A novel passive/active hybrid robot system for orthopaedic surgery

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Background: Computer assisted orthopaedic surgery (CAOS) helps surgeons to perform surgical procedure with high precision resulting in better clinical outcomes. However, the physical tremor of the surgeons, surgical targeting display accuracy, visual misinterpretation of the trajectory, variation of surgeons' dexterity, during intraoperative procedure are the major factors giving rise to inaccuracies, which may cause serious or fatal neurovascular complications. This is particularly important for the minimally invasive procedures where accurate and precise execution is needed. Thus the development of semi-active surgical robotic arm system providing optimal positioning is essential.

Materials & Methods: A novel passive/active hybrid robot (HybriDot) system (Fig1) for orthopaedic surgery is presented based on the clinical-oriented user requirements. The modular system consisted of a robot, which works as an intelligent gauge for locking a jig or fixing in position and to guide and support the surgical tools and instruments during drilling and cutting in various orthopaedic surgeries, and a 2-D fluoroscopy-based surgical navigation software system, which is used for surgical interventions planning and robot supervision. The novel mechanical structure of HybriDot can be divided into two parts: a base with 2 DOF and a robot arm with 5 DOF (Fig. 6). The first two joints form the base, and the prismatic joint can be used to adjust the height of the robot arm to accommodate operation tables of different heights. The arc-shaped sliding joint can then be used to adjust the position of the robot arm around the axis of the patient's body. The five revolute joints supply the five degrees of freedom to the robot arm, thereby providing sufficient dexterity for most surgical procedures. The five revolute joints are driven by DC servo motors, and each one also contains an optical encoder, a harmonic reducer, and an electromagnetic brake. Each joint therefore offers active-passive hybrid control, which means that the revolute joints can be driven both by electric power and manually.

The control mode change between the active mode and passive mode of any individual motor can be achieved by changing the power status of the motor. When the motor is powered, the holding torque of the motor will lock the joint, and the joint can operate under an active control mode driven by electric power. When power is no longer supplied to the motor, the joint can be operated manually under the passive control mode. In both the active and passive control modes, the movement of the joint can be monitored by an optical encoder, and the joint can be freely changed from active mode to passive mode and vice versa. An electromagnetic brake that is engaged when overload of the robotic system is detected provides extra holding torque to ensure the safety of the robot system. It is well designed to have an appropriate workspace and to prevent the surgical system from the risk of collision to the operation theatre environment. At the same time, basic principle and the workflow of the robot system are also introduced. Three experiments were performed for test and validation: firstly, the positioning accuracy of the robot under the feedback of stereo camera, which is used for navigation system, is examined and validated. Secondly, the passive operation experiment of the robot was conducted under the simulation platform of a surgical model of intramedullary nail with distal locking holes (US Patented) to determine if the robot can be used as a passive robot. Lastly, clinical trials on distal locking procedure of intramedullary nails of femoral fractured patients were conducted and validated.

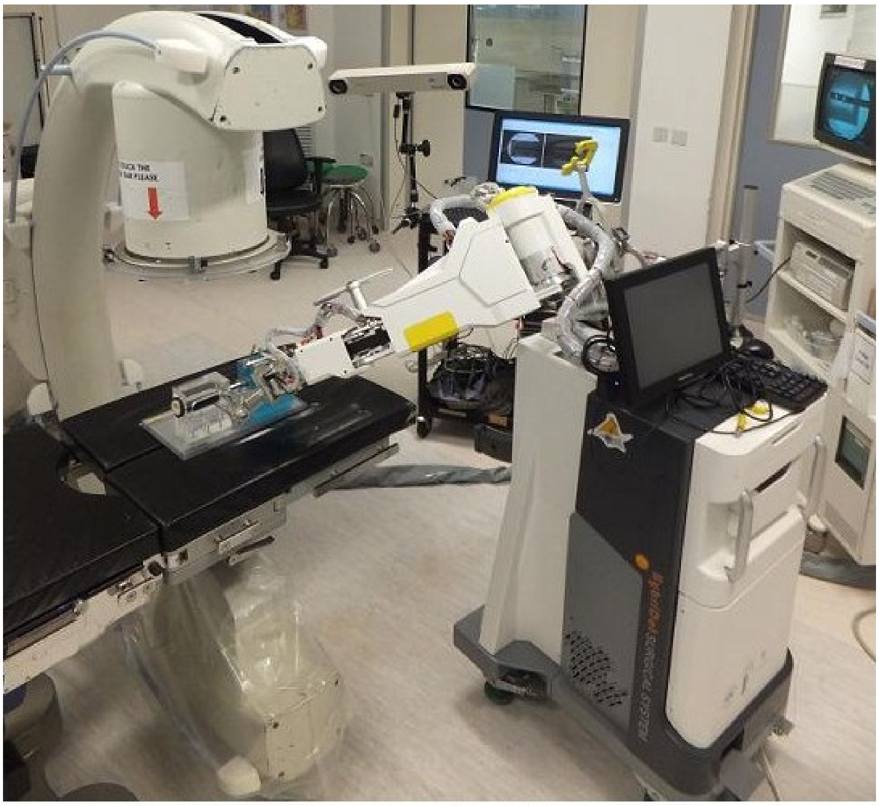

Fig.1. HybriDot System for Orthopaedic Surgery

	Mean error (ε_{avg})	Root mean square error (ε_{rms})	Standard deviation (ε_{std})	Maximum deviation (ε_{max})
Position (mm)	0.726	0.811	0.361	1.497
Orientation (°)	1.978	2.186	0.932	3.978

Table 1. Robotic system accuracy. The accuracy was determined as the root mean square error ()

Results: The positioning precision of the HybriDot system is tested. The root mean square value of the position accuracy is 0.811mm with the standard deviation of 0.361mm; and the root mean square value of the given orientation accuracy is 2.186º with the standard deviation of 0.932º, which are shown in Table 1. The passive operation experiment showed that the surgical system can provide the surgeons with enough rigidity and it can prevent the drilling tools from slipping and deviating from the planned trajectory during drilling process. Trials on distal locking of intramedullary nails in the operation theatre on patients with the HybriDot surgical system were completed successfully in one straight pass.

Conclusion: The robot with the novel structure and passive/active hybrid modes possess the advantages of appropriate workspace, well-designed human-robot cooperation, high accuracy, good rigidity, and easy implementation in the operation theatre. Experimental results have shown that it can be used as a positioning and guiding tool for multiple orthopaedic surgery procedures. More optimizing work and clinical tests will be done in future to improve the performance of the robot.

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