Robotic System with Intuitive Control for Endoscopic Bone Cyst Surgery

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INTRODUCTION

With a rise in total joint replacement and bone tumor surgeries, complications such as osteolysis increasingly occur. Osteolysis can promote bone cysts to form, which reduces bone density and can delay the recovery process by causing fractures [1]. To prevent these fractures, bone cysts are often surgically removed.

Conventional bone cyst surgery requires a large incision to gain access to the entire lesion. Through this access window, the cyst is removed using a curet. The inside of the bone is cleaned by following suction and irrigation before it is injected with a drug to promote bone regeneration [2]. The large access window for reaching the lesion may weaken the bone and can be the cause of additional fractures, further delaying the patient's recovery. Preventative measures such as internal plate fixation also require additional scans and expose the patient to more radiation.

The da Vinci Surgical System (da VinciTM Surgical System, Intuitive Surgical Inc, Sunnyvale, CA, USA) is used for minimally invasive surgery on soft tissue. Due to the limited bending and drilling functions, the robot is not applicable to the lesion inside bone. Various continuum robots [3][4] have been developed to overcome this limitation. However, the developed robots have difficulty removing hard, fibrous membrane inside the lesion because of their insufficient rigidity.

In this study, we propose a robotic compliant joint based endoscopic surgery system for minimally invasive bone cyst surgery. The proposed system includes a flexible bone drilling instrument with high rigidity which removes the bone cyst, and a roboticized commercial flexible endoscope to provide visual feedback as well as suction and irrigation to clean the lesion. An intuitive control device with auto-rotation display is integrated. Several experiments in which simulated lesions have been removed from cow femurs have been performed to evaluate the system.

MATERIALS AND METHODS

The proposed system consists of three parts as shown in Fig 1. The drilling robot for removing the bone cyst, the endoscopic robot to provide visual feedback as well as suction and irrigation, and the control device to manipulate the drilling and endoscopic robot.

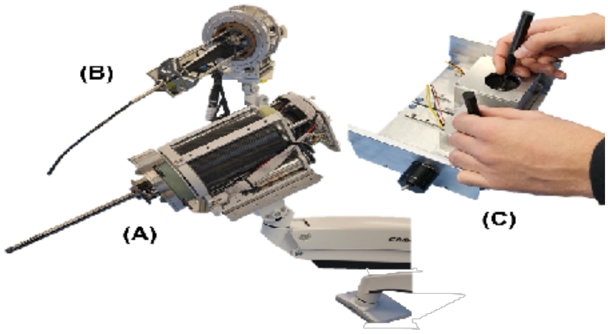

Fig. 1 (A) Drilling robot, (B) endoscopic robot, (C) leader devices

A. Drilling robot

The curved drilling instrument is actuated by the drilling robot giving it 3 degrees of freedom (DOF) (bend, rotate, translate). The notched compliant joint of the drilling instrument enables the drill to bend inside of the lesion after being inserted into the port. An additional DOF is used to rotate the drill bit, located at the distal end of the instrument. Bending of drilling instrument is enabled by the deformation of the notches from wire tension. Compared to other continuum robots, our robot can hold high wire tension because due to high intrinsic rigidity from the shape of the notches. For additional rigidity, two separate motors are used for each of the two bending wires. This enables counter-tensioning between the two wires. The high bending rigidity enables the drill to be precisely positioned during drilling despite repulsive forces being generated during the cyst removal.

B. Endoscopic Robot

The endoscopic robot provides visual feedback through 3 degrees of freedom (bend, rotate, translate) by using a motorized commercial endoscope (Olympus CYF-VHA). Cleaning inside the bone is performed through suction and irrigation added to the robot.

C. Control Device

Two control devices are used to manipulate the drilling and endoscopic robots respectively. It consists of a joystick and a linear guide with an encoder. The joystick controls the bending and rotation motion with each axis representing one motion, while the linear guide with the encoder controls translation separately. A joystick without spring-return is used for strict alignment with the drilling robot. The position of the joystick represents the position of the bend and rotation axes of the robot. Safe and intuitive control is possible because the surgeon can deduce the current robot position from the position of the joystick.

