebral pedicles. Any failures in this process will hurt important vessels and nerves of the patient. In this paper two aspects of the safety issues with using the Robotic Spinal Surgery System (RSSS) are analyzed: movement control and real-time operation control. For the safety motion control of the RSSS, two modes are developed: the cooperative control mode for positioning and the fine adjustment mode for precisely adjusting orientation. An automatic calibration algorithm for force/torque sensors is proposed to eliminate gravity effects. Guidance Virtual Fixtures (GVFs) and Forbidden Region Virtual Fixtures (FRVFs) are used to limit the movement of the RSSS. Damping Region Virtual Fixtures (DRVFs) are proposed to prevent the RSSS from crossing the constraint surface and harming the patient's body. In the path drilling process, a state recognition algorithm is proposed to simulate the feeling in the hand of the surgeon during surgery. Based on force feature extraction and state recognition algorithm, 5 states in the drilling process are recognized, and the control point, which is the stop point of drilling, is found. Experiments are carried out to verify the DRVFs effects in the motion control of RSSS, the state recognition and safety control of the pedicle drilling.

1. Introduction

With the rapid progress of robotic technology, many researchers focus their endeavor to robot assisted orthopedic surgeries. In the spinal orthopedic surgery, bone screws need to insert into the vertebral pedicles in order to prevent spinal movement, and two rods are used to connect them to generate extra supports. Fig. 1a shows the schematic of this operation. From the figure, one can see that the drilling quality of the paths for screw insertion is the most critical process [1]. Fig. 1b shows the complex structure of the vertebrae. In front of the vertebra, there are thoracic and abdominal aortas; in the vertebral canal, there is a spinal cord. In the operation, the screw path requires penetrating into the vertebra body through a narrow pedicle. The width of the pedicle is about 5–6 mm on the lumbar vertebrae and only 3.5–4 mm on the cervical vertebrae; however, the diameters of the bone screws for lumbar and cervical vertebrae are 4–4.5 mm and 2.5–3 mm respectively, so that the operation error has to be set at ±1 mm. Moreover, the desired depth of the screw path has to be about 80% of the length of the pedicle axis in order for it to obtain enough biomechanical strength, otherwise, the screw path will be of low quality or penetrate the inner cortical bone and harm the patient [2,3]. In some complex surgery cases, more than 20 screw paths need to drill; this will also increase the surgical difficulties and risks [4]. To reduce the surgical risks, a robotic spinal surgery system capable of movement control and force sensing is desired.

In order to guarantee the surgical safety, high precision in both the movement process and the operation process is a key issue. Focusing on the key safety issue, the movement control and real-time operation control of the surgical robots have been highlighted by many scholars, and several robotic systems for spinal surgery have been developed [5–19].

In recent research on motion safety, two kinds of Virtual Fixtures (VFs) such as GVFs and FRVFs are usually used to guide and constrain the movement of the robot for accurate position and safe movement. In 1993 Rosenberg proposed Virtual Fixtures to constrain the motion of telerobotic manipulation [5]. He also indicated that the compliant surface, damped surface and friction contact effects should be considered in VFs. However, the implementation method of VFs aimed at damped surface has not been developed.

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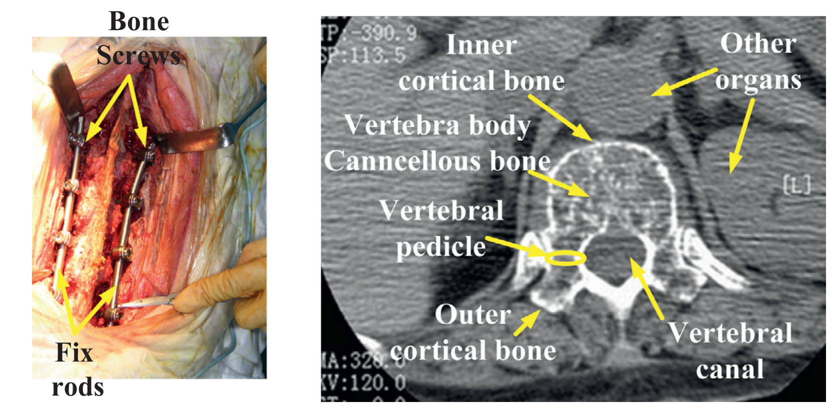

(a) Scheme of the operation (b) Structure of vertebra

Fig. 1. Diagram of screw paths on vertebra (from Beijing Jishuitan Hospital).

