A total hip surgery robot system based on intelligent positioning and optical measurement

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Abstract—This paper represents the development and experimental evaluation of an autonomous navigation surgical robot system for total hip arthroplasty (THA). Existing robotic systems used in joint replacement surgery have achieved good clinical results, with reported better accuracy. While the surgeon needs to locate the robot arm to the target position during the operation, which is easily affected by the doctor’s experience. Yet, the hand-hold acetabulum reamer is easy to appear with uneven strength and grinding file. Further, the lack of steps to measure the femoral neck length may lead to poor results. To tackle this challenge, our design contains the real-time traceable optical positioning strategy to reduce unnecessary manual adjustments to the robotic arm during surgery, the intelligent end-effector system to stable the grinding, and the optical probe to provide real-time measurement of femoral neck length and other parameters to choose the prosthesis. The length of the lower limbs was measured as the prosthesis was installed. Experimental evaluation showed that the robot’s precision, execution ability, and robustness are better than expected.

Index Terms—THA, surgery navigation, end effector, center of rotation of the femoral head, femoral neck length.

I. INTRODUCTION

THA is one of the most important methods to significantly improve the symptoms of patients with hip diseases [1]. The quality of traditional THA surgery relies too much on the experience of doctors, and the intraoperative field of vision is limited, which is easy to cause the incorrect size choice and placement of the prosthesis. There may be complications like early dislocation, postoperative leg length discrepancy, and others [2]. Karl-Heinz Widmer et al. [5] suggested to reduce postoperative complications that the normal angle range of acetabular prosthesis placement: the abduction angle is 40°±10°, and the anteversion angle is 15°±10°. During the operation, the surgeon is difficult to correctly place the prosthesis due to lack of positioning information [6]. Bavarian Institute for Shock Trauma (BAMIT) and others [9], [10] suggested the appropriate grinding angle and the length of the femoral head prosthesis, thus reducing the unequal length of lower limbs after the operation. Currently, commercial hip surgery robots use visual navigation technology to guide doctors to accurately and quickly place the prosthesis with the help of external tracking devices [19], [20]. Early in 2007, RoboDoc (Integrated Surgical Systems, USA), has got results comparable to traditional surgical procedures [21]. Current hip surgery robots on the market, such as MAKO (Stryker, USA), have achieved good results in assisting THA. Its navigation system ensures accurate placement of the acetabular prosthesis [22], [23]. However, the existing hip surgery robot system has the following three shortcomings: Firstly, the cost is high and the popularity is low; Second, during the operation, doctors need to drag the robot arm to the position and require good clinical experience; Thirdly, when the length of femoral neck and the difference of both lower limbs after operation can make the patients feel better and recover faster. At present, there are several methods to adjust the length of femoral neck during operation. Kyoichio h et al. [14] used a ruler to measure the marked position of the posterior acetabulum before dislocation. The disadvantage of these mechanical structures is that the deployment of measuring equipment requires direct intervention in the patient’s surgical lesion, which may interfere with the surgeon’s operation. In addition, its versatility is not strong, and it is not convenient for surgeons to read quickly.

Recently, the clinical efficacy of surgical robots represents a hot topic among joint surgeons. It is reported that robot-assisted THA can significantly improve the precision of prosthesis placement and has obvious advantages over conventional THA in reducing the difference between the lower limbs [15]. Wider implementation of robotic surgery is expected as surgeons become more familiar with this method [18]. We can make the patient better recovery effect by selecting the appropriate grinding angle and the length of the femoral head prosthesis, thus reducing the unequal length of lower limbs after the operation. Currently, commercial hip surgery robots use visual navigation technology to guide doctors accurately and quickly place the prosthesis with the help of external tracking devices [19], [20]. Early in 2007, RoboDoc (Integrated Surgical Systems, USA), has got results comparable to traditional surgical procedures [21]. Current hip surgery robots on the market, such as MAKO (Stryker, USA), have achieved good results in assisting THA. Its navigation system ensures accurate placement of the acetabular prosthesis [22], [23]. However, the existing hip surgery robot system has the following three shortcomings: Firstly, the cost is high and the popularity is low; Second, during the operation, doctors need to drag the robot arm to the position and require good clinical experience; Thirdly, when the length of femoral neck and the difference of both lower limbs are measured during operation, the manipulation process is subject to the registration process of image space and surgical space, and the operation accuracy also depends on the registration accuracy. In addition, the real-time registration process is complicated and the surgical learning curve is long [24], [25].