In addition, as the surgeon rotates the endoscope, the frame of reference rotates, making it more difficult to remain oriented and moving the drill in the correct direction. To overcome this issue, the endoscope video feed is counter-rotated against the endoscope rotation, enabling the view to remain unrotated regarding the determined view axis (Fig 2). As such, the endoscope can be manipulated freely without confusing surgeon's sense of direction.

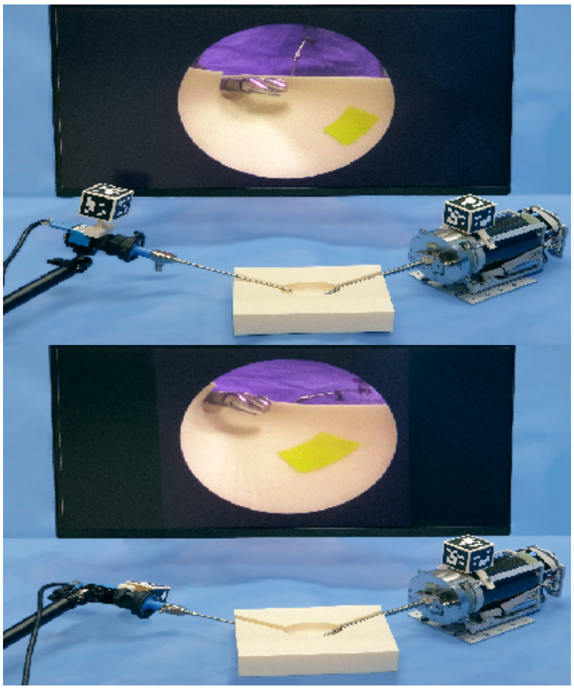

Fig. 2 (Top) 0° Endoscope with endoscopic view. (bottom) 90° Endoscope with adjusted endoscopic view (auto-rotation)

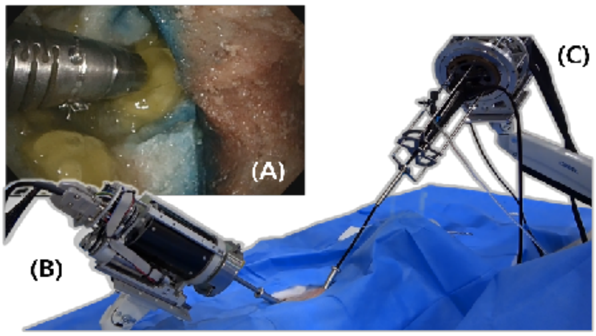

Fig. 3 (A) Experimental setup with endoscopic view, (B) drilling robot, (C) endoscopic robot

D. Experiment

To evaluate the feasibility of the proposed system animal experiments were conducted on cow femurs. Prior to the experiment, lesions were simulated by drilling out part of the femurs and filling it with agarose which has similar characteristics with a bone cyst. During the experiment, ports were drilled based on MRI scans of the femur. The drilling and endoscopic robots were inserted through the ports and removed the simulated bone cyst (Fig 3). To clean up the removed lesion, suction and irrigation of the endoscopic robot was used.

RESULTS

The experiments were conducted by three orthopedic surgeons. Without previous experience using the proposed robotic system, they were able to control the robot with little practice before the experiments. It was possible to approach to the entire lesion using the bendable drill. Because the drill has high rigidity and enough speed to drill the lesion, it was easy to remove the lesion from the bone. In consequence, the experiments verified the feasibility of the proposed system in terms of ability to remove bone cysts.

DISCUSSION

The proposed system is expected to reduce recovery time and decrease the risk of additional fracture due to the minimally invasive approach. The system's capability of removing bone cysts has been verified through a series of phantom and animal experiments. It is possible to apply the robot to various other orthopedic surgeries with requirements for high flexibility and high rigidity. The system will be further developed regarding user feedback, including both visual and force feedback. In addition, control interface modifications based on the kinematics will be developed for intuitive control by combining rotation and bending motions of the robot.

ACKNOWLEDGMENT

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