Abbott et al. from ETH Zurich implemented an FRVF based on impedance control to forbid the slave device of a master–slave robot to enter undesired areas [6]. Marayong et al. from The Johns Hopkins University developed GVF algorithms for the admittance control structure of the surgical robot. By comparing the open-loop and close-loop GVFs in their research, it is shown that close-loop GVFs based on visual information have a better guiding ability [7]. Based on these admittance type VFs, Taylor et al. developed a Steady-Hand robot used in retinal surgery and sinus surgery [8]. The robot works in the cooperative control mode and is guided and limited by the GVFs and FRVFs respectively in a small operation region. In the research on constraint control of surgical robots, Li et al. from The Johns Hopkins University proposed several element VFs, and combined them for different applications [9,10]. Ghanbari et al. from the University of Canterbury use the combined VFs containing a paraboloid and a planar FRVF to limit the motion and prevent penetration in microrobotic cell injection [11]. In these researches the robotic systems work in a small area and at low speed, while the operation regions of spinal surgery are much larger and the motion speed of the robot is higher.

A large number of experiments show that the FRVFs cannot completely prevent the robot from penetrating the constrained surface while operating in a large area and at high speed. The robot stops until it has detected the FRVFs along the motion direction in a control cycle, and at the same time the robot has penetrated the constraint surfaces of the FRVFs and even harmed the patient in the last control cycle. When the speed of movement is too high, the penetration into the constraint surfaces may be deep, so in this case the protection from FRVFs fails.

In order to avoid the risk from undesired movements, DRVF is proposed to reduce the speed of the robot. When the robot enters the small zone approaching the target point, i.e. the sensitive zone, the motion starts to slow down with the effect of the DRVF. In the sensitive zone the robot can be manually pulled to the target point slowly under the cooperative control mode; it can also be precisely positioned under the fine adjustment mode. In this paper the combined VFs with GVFs, FRVFs and DRVFs are used in the control of RSSS.

For the operation process safety control, the method of sensing and recognizing to simulate the feeling of a surgeon's hand in a real-time orthopedic operation is a key solution. In the screw path drilling process of orthopedic surgery, some scholars attempt to simulate the surgeon's hand feeling and to sense real-time operation force. Kasahara et al. from Keio University (Japan) proposed a linear master–slave manipulator to control the drilling process and estimate the cutting torque [12]. Furthermore, a teleoperated device is designed by Lee et al. to reflect the torque in the screw insertion process [13,14]. These procedures focus on the force signal acquisition and feedback to the surgeon. Bouazza-Marouf and Ong from Loughborough University (UK) developed an orthopedic drilling system to research the bone drilling process. The thrust force and the force difference are used to recognize the breakthrough point in their research [15]. Allotta et al. from Scuola Superiore Sant'Anna (Italy) developed another hand-held device also used in orthopedic surgery. It performs the drilling process and acquires the thrust force of the drill, and discriminates between the layers of different tissues [16,17]. But the stability of the manual operation with hand-held devices is still difficult to guarantee. Louredo et al. from University of Navarra (Spain) developed a mechatronic bone drilling tool in orthopedic surgery. The thrust force and drilling torque are sampled to recognize the breakthrough point of the outer and the inner cortical bone [18]. Aiming at the screw path drilling process in spinal surgeries, Lee and Shih developed an instrument for sensing the thrust force and the torque using a twist drill. By processing these signals, the breakthrough status in drilling is detected, and the drilling motion is constrained in real-time [19,20]. Furthermore, they implemented this instrument on a 3-DOF robotic arm to perform robotic assisted surgery [21]. Bouazza-Marouf and Ong from Loughborough University (U.K.) developed a similar device to study the thrust force and its difference during bone drilling [22]. In the above three research projects the breakthrough point of two cortical walls can be recognized, but the point cannot be used in the safety control of the robot in advance. In clinical surgery, a control point which is the beginning point and the start point of the inner cortical bone should be detected on time and control the robot to stop drilling immediately to obtain a proper and safe screw path.

In this paper, two key safety issues are analyzed for our robotic spinal surgical system. An accurate and safe motion control method including a cooperative control mode and an active fine adjustment mode is developed. Combined VFs including GVFs and FRVFs are used to constraint the motion of the robot. Furthermore, a DRVF is proposed to prevent the robot from penetrating the constraint surfaces. In the screw path drilling process, a real-time state recognition and control algorithm is proposed. Each state in the drilling process is recognized and the control point is detected by this algorithm for real-time safety operation control.

The paper is organized as follows. In Section 2, the surgical process with the RSSS is analyzed. A motion control algorithm of the RSSS is developed in Section 3, and a method for constraining the robot motion by combined VFs and DRVFs is proposed in Section 4. The real-time force sensing, real-time state recognition and safety operation control algorithm are proposed in Section 5. In Section 6, some experiments to verify the effectiveness of DRVF and real-time