In this paper, Based on the principle of optical localization, this paper first proposes a method based on real-time tracking localization to solve the difficulty of operating the robotic arm during surgery. It can improve the efficiency of the prosthesis position. Secondly, an imageless surgical navigation system
based on optical positioning is proposed. The femoral head rotation center and the femoral neck length were real-time measured by the probe. By comparing the length of lower limbs during operation, postoperative complications can be reduced. Additionally, the development of an intelligent end-effector system can evenly stable the grinding and improve surgery safety.

II. FRAMEWORK DESIGN

A. Autonomous navigation total hip arthroplasty robot system

We developed a surgical robot based on optical positioning and a multi-degree-of-freedom flexible robotic arm to help doctors eliminate subjective errors and improve the quality of hip replacement surgery. The framework of the robot system consists of preoperative planning and intraoperative execution (Fig.1). After preoperative 3D CT reconstruction, grinding path planning and hand-eye calibration were performed respectively. The calibration and navigation systems were designed based on the optical positioning system during the operation. It is very important to obtain accurate target position information from the calibrator and intraoperative navigation system to reduce the error of operation. The automatic calibration of the system solves the difficulty of traditional hand-eye calibration. At the same time, we include the end-effector development based on the 6-DOF flexible robotic arm, which has robust signal acquisition and character feedback functions. This end-effector is used for acetabular grinding during surgery, ensuring the safety of the process. More details are explained in sections II-B, II-C, and II-D.

B. Calibrators and Image Processing

The Calibration tool developed in this study is fixed on the end of the robotic arm through flange (Fig 2). The new coordinate system can be obtained by modifying the offset of the center of the end flange correspondingly. Therefore, the dimension parameters from the end flange connection center to the optical positioning ball center are calculated on the mechanical design drawing. We can read the coordinate information of the optical positioning ball center in the base coordinates of the manipulator. The robotic arm is controlled to move according to the set step length, and the coordinate information of the center of the optical positioning ball in the optical positioning instrument and the robotic arm base coordinate system is recorded. According to the singular value decomposition in referred literature [26], [27], error screening feedback, such as Algorithm 1, is added to complete the hand-eye calibration process.

After completing the hand-eye calibration described above, a 3D reconstruction of CT images of hip bones placed with a certain number of optical positioning balls is performed (Fig 3). On the reconstructed 3D model, the abduction angle, forward inclination angle, and cartilage thickness of the acetabular grinding are determined to plan the grinding path of the end actuator of the robotic arm. The 3D reconstruction model is then converted into a 3D point cloud, and the vertices of each sphere are selected and the contours of each sphere under the image coordinate system are segmented by Kd-Tree algorithm. Using the least squares method, each sphere’s contour under the image space coordinate system is fitted and the center coordinates output. The hip model thus marks the set of sphere center points \( H_{pic}, H_{cam} \) in image space of the optical positioning coordinate system. The transform relationship between the two, \( T_{pic}^{base} = T_{pic}^{cam} \cdot T_{cam}^{base} \), is calculated by the principle of Algorithm 1, and the surgical registration is completed. According to the transforming relationship of coordinates \( T_{base}^{pic} = T_{pic}^{base} \cdot T_{cam}^{base} \), the transform matrix \( T_{base}^{pic} \) is calculated to finish the path positioning. Detailly, \( T_{base}^{pic} \) is from image space to the base coordinate system of the robot arm, \( T_{pic}^{base} \) is from image space to the coordinate system of the optical locator, and \( T_{cam}^{base} \) is from the optical locator to base coordinate system of the robot arm.
Algorithm 1 Robotic calibration process for total hip surgery

**Require:** Plan the initial point and step size of the robotic arm movement

1. The robot arm moves according to the corresponding step length and records the hand-eye point pair set \( P, Q \)
2. \( P \) and \( Q \) are averaged: \( \bar{P}, \bar{Q} \)
3. Subtract the mean (center point) from the data: \( \tilde{P} = P - \bar{P}, \tilde{Q} = Q - \bar{Q} \)
4. Matrix calculation: \( H = \tilde{P}^T \cdot \tilde{Q} \)
5. SVD decomposition: \( U, S, V = SVD(H) \)
6. Rotation matrix calculation: \( R = V \cdot U^T \)
7. Reflection matrix detection
8. Translation matrix calculation: \( T = -R \cdot \bar{P}^T + \bar{Q}^T \)
9. Invert the robotic arm’s coordinate point set with a P point set: \( P_1 = R \cdot P + T \)
10. Error calculation: \( \alpha = P - P_1 \)
11. if \( \alpha = P - P_1 < \beta \) then
12. return \( R, T \)
13. else
14. repeat
15. reject the set of points with significant errors and repeat steps 3 through 11
16. until \( \alpha = P - P_1 < \beta \)
17. end if
18. return \( R, T \)

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Fig. 3. Surgical registration based on image registration.

C. End Actuators

The end effector of the surgical robot is applied to the process of acetabular grinding, and the structural composition is shown in Fig 4. As shown in Fig 5, the user can get the moving information and contact pressure according to the remote host computer and send control instructions to the microcontroller system through the wireless module. The microcontroller system controls the movement of stepper motor components and the rotation of the acetabulum reamer motor according to the control instructions. In this process, we used optical positioning systems to track the positioning balls, visualized the movement of the balls in real-time and passed to the host computer controller. At the same time, the pressure sensor is used to obtain the contact pressure of the reamer feedback. The database is established to store the morphological parameters corresponding to the reamer pressure and thickness in the clinical experiment. If the pressure threshold in the database is reached, the effector can be stopped in time and automatically reset, so as to avoid excessive pressure during the grinding process which causes harm to the patient. It realizes intelligently controlling the acetabulum reamer to grind evenly and safely.

D. Intraoperative Measuring and Navigation

In this study, a control scheme for the spatial measurement of key points in hip replacement surgery is proposed. The hip model is placed in a lateral recumbent position. By using the self-designed position monitoring calibration tool, the established patient’s human body coordinate system is used as the reference coordinate system, to show the real-time intraoperative patient position change monitored by the display of the surgical navigation interface. A rigid body coordinate system is established from three noncollinear positioning balls on the end. The end effector is parallel to the desktop and placed under the optical positioning system. The spatial coordinate information is initialized to zero. When the reamer on the end effector is intelligently positioned, the rigid body coordinate system is visualized in real time relative to the spatial information. It can assist the doctor in determining
whether the grinding angle is within the normal range. In order to improve the accuracy of grinding angle measurement, we propose a method of intelligent adjustment of robotic arm attitude based on real-time optical feedback. After getting the transforming relationship from the optical locator to the base coordinate system of the robotic arm according to Algorithm 1, the theoretical value of the angle of the robotic arm can be calculated by entering the expected value on the optical locator coordinate system. The difference between the expected value and the true value obtained by the optical locator after the execution of the robot arm can be added to the expected value. Thus, the angle of the robot arm can be adjusted when the difference is taken as an input value. This iterates continuously until the error meets the requirements. Importantly, an intraoperative image-free measurement scheme based on optical positioning probes is proposed. As shown in Fig 6, it is realized by probing the rotation center of the femoral head and the length of the femoral neck after the femoral stalk prosthesis is installed. According to the theoretical value of preoperative measurement, the comparison between the selected femoral bulb and the femoral neck prosthesis is determined. Finally, the final femoral bulb prosthesis can be accurately selected. Then the length of both lower limbs under the selected prosthesis is measured for further verification and feedback.

III. METHODOLOGY

In this study, we focused on validating the execution accuracy of the total hip surgery robot, the stability of the acetabulum reamer, and the feasibility of the navigation scheme. The research protocol for the complete surgical procedure is as follows: Preoperative - Prepare a hip model with optical spheres (Fig 7b, male, PVC material), 3D reconstruction after a preoperative CT scan to get the planned surgical path. Intraoperative - A position monitoring tool is firstly installed to simulate the calibration process for position monitoring, use clamps to secure the hip bone to the operating table in the lateral recumbent position (Fig 7a), the robot completes the calibration positioning, the intraoperative precision navigation system measure the grinding angle in real-time (e.g. abduction angle 40°±10°, forward inclination angle 15°±10°), verify the intelligent control function of the end effector during the grinding process. We applied the intraoperative navigation system to a 1:1 skeletal model of the human body (Fig 7e, male, PVC material). Protocol: Use the optical probe (Fig 7d) to measure the rotation center of the femoral head, the length of the femoral neck, the length of both lower limbs and other parameters, use a mechanical device to measure the rotation center of the femoral head and the length of the femoral neck as a comparative experiment, at the same time fix the ankle above the calibration pad and place millimeter paper under the pad (Fig 7f), place a fixed reference block in the hip (Fig 7g), simulate different experimental situations by making the two lower limbs move at different distances with the pad to test the accuracy of the measurement scheme.

A. Test 1

The purpose of the first test is to evaluate the accuracy of the intelligent positioning of the robot. As shown in Fig 7f, we use the self-developed calibration tool to verify the transforming accuracy of the whole machine under the optical locator, the robotic arm, and the image space coordinate system. 1) The operator selects the initial posture \( A_0 \) of the calibration tool at the end of the robotic arm before surgery [28]. That is the position in the middle of the optical locator’s field of view. Once the initial posture has been determined, it is moved in a certain step length in subsequent calibration steps. Initial posture \( A_0 \) can be expressed as the following:

\[
A_j = (x_0, y_0, z_0, r_{x0}, r_{y0}, r_{z0})
\] (1)

2) The robotic arm makes the corresponding offset movement according to the planned step \( k \) and the rotation amount \( \theta \) under the base coordinate system X, Y, Z of the robot arm. The expression of the corresponding posture field is shown in (2):

\[
A_0 = (x_0 + k, y_0 + k, z_0 + k, r_{x0} + \theta, r_{y0} + \theta, r_{z0} + \theta)
\] (2)

3) By the error between the inversed and actual robot arm coordinates, the threshold value is set to 2mm. Then the system calculates the optimal rotation matrix \( R \) and translation matrix \( T \) between point set \( A_i \) and \( B_i \) under the coordinate system of the robotic arm and the optical locator.
B. Test 2

The purpose is to evaluate the effect of arm’s grinding angle measurement in real-time during the operation after intelligent positioning. 1) Fix the hip on the lateral recumbent position on the platform forceps and set the calibration initialization of the end effector parallel to the hip model (Fig 8a). The relative angle of tools on the end effector with positioning balls attached is the abduction angle and forward tilt angle of the intraoperative reamer (Fig 8b). Placement of optical monitoring tools simulates intraoperative real-time observation of hip position changes.

2) After the doctor plans the grinding angle in the image space, the angle is converted to the coordinate system of the robotic arm through the optical locator. The robot autonomously reaches the target attitude according to the theoretical calculation, and the optical locator tracks and outputs the spatial attitude of the optical sphere on the end in real-time, thereby obtaining the angle error value. The desired theoretical value of the optical locator plus the error value is used as input, and the angle error threshold value is set to 0.5°. Iterating continues until the experimental requirements are met.

C. Test 3

This is used to verify the intelligent control function of the end effector. When the arm is positioned, the system locks it. The reamer is moved by a stepper motor, and when it contact with the acetabular, the grinding motor automatically starts. Driven by the stable stepper motor, it grinds the hip bone model evenly in a fixed direction. Simultaneously, real-time visual pressure detection is carried out and the safety threshold is set to 30N. When the grinding file process reaches the threshold value, grinding intelligently stops and resets.

D. Test 4

To evaluate the measurement of the rotation center of the femoral head, femoral neck length, and double lower limb differences in the intraoperative precision navigation system. The experimental setup is shown in Fig 9. Firstly, the rotation center and the femoral neck length are measured by an optical positioning probe. The measurement is repeated 10 times. Secondly, by simulating the measurement of the difference between the two legs after surgery, the left leg and the right leg are moved along the longitudinal direction of the millimeter paper by 5 mm and 10 mm and repeated 10 times respectively. 1's shown in Fig 9a, a 3D printed model (femur stalk inserted into the femur) is used to simulate the anatomy measurement during surgery. The actual length of the rotation center of the femoral head to the femoral neck c is obtained by the end of an optical probe, which measures the distance from the highest point to the osteotomy surface minus the radius of the femoral head prosthesis (Fig 9b). The coordinates P1 (x1, y1, z1), P2 (x2, y2, z2), and P3 (x3, y3, z3) of the three reference points are taken sequentially from the osteotomy surface of the affected limb, and the coefficients A, B, C, and D of the osteologic surface equation are calculated by equation (3).

\[ Ax + By + Cz + D = 0 \]  

The measurement point of the femoral spheroid prosthesis is the highest point P4 (x4, y4, z4) on the femoral spherical prosthesis, and the distance calculation formula (4) is used to calculate the distance between the osteotomy surface of the affected limb and the measurement point e.

\[ e = \frac{Ax + By + Cz + D}{\sqrt{A^2 + B^2 + C^2}} \]  

where x, y, and z represent the coordinate values of the measurement point respectively, e represents the distance between the osteotomy surface of the affected limb and the measurement point.

2) Choose the right type of femoral head prosthesis. Prepare three different depth models of red, blue, and white femoral head prostheses (Fig 10), and make reasonable adjustments to compensate for preoperative errors according to the rotation center and the femoral neck length measured in real-time.

3) After the prosthesis is installed, the length of the affected leg is measured in real-time. We compare the measured values obtained with the preoperative measurements. Finally, the reliability of the measured values is further verified and fed back by comparing the length of the affected leg with the length of the normal leg measured before surgery.
Fig. 10. Selecting prosthetic specifications; c is the actual length from the rotation center to the osteotomy surface.

Fig. 11. Preoperative robot reamer entry path planning.

IV. RESULTS & DISCUSSION

A. The surgical robot calibrates the positioning control

In order to further accurately evaluate the positioning accuracy of the surgical robot, the calibrated robot moves from the safe position and locks the robotic arm at the actual position before performing the grinding action. Preoperative surgical path planning (Fig 11) is performed to determine the optimal grinding angle of the robot, and then determine the safe point, grinding point, and target point position in the image space.

The actual motion trajectory of the reamer at the end of the manipulator during surgery (Fig 12) requires the calculation of the spatial distance between its theoretical positioning value and the real positioning value. As shown in Fig 13, the average Euclidean error of the experiment in the three-dimensional direction is 2.467mm on the x-axis, 2.289mm on the y-axis direction, 3.233mm on the z-axis direction, and 4.862mm is the total error.

B. Robot measurement navigation system evaluation

The measurement results of the surgical robot for the patient's hip morphological parameters are as follows. When the robot reaches the theoretical coordinate point, no feedback adjustment is added, and the average error of the forward tilt angle and abduction angle (Fig 14a, Fig 14c): 0.99°, 1.79°. After adding feedback to adjust the attitude of the robot, the average error of the forward tilt angle and abduction angle (Fig 14b, Fig 14d): 0.22°, 0.15°. After the robot arm reaches the theoretical value, it is fed back by the output data of the optical positioner to improve the accuracy of the grinding angle. CAD models of femoral neck prostheses with red, blue, and white femoral heads are 58 mm, 59 mm, and 60 mm in size. As shown in Fig 15, they use optical probes to measure that the average error is 0.071mm, 0.118mm, and 0.087mm, respectively. The average error measured by mechanical equipment is 0.287mm, 0.278mm, and 0.307mm. So, it is proven that the optical probe has high precision and can effectively assist doctors to perform surgery.

As can be seen from Table 1, the following conclusion can be drawn: When the two lower limbs do not move, the average difference between the two lower limbs is 0.17 mm. When the affected limb moves down 5 mm and 10 mm longitudinally
The end effector. It is more intelligent than existing total hip replacement surgery robots and has important implications. In addition, we used the accurate intraoperative measurement navigation system of optical probes, which measures the rotation center of the femoral head, the femoral neck length, and the difference between the two lower limbs in real-time during the operation. It can effectively assist the doctor in making surgical decisions and selecting the appropriate prosthesis to minimize preoperative errors. This study is only analyzed in simulation experiments, and the next step will be expected to enter clinical trials for further verification.

V. CONCLUSION

Overall, this paper proposes an autonomously navigated robotic system for THA surgery. During the operation, intelligent positioning to the preoperatively planned target and the grinding angle with high accuracy, and automatic operation of the end effector.

C. End effector control

The motor of the end effector performs the grinding scheme according to the data instructions for grinding the cartilage model and the hip bone model. As shown in Fig. 16a and 16c, the end effector file can be ground normally and stopped. In Fig. 16b and 16d, it can stop and exit with an emergency shutdown given a pressure value of 30 N.

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Fig. 14. Real-time measurement of the grinding angle after the robotic arm is positioned. a) The change curve of the forward tilt angle and abduction angle without feedback; b) The change curve of the forward tilt angle and abduction angle after adding feedback.
Fig. 15. Comparison of HPTOS measurements. a), b), and c) are the measurement of HPTOS with red, blue, and white femoral heads respectively.

Fig. 16. Grinding pressure change curve. a) normal pressure withdrawal when grinding the cartilage model; b) excessive pressure withdrawal when grinding the cartilage model; c) normal pressure withdrawal when grinding the bone model; d) excessive pressure withdrawal when grinding the bone model.

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